NSTX-U

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NSTX-U 5 Year Plan for Particle Control and Analysis for ST-FNSF

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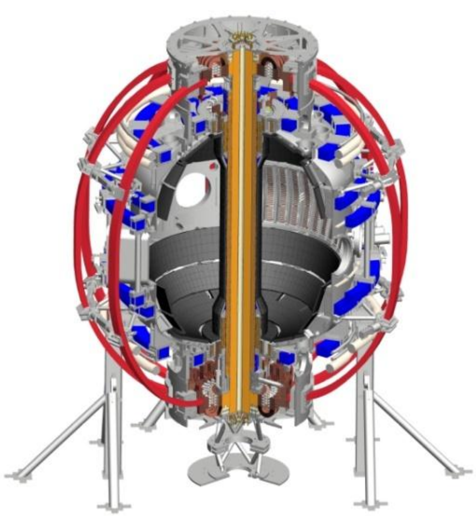
For the NSTX Research Team

NSTX-U PAC-33 Meeting
PPPL – B318
February 19-21, 2013



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Motivation and overview of talk

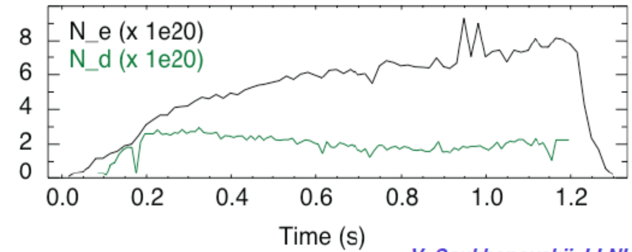
- Particle control needs for NSTX-U:
  - Need to avoid density limit, radiative collapse during long-pulse shots
    - Greenwald fraction f_G~0.7-1.0 sufficient for non-inductive studies
  - Lower density to access reduced collisionality physics
    - f_G~0.3-0.5 desired
  - Develop FNSF-relevant pumping scenarios
- Plans for Years 1-2 of NSTX-U operation: lithium and ELMs
  - Lithium provides deuterium control, without saturation in ~1 s in NSTX
  - Impurities can be flushed using ELM triggering to control radiation
  - Lithium granule injector is main upgrade to NSTX-U
- Plans for Years 3-4 of NSTX-U operation: cryo-pumping
  - Physics design of pumping system
  - Preliminary analysis of FNSF pumping geometry
- Goal for end of 5-year plan: stationary n_e, f_G~0.5, low Z_{eff}~2-2.5

Particle control in NSTX-U will be accomplished with variety of fueling and exhaust techniques

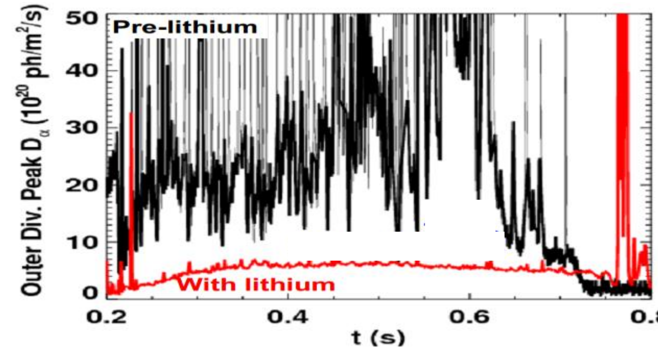
- NSTX-U will compare novel and conventional exhaust techniques
  - Lithium for deuterium pumping+ELM-triggering for impurity expulsion
  - Cryo-pumping of ELMy H-modes
- Conventional and advanced fueling techniques will be used
  - Supersonic gas injector (fast time response, ~1ms)
  - Conventional gas injectors (located at HFS, LFS, shoulder)
- Ultimately these will combined for active control over density
  - Will require efforts of ASC and BP TSGs
  - This talk will focus on exhaust (most challenging aspect in NSTX)

Lithium is sufficient for controlling deuterium, with no evidence of saturation of lithium pumping in ~1 s discharges

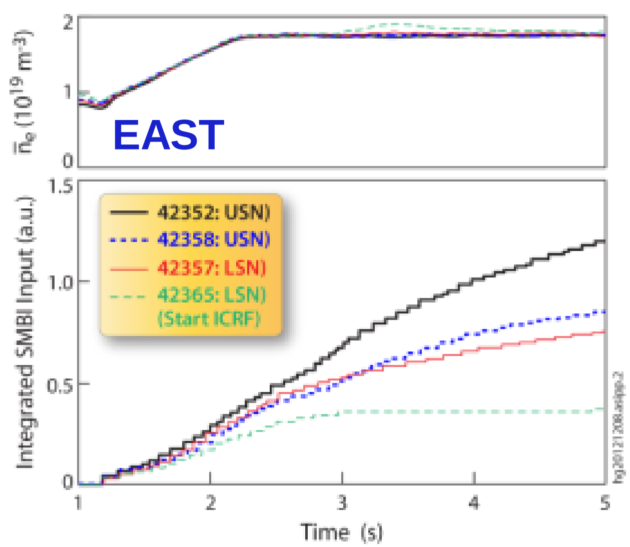
- Plasma following strong lithium conditioning show stationary, low deuterium content
- Recycling remains reduced throughout ~1 s discharges (Boyle, PSI '12)
  - No increase near end as expected if lithium pumping is saturated



V. Soukhanovskii, LLNL

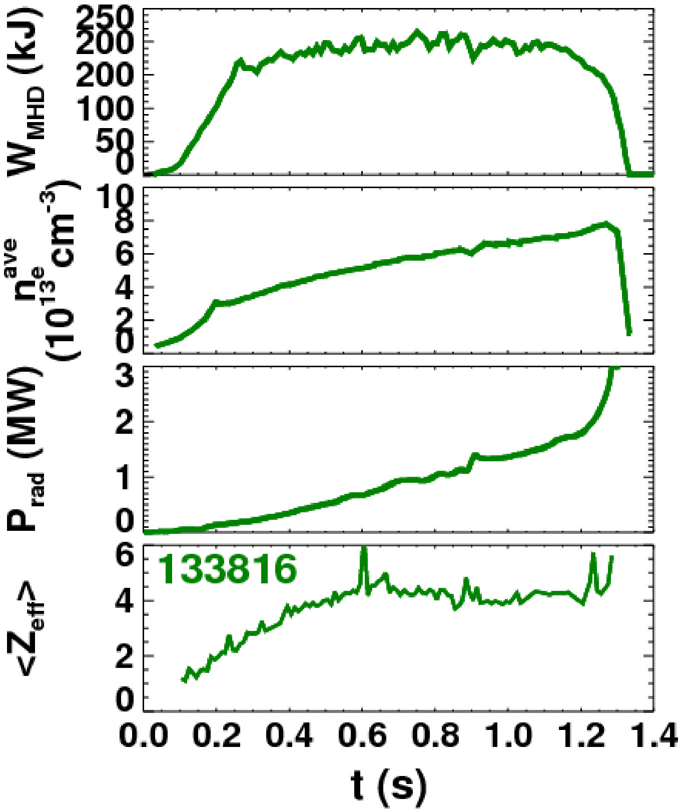


- EAST collaboration supports use of pumping by lithium coatings for NSTX-U pulse lengths (Guo, IAEA '12)
  - L-mode, I_p=0.4 MA, P_{RF}=1MW, LSN shots
  - Fueling required to maintain constant n_e compared for shots following Li deposition
  - Effective e-folding time for lithium pumping is ~18 shots or 180 s
    - Pumping persistence in higher-power H-mode plasmas to be assessed in future experiments



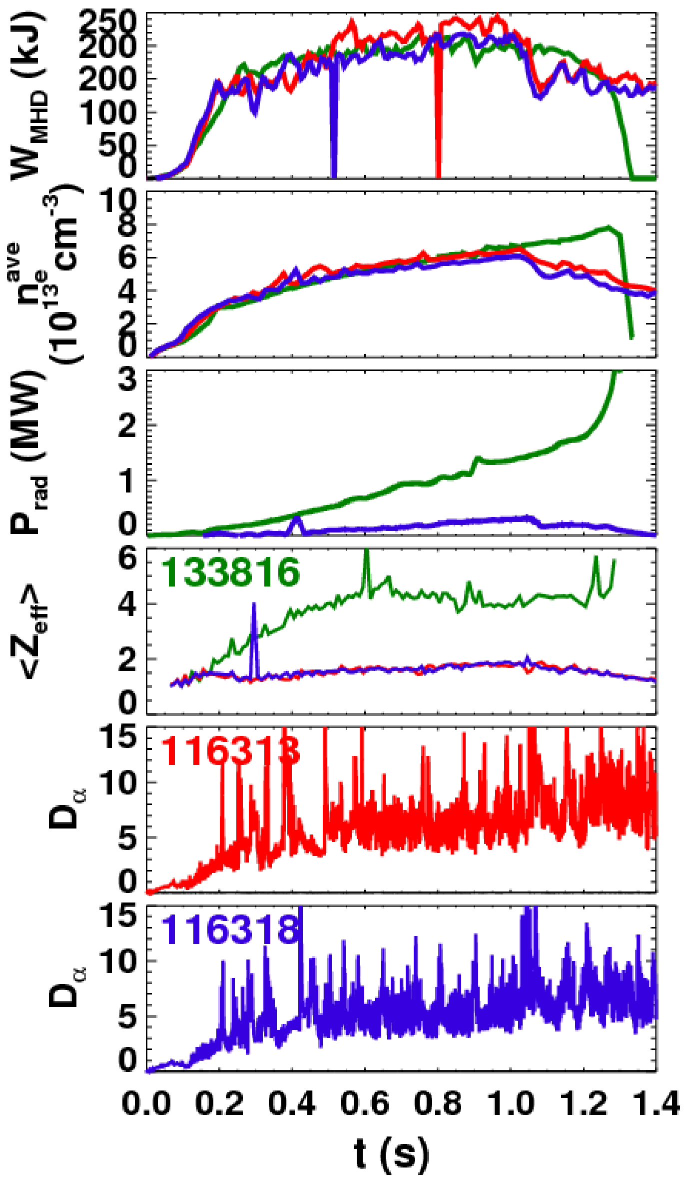
ELM-free lithium operation exhibits impurity accumulation

- Without impurity flushing from ELMs, P_{rad} ramps, Z_{eff} is high (~4)
  - Radiation from high-Z, Z_{eff} from Carbon
  - Fairly typical for ELM-free H-mode



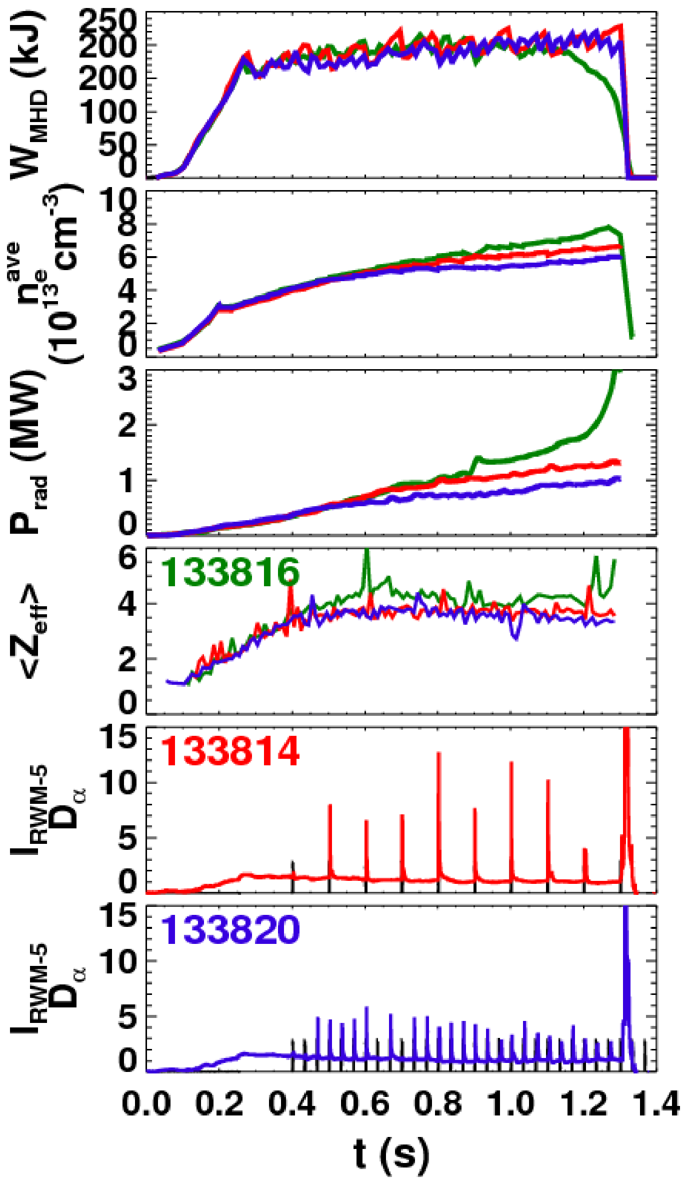
ELMy H-modes with boronized carbon PFCs will be developed in years 1-2 of NSTX-U operation

- ELMy discharges without lithium showed low impurity content
- Density still ramps throughout shot (until core MHD)
- Low-Z_{eff} plasmas with boronized PFCs discharges will be further developed
  - Optimize fuelling and discharge formation to minimize gas input
  - Utilize between-shot He glow to provide a conditioned wall
  - Deuterium inventory likely to rise throughout the discharge
  - Will serve as basis for cryo-pumped scenarios when cryo is installed



Years 1-2 of NSTX-U operation will test lithium for deuterium control, with ELMs to mitigate impurity accumulation

- ELM-triggering with 3D fields helps to expel impurities (Canik NF '12)
  - P_{rad} can be kept below ~1 MW fairly easily
  - Modest reduction in n_e ramp, Z_{eff}
- Initial NSTX-U operation will test the use of lithium+ELMs for particle control
  - Likely limited to high f_G(~0.8-1.0) and high Z_{eff} (3-3.5)
  - Should allow pulse lengths past ~1.5 s, how far past is TBD
- FY15 goals will be to re-establish, and extend ELM-paced scenarios
  - Combine with other methods for reducing impurities (e.g., divertor gas puff, snowflake)
  - Improve ELM triggering (vertical jogs, Li optimization to avoid ELM suppression)

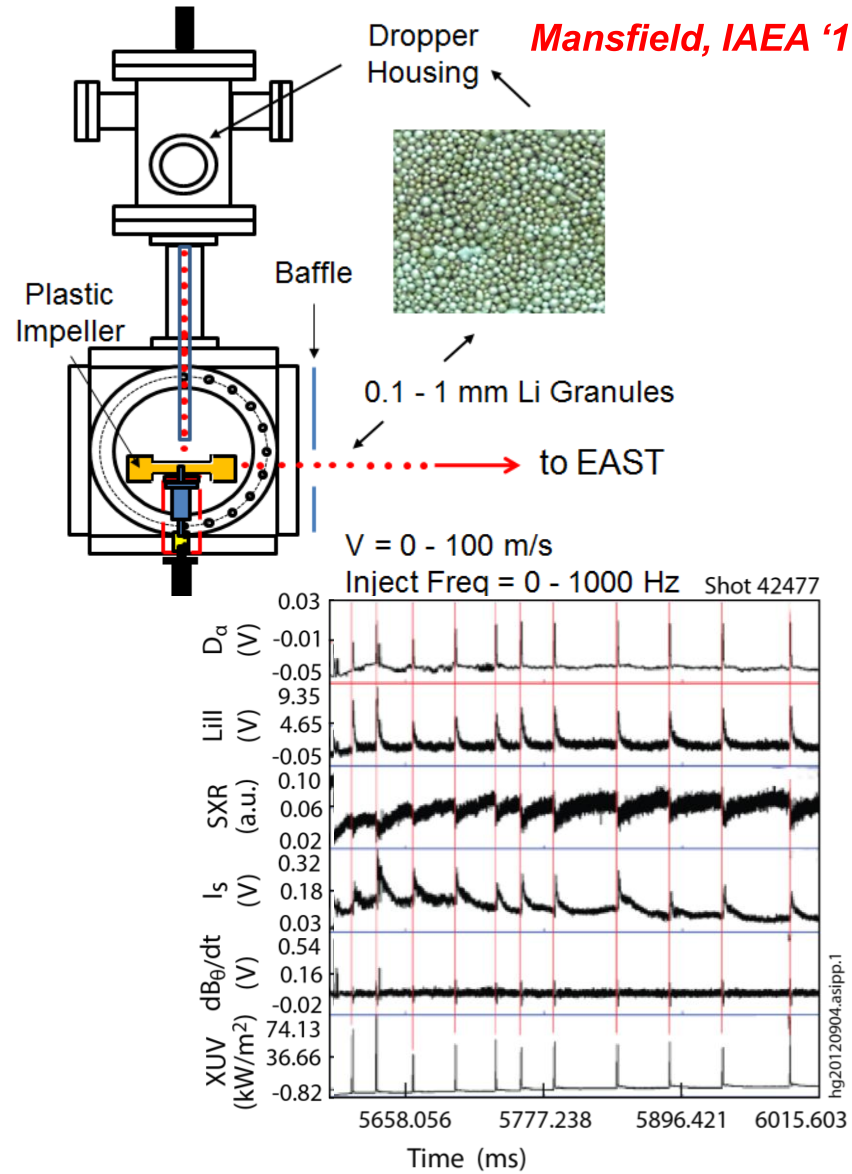


Late FY15/early FY16 lithium+ELMs scenarios will be enhanced by Lithium Granule Injector

- LGI will be tested for high-frequency ELM pacing for impurity control
  - Pellet ELM pacing established method for reducing ELM size, controlling impurity content (Baylor APS/IAEA '12)
  - Potential for more benign, high frequency ELM triggering
  - Injection of lithium pellets could potentially replenish coatings on PFCs
  - Scheduled to be installed at end of FY15
  - Goal: reduce Z_{eff} to ~2-2.5

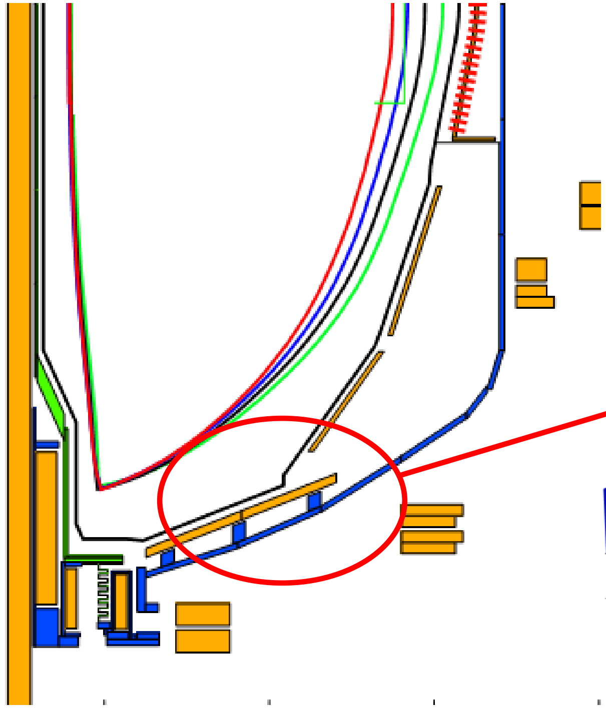
- EAST collaboration has shown LGI ELM-pacing potential
  - Demonstrated ELM-pacing at 25 Hz with nearly 100% triggering reliability
  - Capable of up to 1 kHz injection

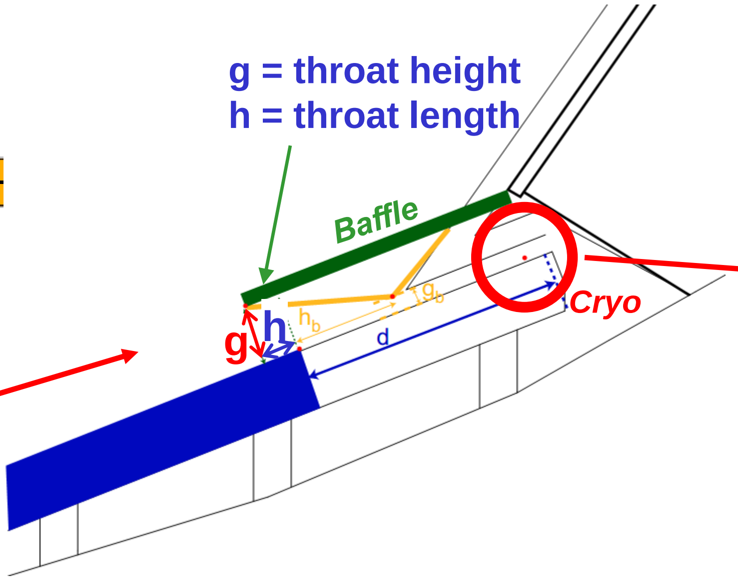
Mansfield, IAEA '12

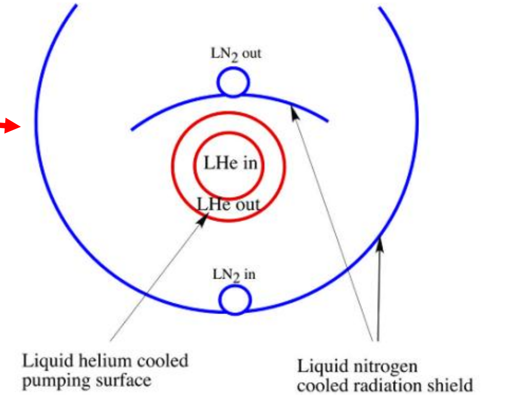


NSTX-U Years 3-4 will utilize cryo-pumping for particle control

- Cryo-pump is proven technology for plasma density control
  - More conventional pumped ELMy H-mode scenario
- NSTX-U design is similar to DIII-D outer lower pump
  - Plenum located under new baffling structure near secondary passive plates
  - Pumping capacity of a toroidal liquid He cooled loop
    - S=24,000 l/s @ R=1.2m (Menon, NSTX Ideas Forum 2002)
  - Need plenum pressure of 0.6 mTorr to pump beam input (TRANSP)



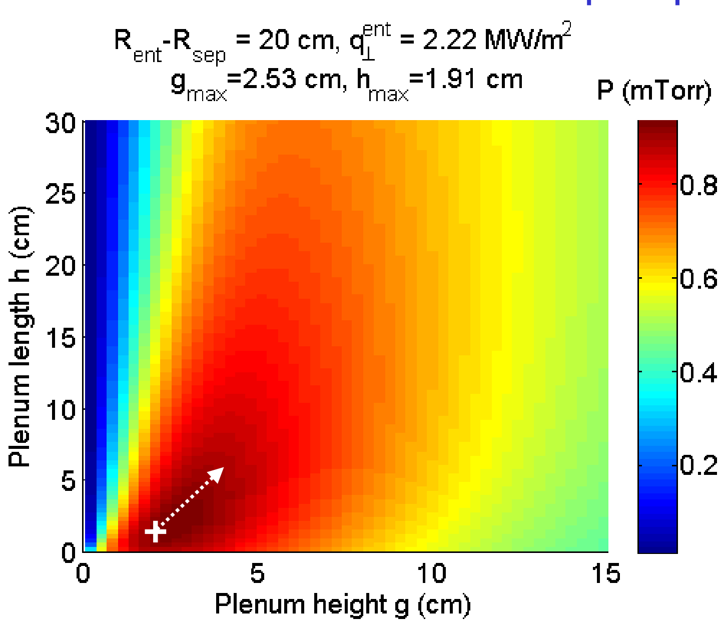


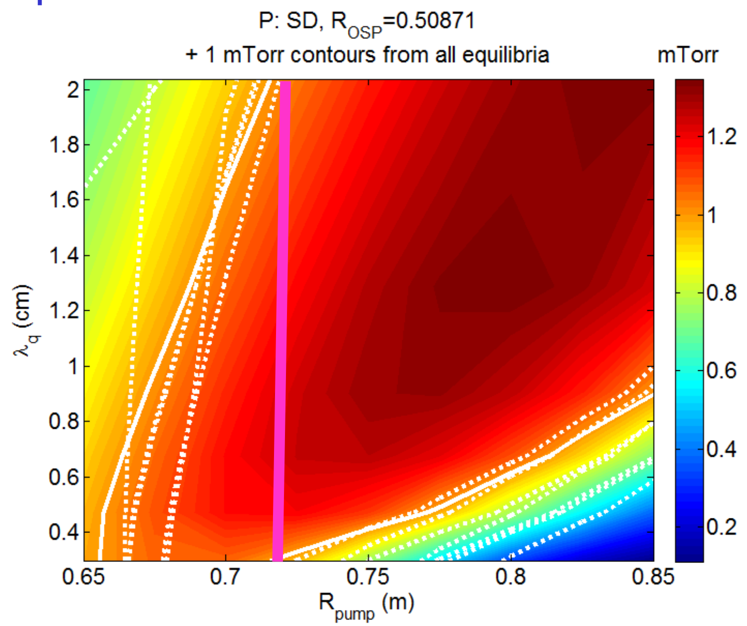


Cross-section of the pump (10 cm outer dia.)

Semi-analytic pumping model used to optimize plenum geometry

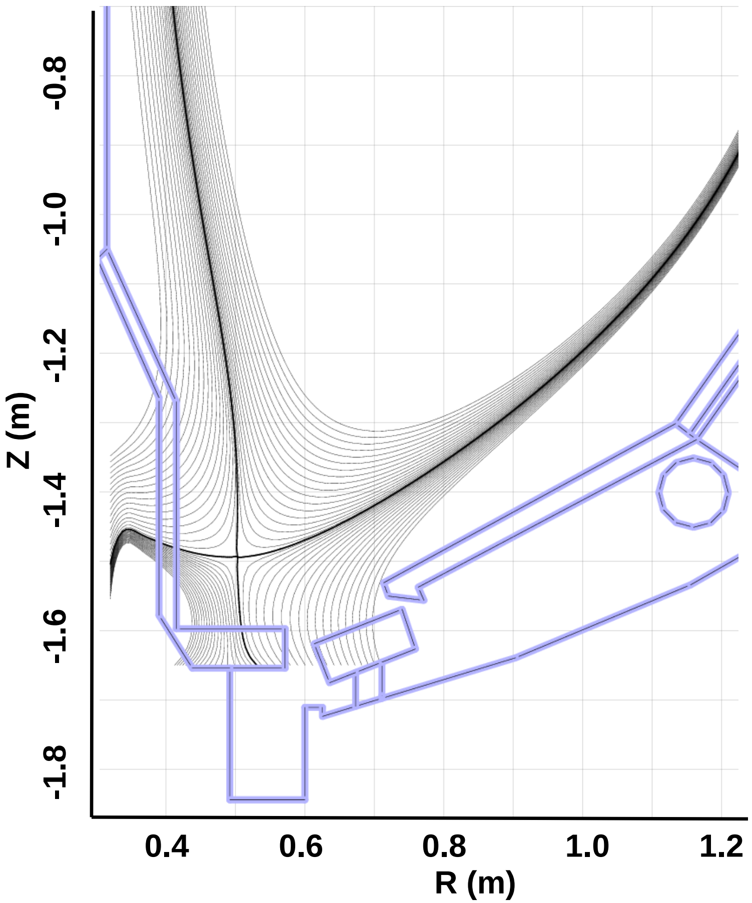
- Model developed for DIII-D pumping studies (Maingi, NF '99)
  - Predicts plenum pressure, validated with DIII-D data
  - Projected NSTX-U heat flux (I_p scaling) and divertor T_e (~15 eV) used as input
  - Uses first-flight neutral model (insufficient for detached divertor)
- Pressure is maximum for duct height g~2.5 cm, length h~2 cm
  - But is only weakly reduced if these are increased together
- With pump entrance at R=0.72m, pressures >1 mTorr can be reached over wide range of plasma shapes and SOL widths
  - Comparable to pressures in DIII-D plenum
  - Well above that needed to pump NBI particle input



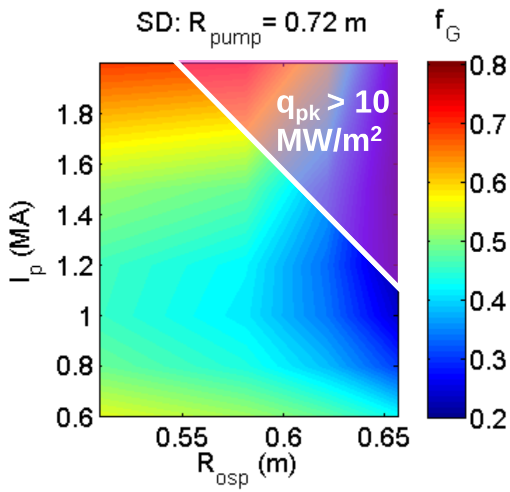


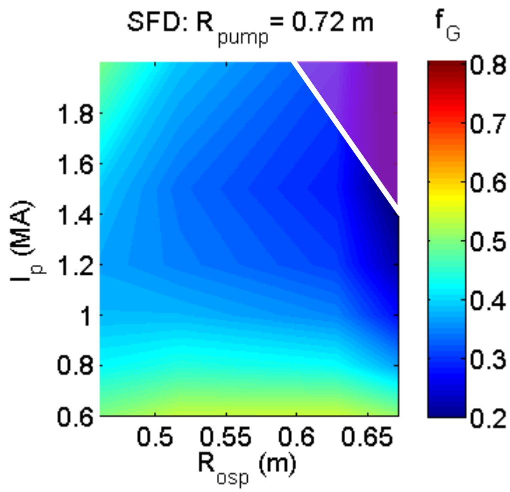
Optimized plenum geometry can pump to low density for conventional and snowflake divertors over a range of R_{OSP}, I_p

R_{OSP}: outer strike point radius
R_{pump}: plenum entrance radius
SD: standard divertor
SFD: snowflake divertor
f_G: n_e/n_G



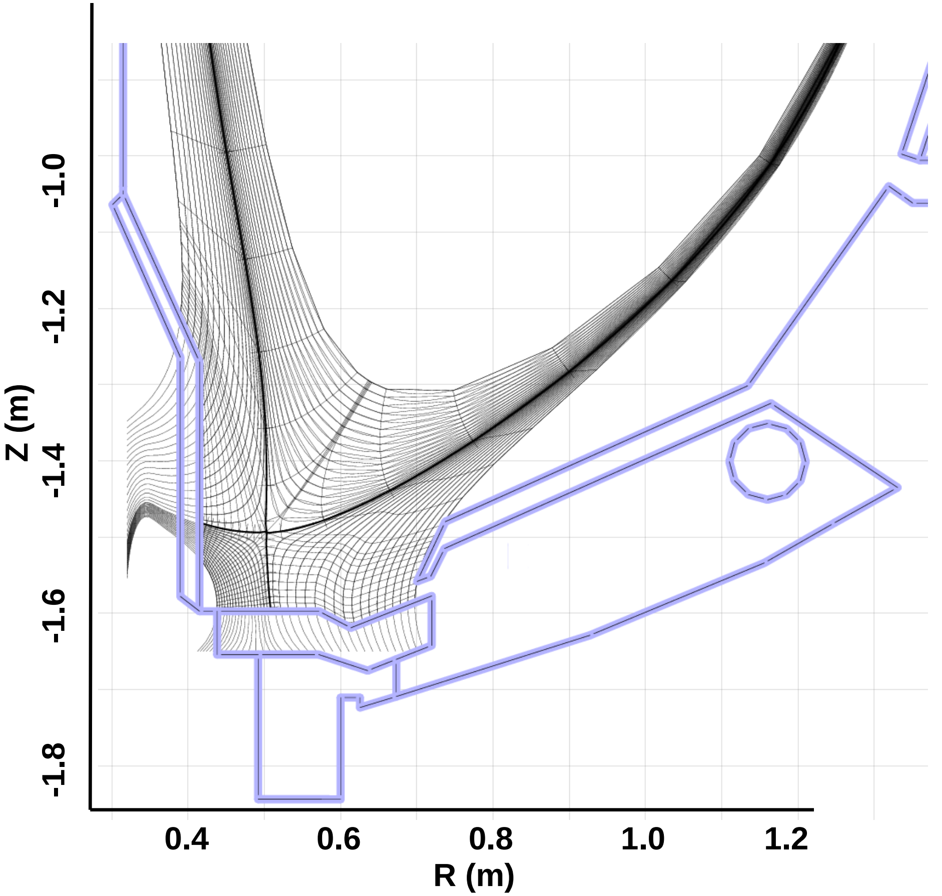
- Core density estimated assuming pumped flux=NBI input
  - 2-pt model used to estimate upstream density
  - Assume n_e/n_e^{sep}~3
- Can pump to f_G<0.5
  - f_G~0.7 desirable for all scenarios, lower provides more flexibility
  - Moving R_{OSP} closer to pump allows lower n_e, but limited by power handling
- 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 calculations confirm optimization approach based on analytic model

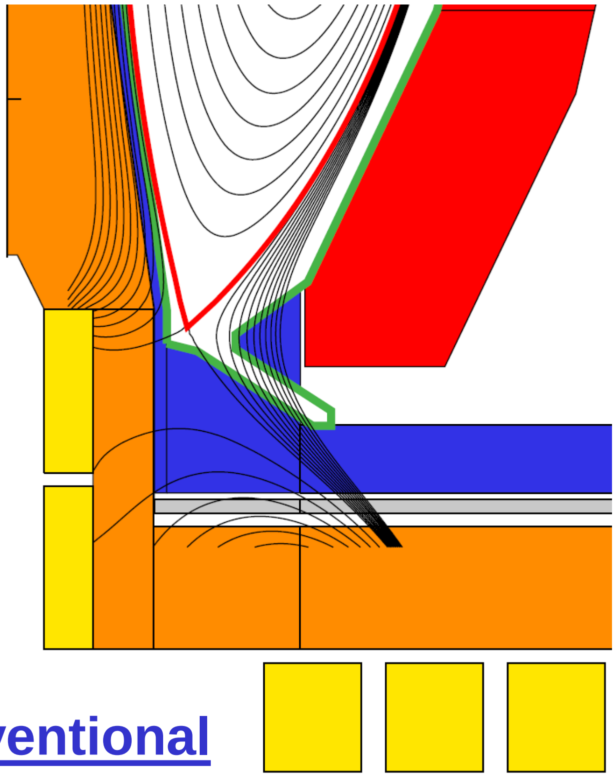
- SOLPS: 2D fluid plasma/neutral transport
  - Plasma transport classical parallel to B (+kinetic corrections), ad-hoc cross-field transport coefficients
  - Kinetic neutral transport using MC code EIRENE
    - More comprehensive treatment of neutral transport (beyond first-flight)
    - Can treat radiative/detached divertor
- Range of divertor conditions have been produced using standard and snowflake equilibria
- SOLPS-calculated plenum pressure agrees with analytic model for T_e^{div}>2 eV, factor of ~3 higher in detached regimes



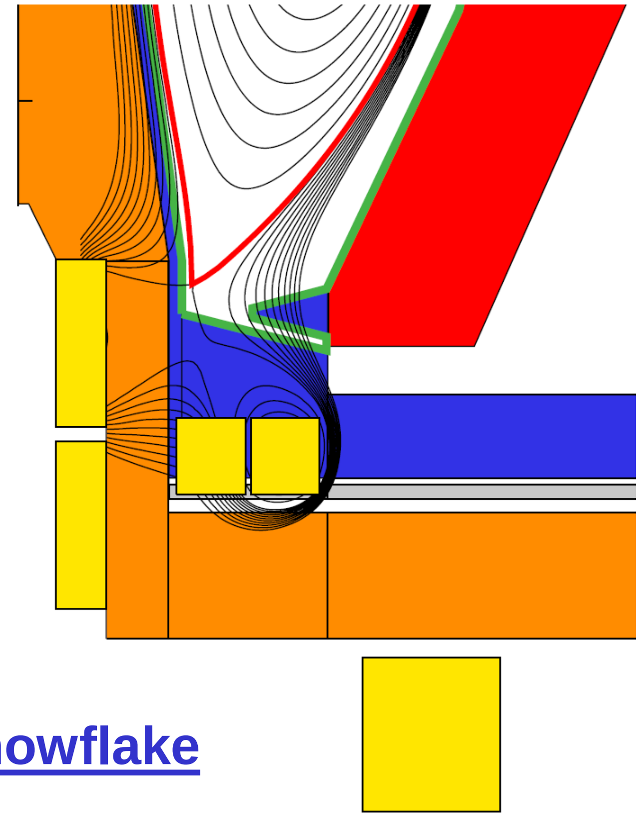
⇒ ***Optimization of design presented here is conservative***

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

NSTX-U cryo experiments will support FNSF



Field-line angle of incidence at strike-point = 1°



Conventional

- **Flux expansion = 15-25, δ_x ~ 0.55**
- **$1/\sin(\theta_{plate})$ = 2-3**

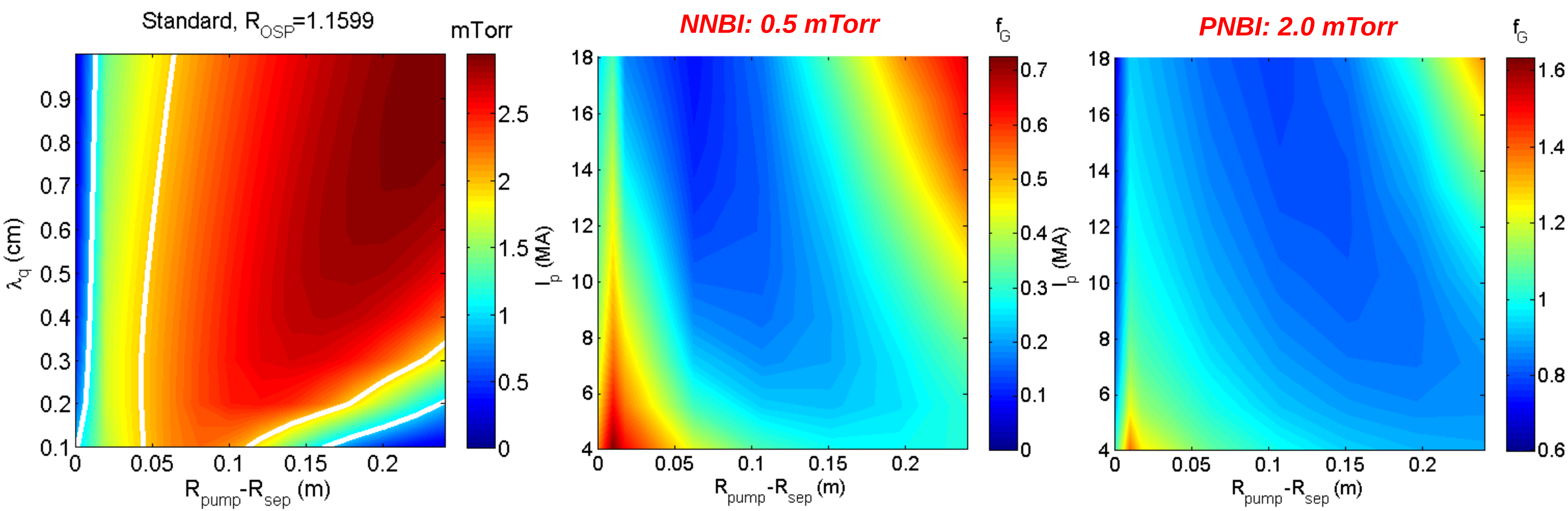
Snowflake

- **Flux expansion = 40-60, δ_x ~ 0.62**
- **$1/\sin(\theta_{plate})$ = 1-1.5**

- SOL-side pumping could enable FNSF
  - Compact FNSF designs leave little room for vertical target+dome for ITER-like PFR pumping

FNSF pumping trends are similar to those in NSTX-U design, projections will be improved by NSTX-U measurements

- Analytic model used to optimize geometry, with assumed T_e(=5 eV) and λ_q
- High pressures (>2.5 mTorr) are achievable with SOL-side pumping
  - With NSTX-U-like pumping speed, need to reach 0.5 (NNBI) to 2 (PNBI) mTorr
  - SD and SFD results are similar, since PFC geometry is altered to keep the plasma-wetted area the same
- Achievable densities are promising
  - NNBI leads to f_G<0.2 (compatible with Peng, FS&T '11 FNSF designs)
  - For PNBI, f_G~0.8 (sufficient for Menard, NF '11 ST-FNSF designs)
- NSTX-U will provide first results on density that can be achieved with an FNSF-like pumping system
  - Needed to benchmark and improve models for projecting the density and SOL width



NSTX-U particle control plans will develop and compare complementary approaches to particle exhaust

- FY14: remainder of NSTX-U outage
  - Begin engineering design of cryo, update physics as needed
  - Use EAST collaboration on lithium pumping, comparison with cryo
  - EAST collaboration on ELM-triggering with lithium granules
- FY15: initial NSTX-U operation with lithium
  - Re-establish lithium scenarios with triggered ELMs, extend to longer pulse
  - Get first divertor data in NSTX-U, confirm/finalize cryo design
- FY16: optimize lithium+ELM operation
  - Test pacing with lithium granule injector
  - Evaluate combinations of impurity reduction techniques
- FY17: test newly-installed cryo-pump
  - Characterize pressure, pumping, impact on density, compare to models
  - Develop strongly pumped scenarios
- FY18: routine use of cryo-pump in physics studies
  - Incorporate cryo into closed-loop density feedback control
  - Use pumping to control density in physics expts, e.g. for low ν^* studies

Summary: NSTX-U will test complementary methods for achieving particle control

- Lithium+ELM scenarios
  - Primary control technique in early NSTX-U operation
  - May benefit from LGI for improved ELM pacing

- Cryo-pumped ELMy H-mode
  - ELMy discharges with boronized PFCs to be developed in FY15/16
  - Cryo to be installed in outage prior to FY17 operations

- Goal for end of 5-year plan
  - $f_G \sim 0.5$
  - $Z_{eff} \sim 2\text{-}2.5$
  - Stationary density

  $\Rightarrow$ Up to an order of magnitude reduction in ν^* compared to NSTX

BACKUP SLIDES TO BE ADDED

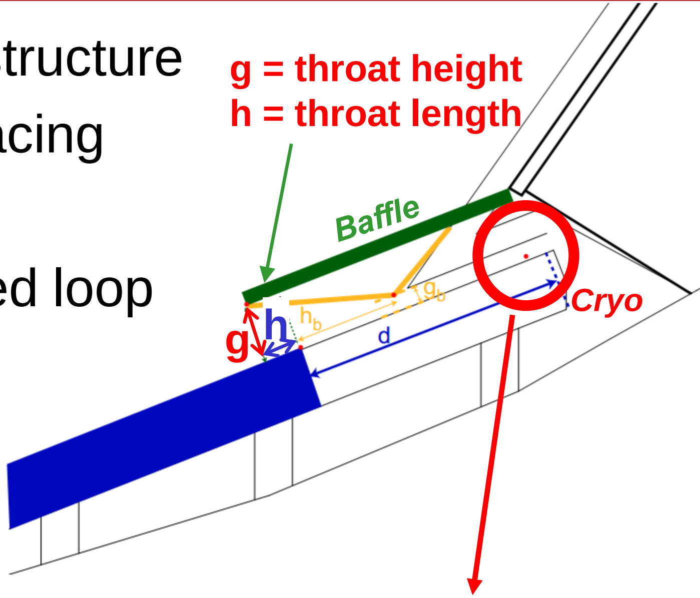
- Previous PAC slides/APS talk on cryo details
- EAST lithium slides
- EAST dropper slides
- FNSF details

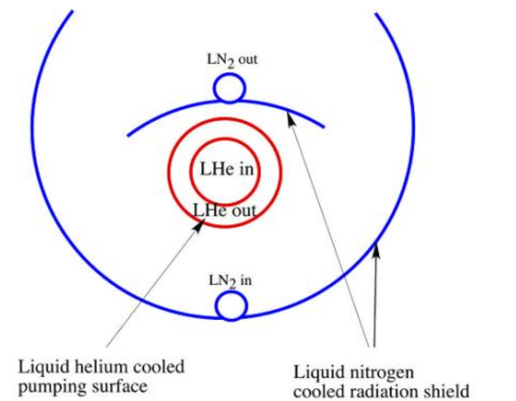
General layout similar to DIII-D lower outer cryo-pump system is taken as starting point for design analysis

- 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)

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

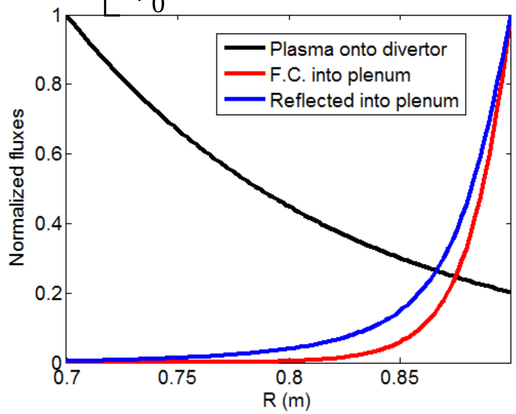
Neutral current into plenum

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

Solid angle of plenum entrance

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

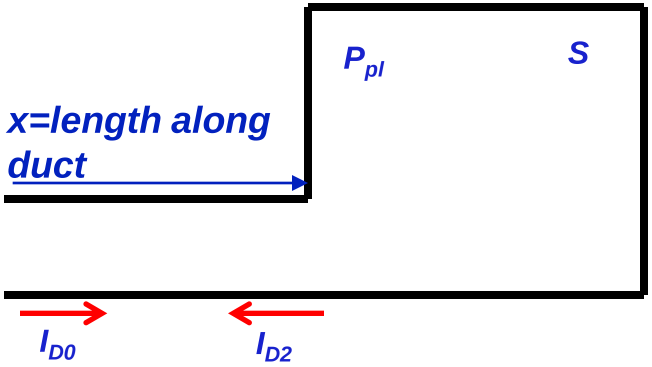
Transmission of neutrals through plasma



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

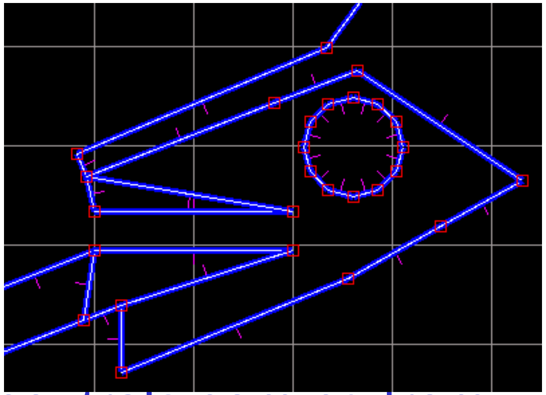
$$P_{pl} = \int_o^h I_{D2}(x)\sigma(x)dx = \int_o^h I_{D0}(x)\sigma(x)dx - \int_o^h P_{pl}S\sigma(x)dx$$

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

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

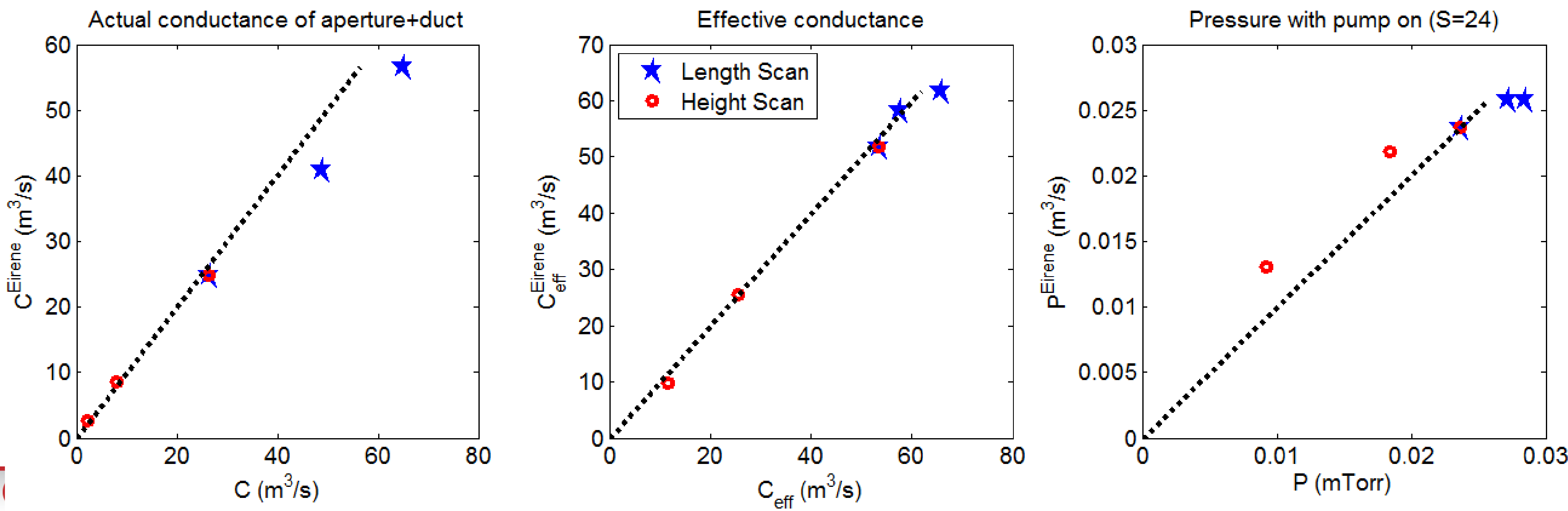
Expressions for conductance, pressure have been checked with Monte Carlo neutral code EIRENE

- 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



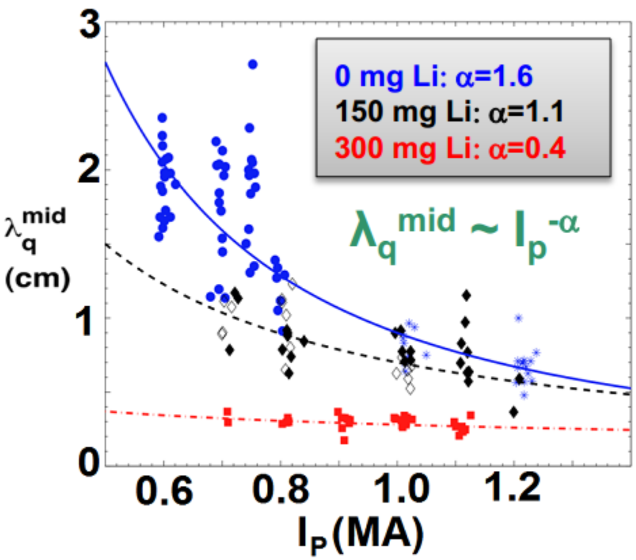
Projected divertor parameters combined with semi-analytic pumping model are used to calculate pumping rates

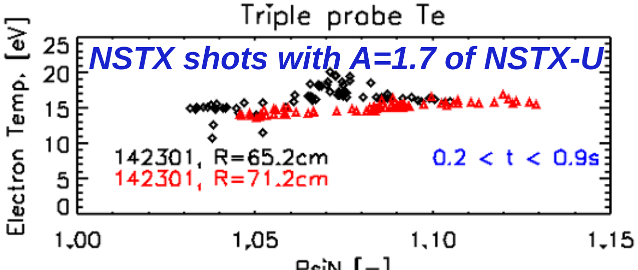
- Analytic model requires divertor n, T, Γ profiles
- Heat flux, angle of B wrt PFC surface (α), and plasma temperature are sufficient to calculate n, Γ:

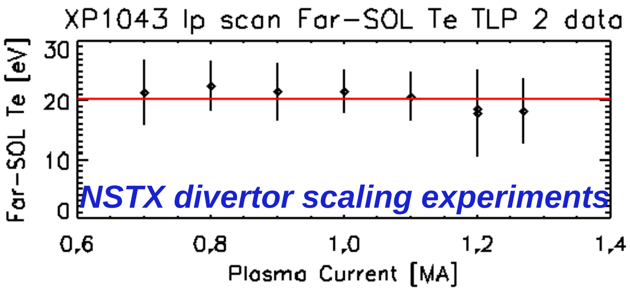
$$\Gamma_{\perp} = q_{\perp}/7T$$

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

  - 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)

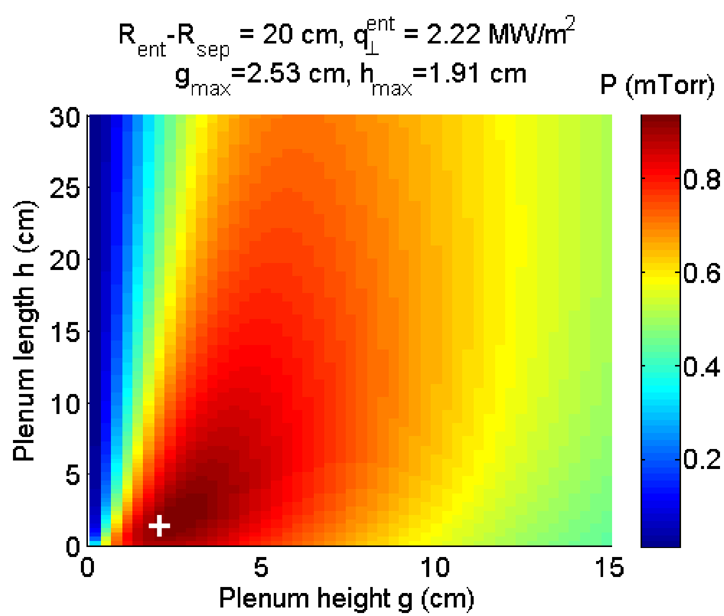


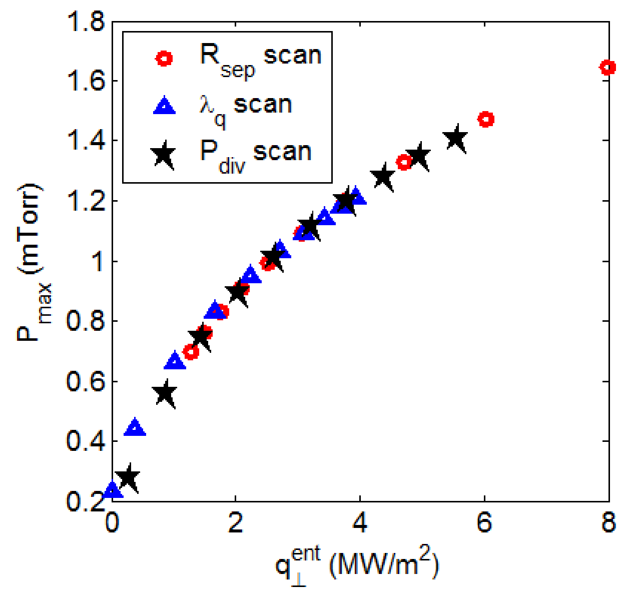




Pressure projections are used to optimize plenum geometry parameters

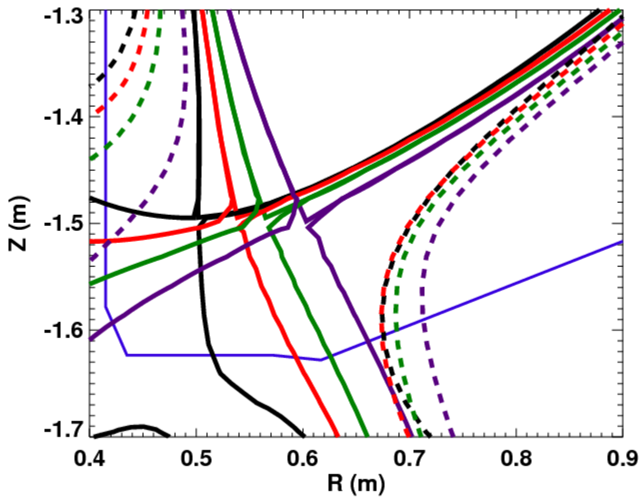
- Exponentially decaying heat flux footprint imposed, with T_e=15 eV
- Plenum entrance height, length are varied to maximize pressure
- Pressure in optimized plenum depends primarily on heat flux at pump entrance
  - Varied through R_{OSP}, flux expansion or P_{tot} $\Rightarrow$ profile effects not 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

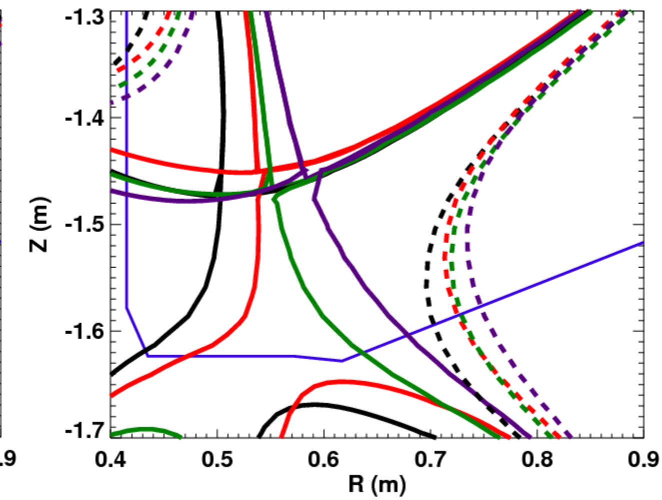




Equilibria with variety of R_{OSP}, flux expansion are used to map heat flux profiles, assess candidate pump entrance locations

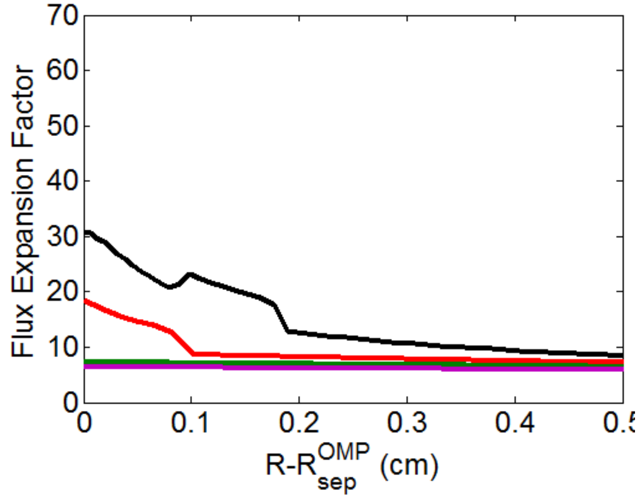
- Standard and snowflake divertors considered
  - Four R_{OSP} each
  - ψ_N=1.0,1.03 shown
  - Movement of ψ_N=1.03 strike line is much less than that of R_{OSP}
- Flux expansion, flux surface geometry used to convert midplane heat flux profile (from scaling) to divertor heat flux
  - As R_{OSP} is increased,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

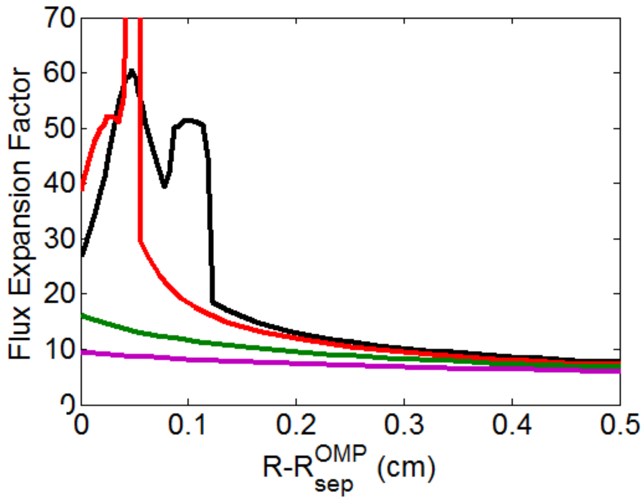




Standard

Snowflake

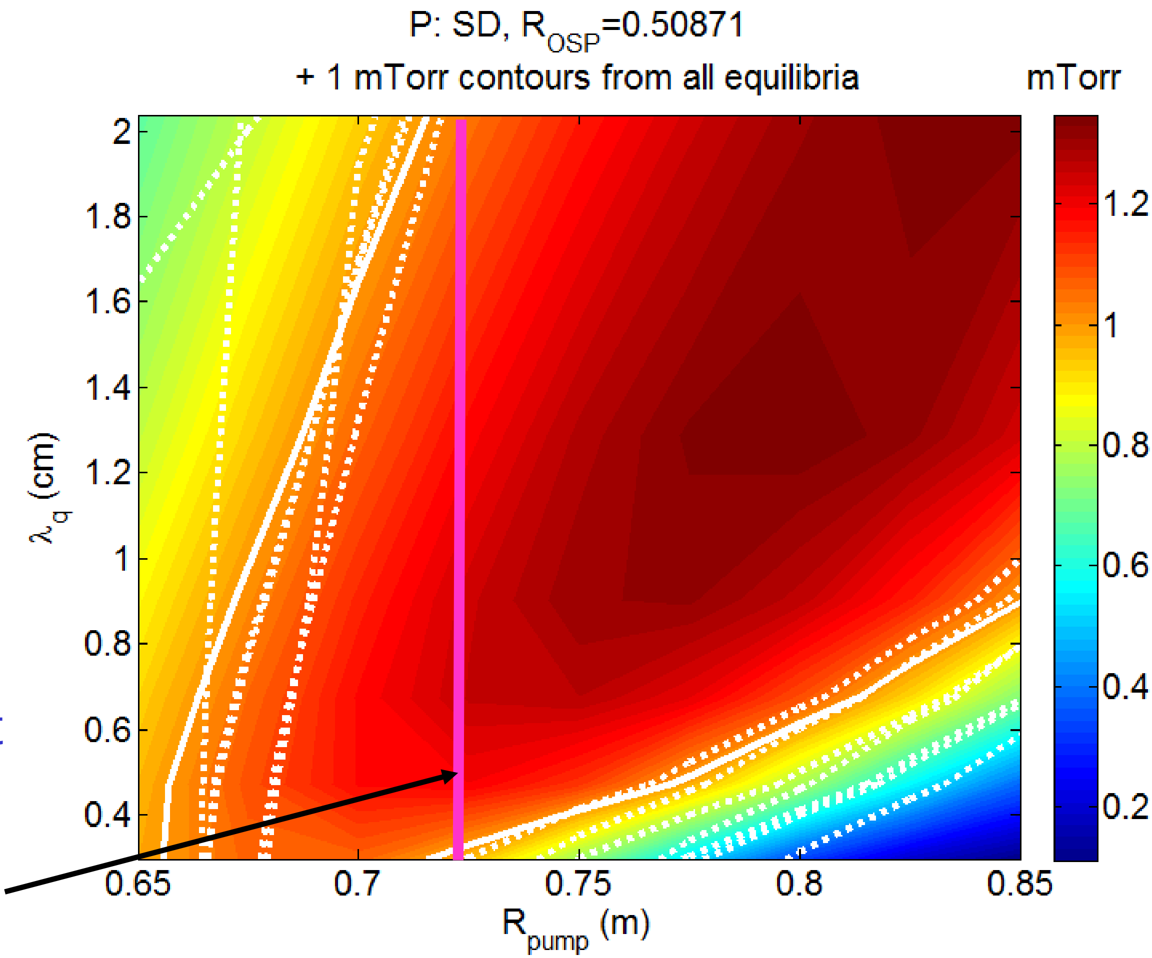




Realistic equilibria, heat flux scaling, and empirical T_e^{SOL} are used to project plenum pressure for candidate location R_{pump}

- 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}

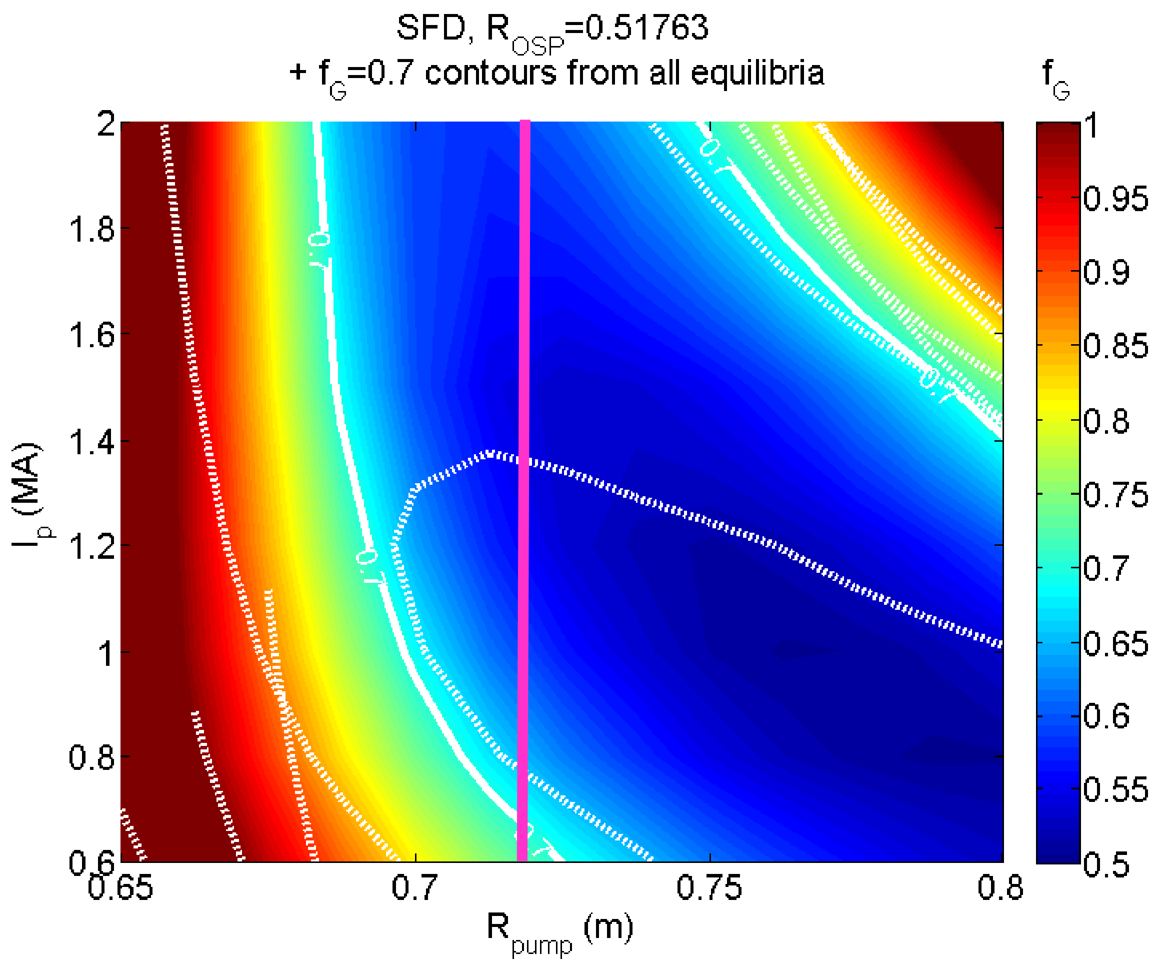
$$T_{OMP} = \left(T_{DIV}^{7/2} + \frac{7}{4\kappa_{0e}} q_{\parallel}^{sep} L \right)^{2/7}$$

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

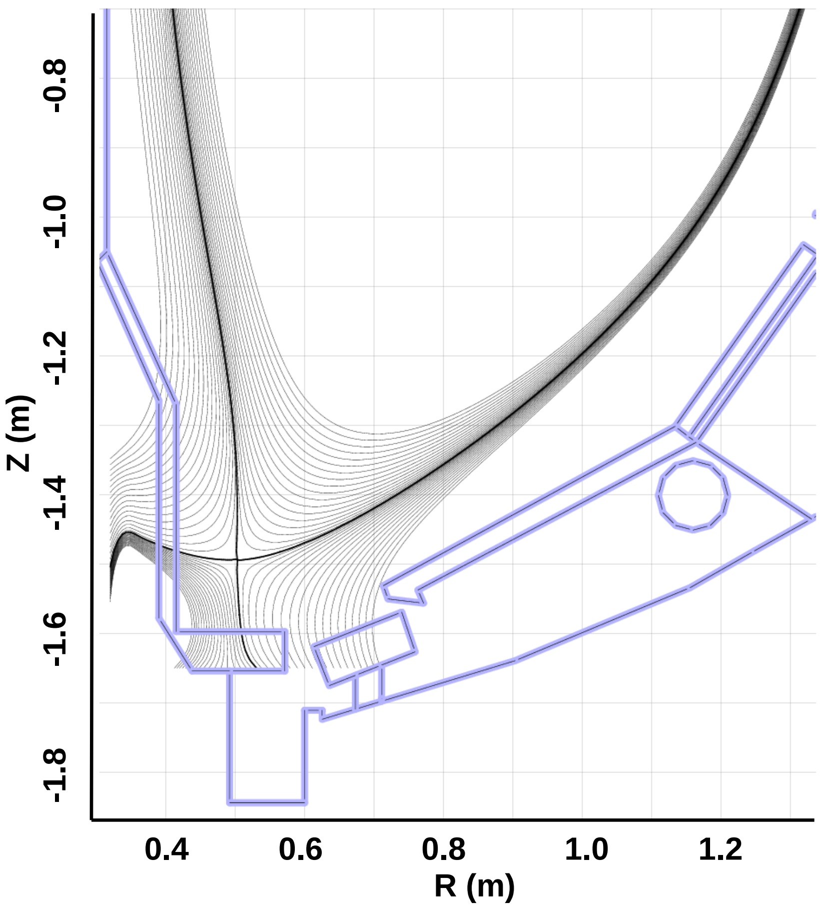
  - $q_{||}^{sep}$ from I_p scaling, T_e^{div} varied
  - Final n_e^{sep}: pumping=NBI input

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

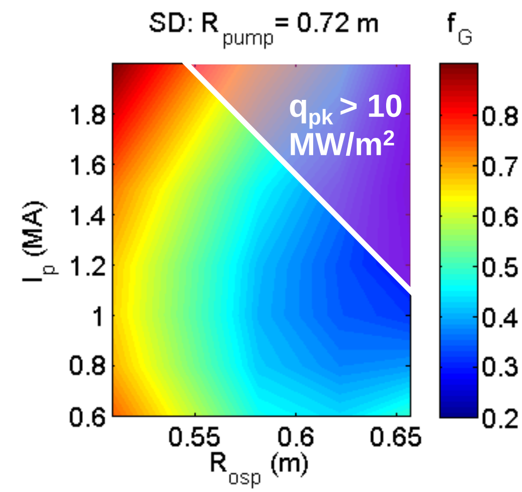
SNOWFLAKE DIVERTOR n/n_G



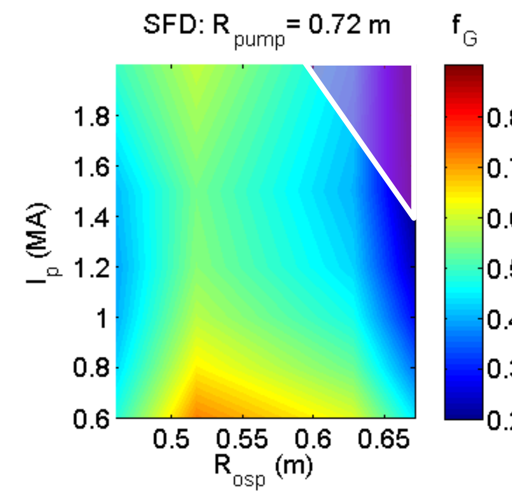
Optimized plenum geometry capable of pumping to low density for a range of R_{OSP}, I_p



- Equilibrium f_G down to < 0.5
  - Moving R_{OSP} closer to pump allows lower n_e, but limited by power handling

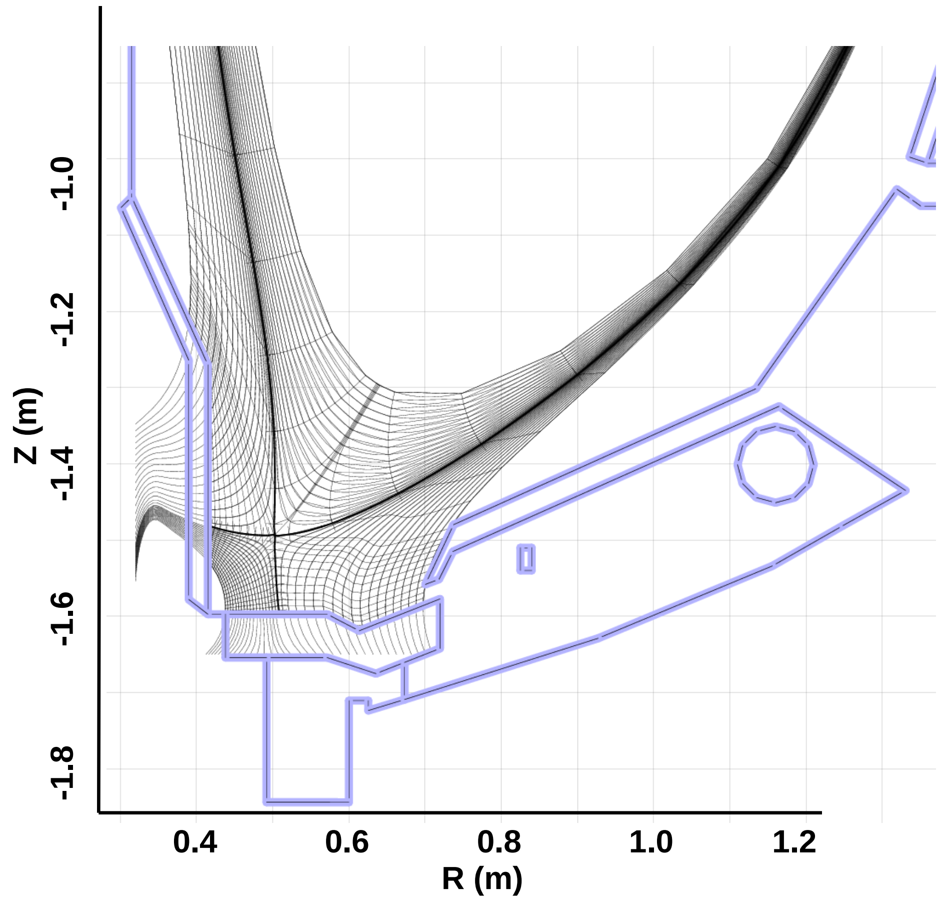


- High flux expansion in SFD gives *better* pumping with SOL-side configuration
  - More plasma in far SOL near pump
  - More room to increase R_{OSP} at high I_p



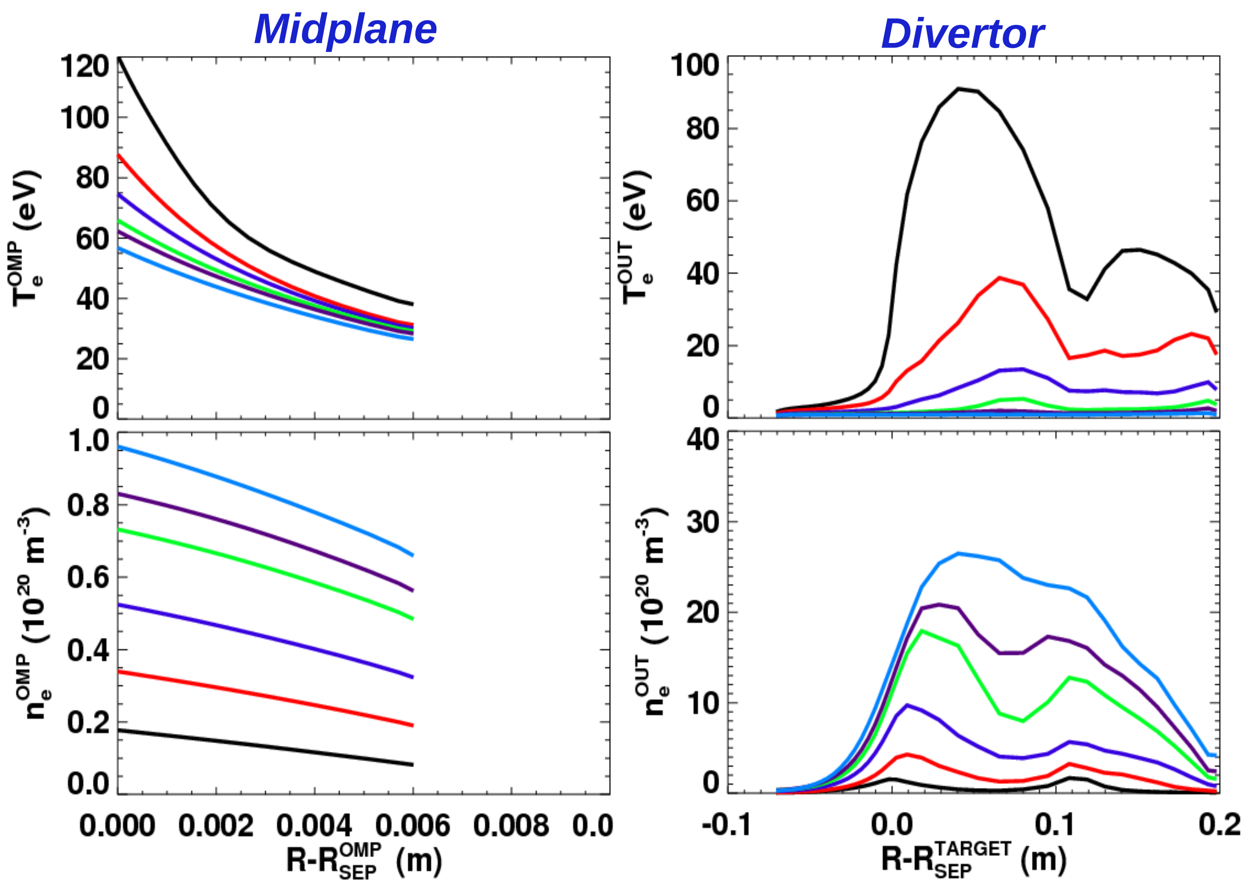
SOLPS is used to analyze pumping including near-detached conditions

- 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 λ_q^{mid} ~ 3mm
  - No attempt to match expt
- Simulations both without and with carbon included have been performed



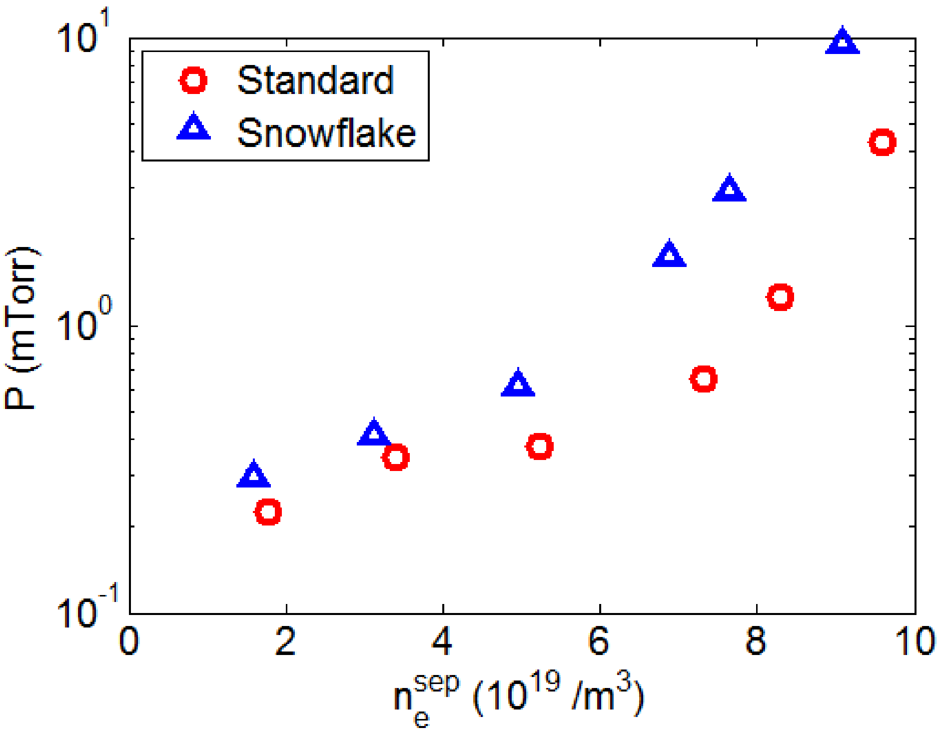
A wide range of divertor plasma parameters have been modeled

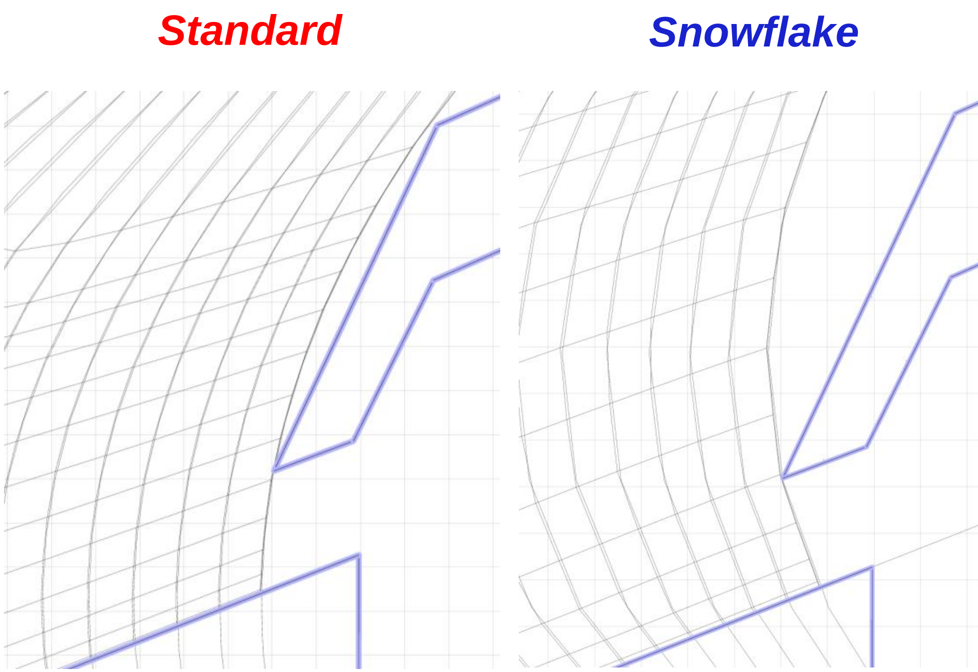
- Input power P=10MW in all cases
- n_e at core grid edge set as boundary condition
  - Scanned to vary divertor conditions
- Resulting divertor parameters vary from strongly attached to nearly detached (T_e~1eV)



Snowflake shows higher plenum pressures that standard divertor for similar conditions

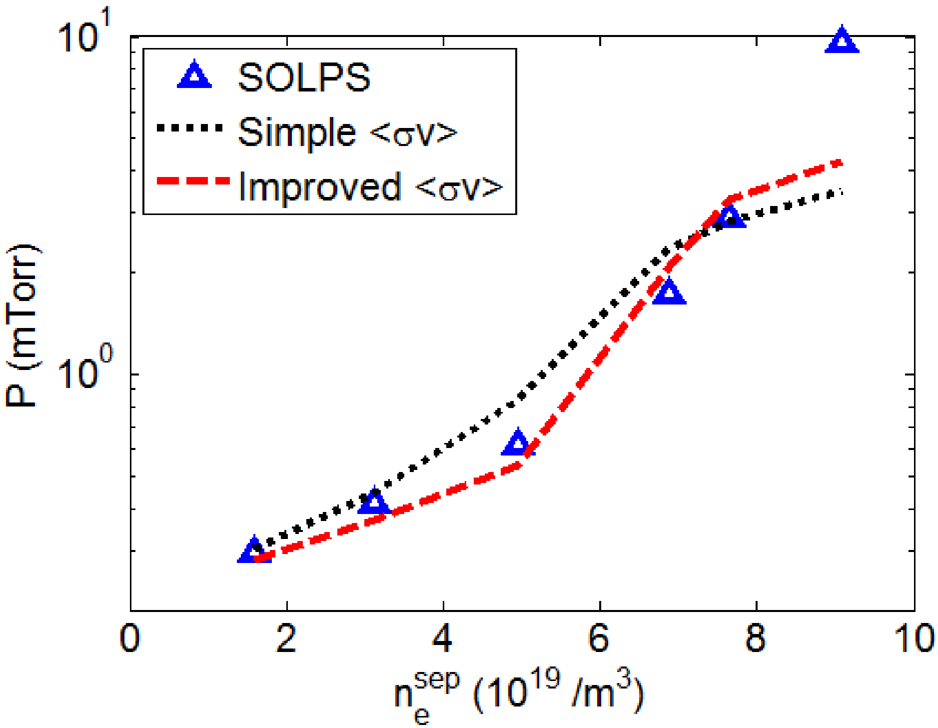
- At same separatrix density, pressure is ~2x higher with Snowflake divertor configuration
- Partially due to geometry of field lines at pump entrance (plasma flux reaches nearer entrance; not accounted for in earlier projections)
- Pressures above 1 mTorr can be reached at high n_e in both cases

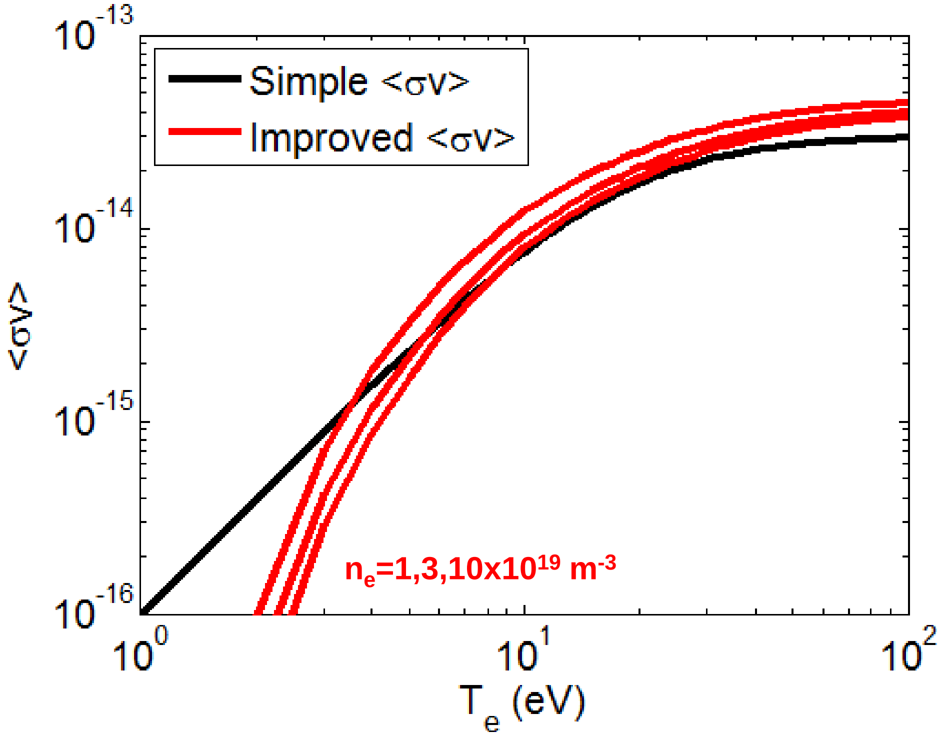




Plenum pressure from SOLPS shows good agreement with semi-analytic expressions when divertor is attached

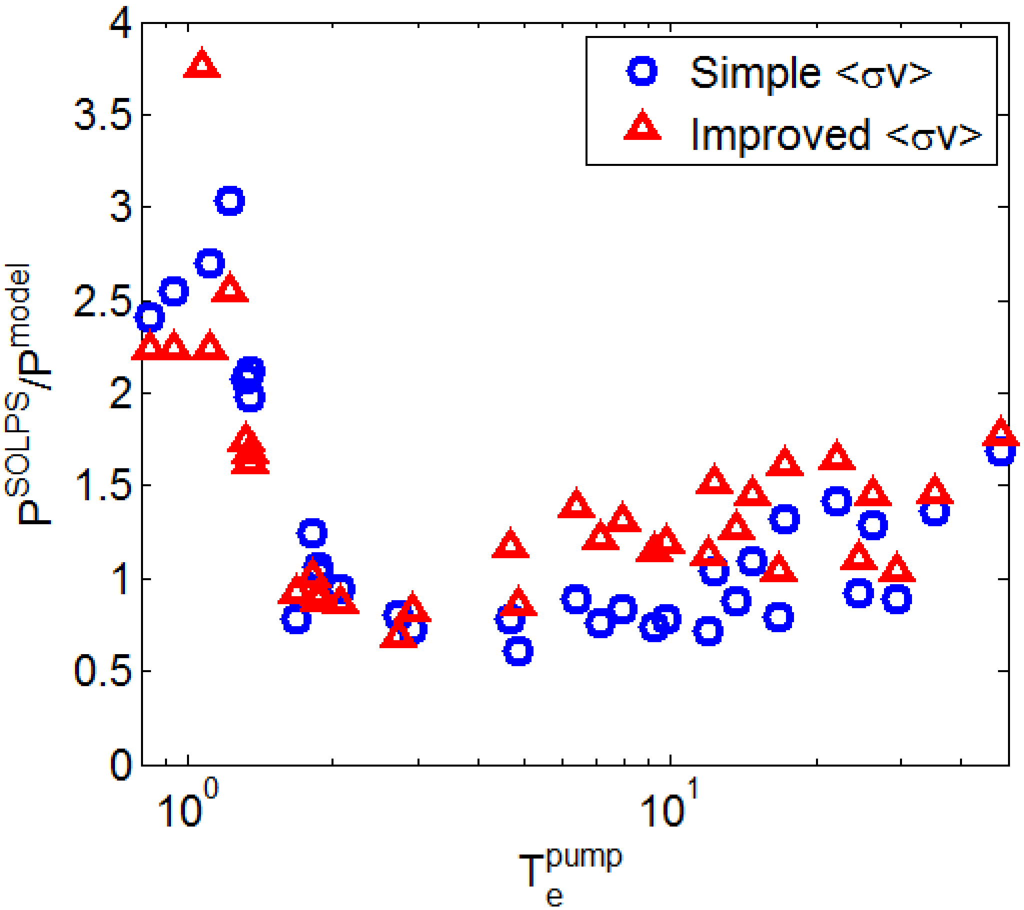
- Divertor n_e, T_e, $\Gamma_\perp$ from SOLPS used in semi-analytic model
- Model reproduces pressure within factor of ~2 (except high n_e)
- Agreement is improved using more accurate ionization rate
  - Simple rate coefficients used in original model: $\langle \sigma v \rangle_{EII}(r) \approx \frac{3 \times 10^{-16} T_e^2(r)}{3 + 0.01 T_e^2(r)}$
  - 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

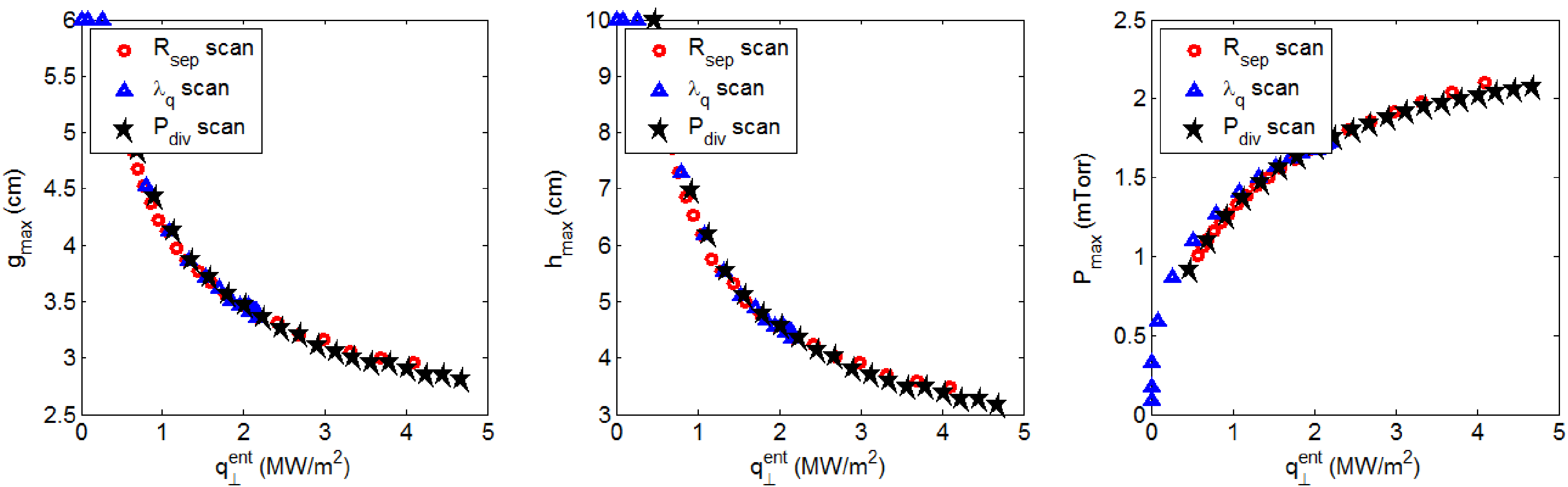


⇒ *Optimization of design presented here is conservative*

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

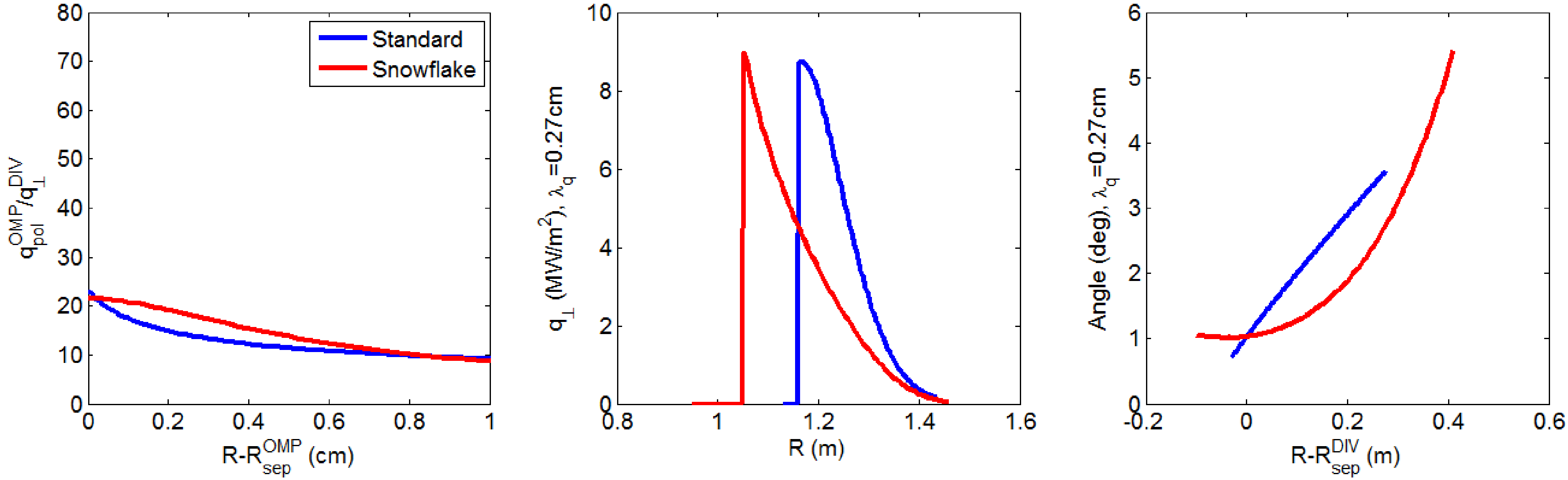
Duct optimization for R_{pump}=1.3 m

- Exponentially decaying heat flux assumed, based loosely on parameters from the Menard/Brown DEMO talk
  - Assuming T_e=5 eV, due to erosion requirements
- It's actually pretty easy to get to P=0.5 mTorr
- Aiming for 1 mTorr gives a duct with g~4.5, h~7 cm
  - Need ~1MW/m^2 at pump entrance
- Can already see that if PNBI is used this will be harder
  - Need ~5 MW/m^2 at pump entrance to get to 2 mTorr
  - Would probably need to increase pumping speed in that case (or maybe play more with divertor geometry—still want to try vertical target)



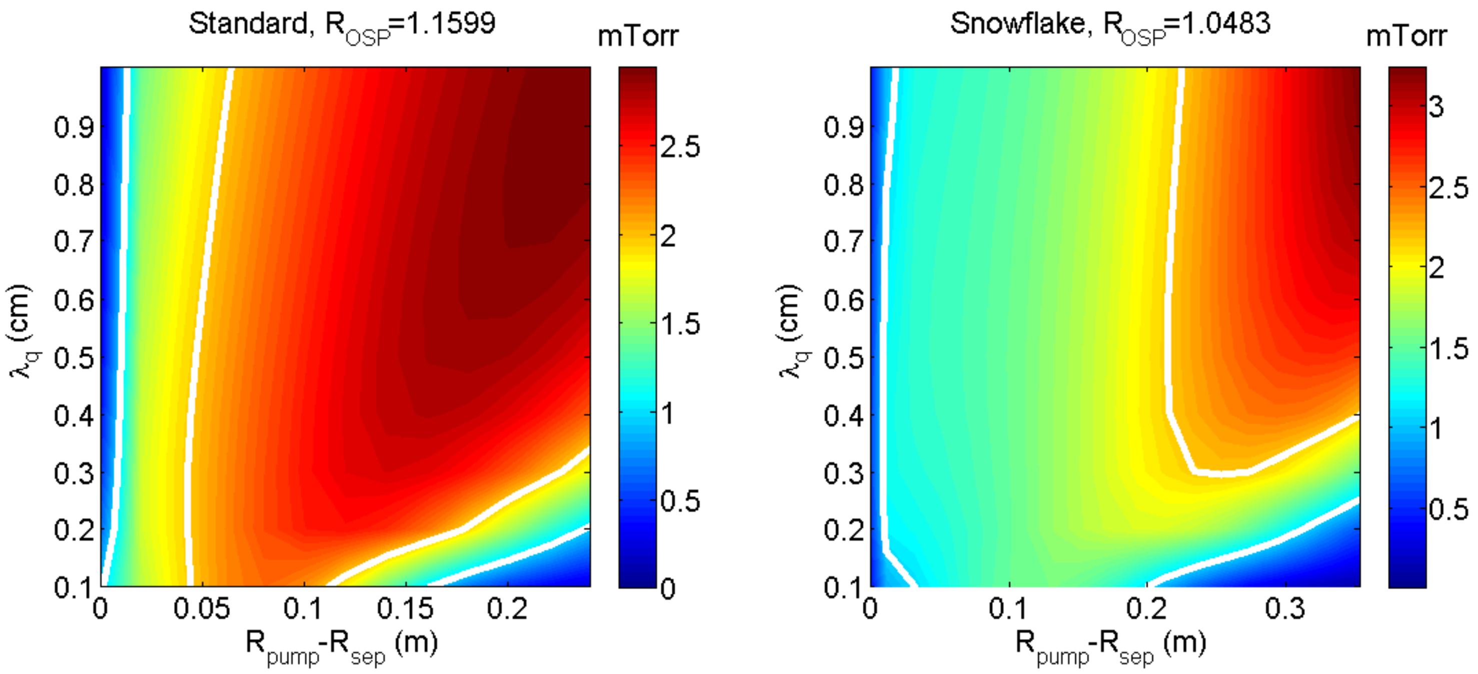
Standard and Snowflake equilibria used to map fluxes onto divertor

- Flux surface shapes can be found in Menard/Brown DEMO talk
- Both divertors have ~the same geometric heat flux reduction
  - Snowflake gets it through flux expansion, standard through poloidal inclination of target
  - Note that target geometry is different in the two cases
  - Total field angle of incidence is similar at OSP (~1 deg)



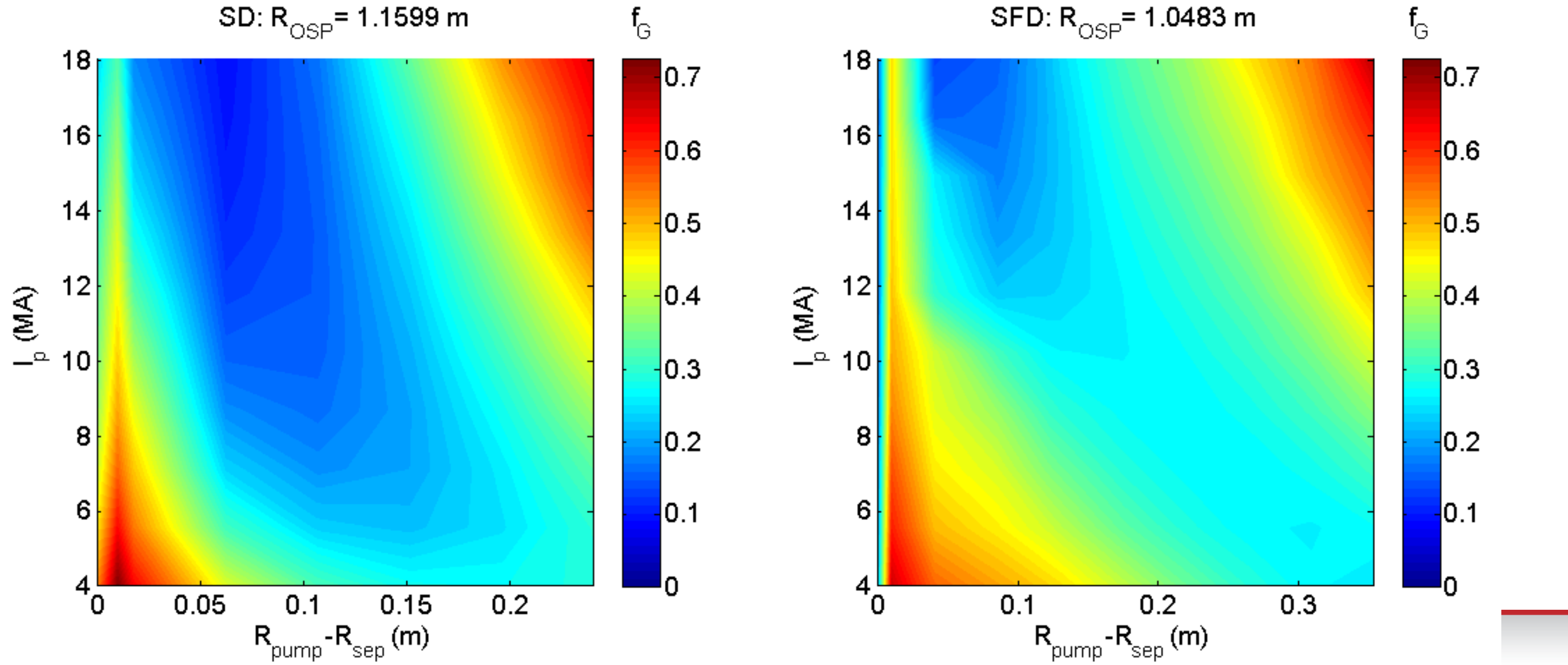
Looks like reasonable pumping can be achieved

- Assuming Te=5 eV
- Projected pressure shows usual maximum in pump position that varies with SOL width
  - Even though heat flux is higher near OSP, the angle is lower too, so that plasma density is high and ionizes more neutrals
- For λ_q~2.7mm, a pump at R~1.3 looks like its close to optimal for both divertor configurations
- Reaching 0.5 mTorr is easy, and it looks like even 2 mTorr is within reach (one of the white contours, not sure why there are two…)



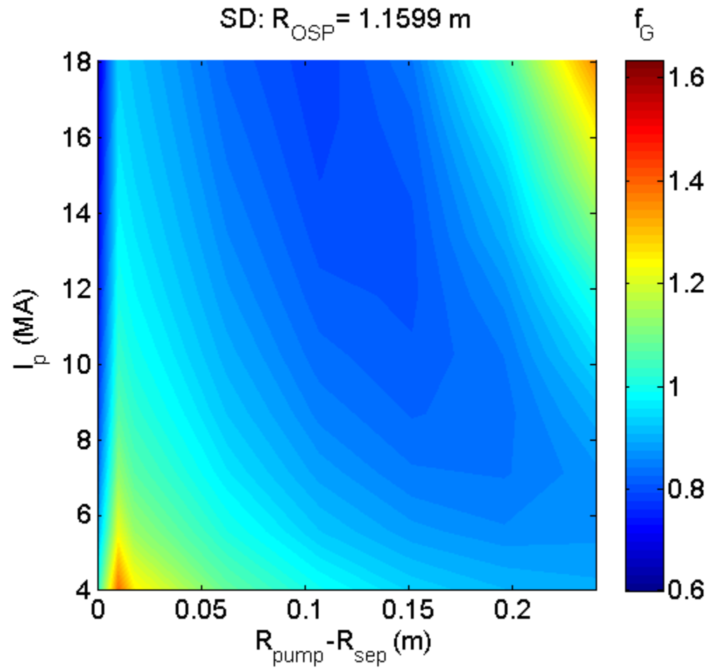
Achievable Greenwald fraction assuming we only have to pump 500 keV beam input

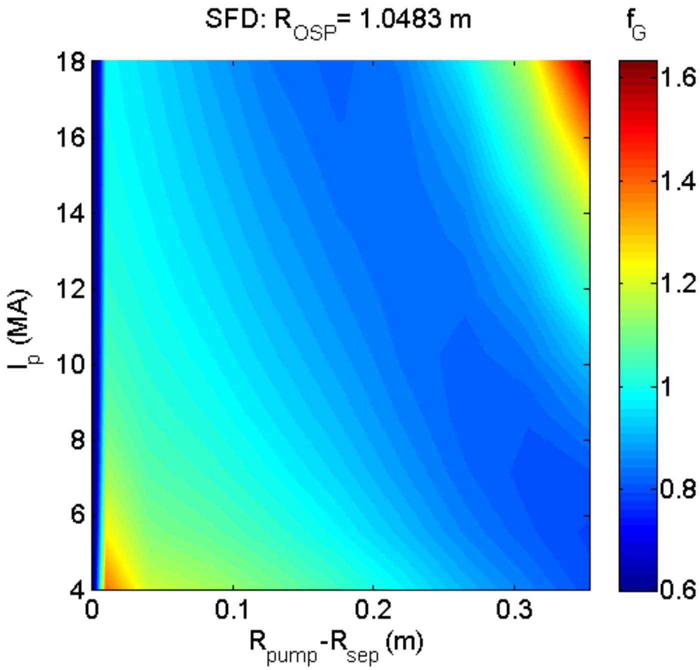
- Eich scaling for SOL width used during I_p scan
- Note that 2-pt model used here doesn't account for radiation
  - E.g., assumes that the full 80% radiated power is in the core
- Can easily reach very low f_G, consistent with pressure plots
- Might be better to move pump inwards a bit, maybe to ~1.25 or even 1.2 to be able to pump high current shots



Achievable Greenwald fraction assuming we only have to pump 150 keV beam input

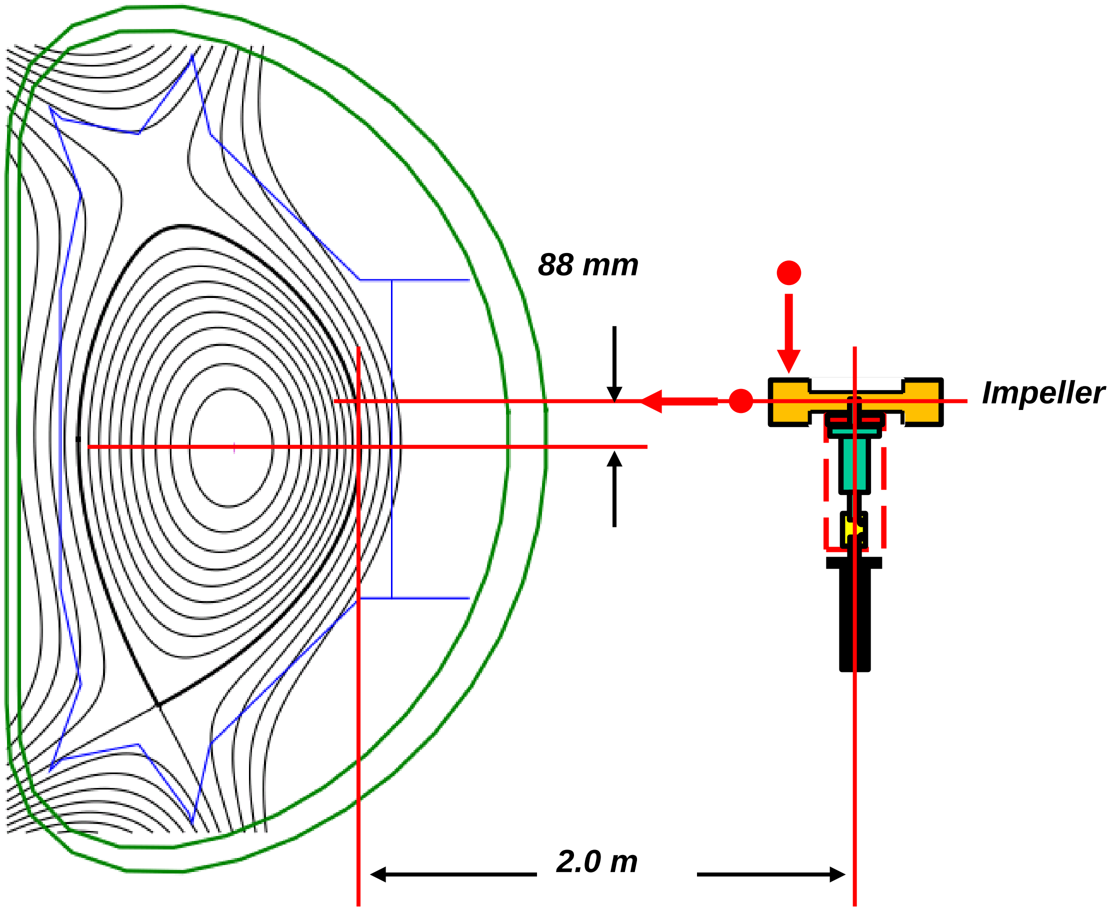
- Assuming that you need ~4 times the pressure with low energy PNBI
- Can still pump down to reasonable densities (~0.8 GW)
- Contours are pushed out to the right a little bit compared to previous slide, so the R=1.3 pump looks good in this case





Configuration of EAST shot 42477 LSN during Li granule injection

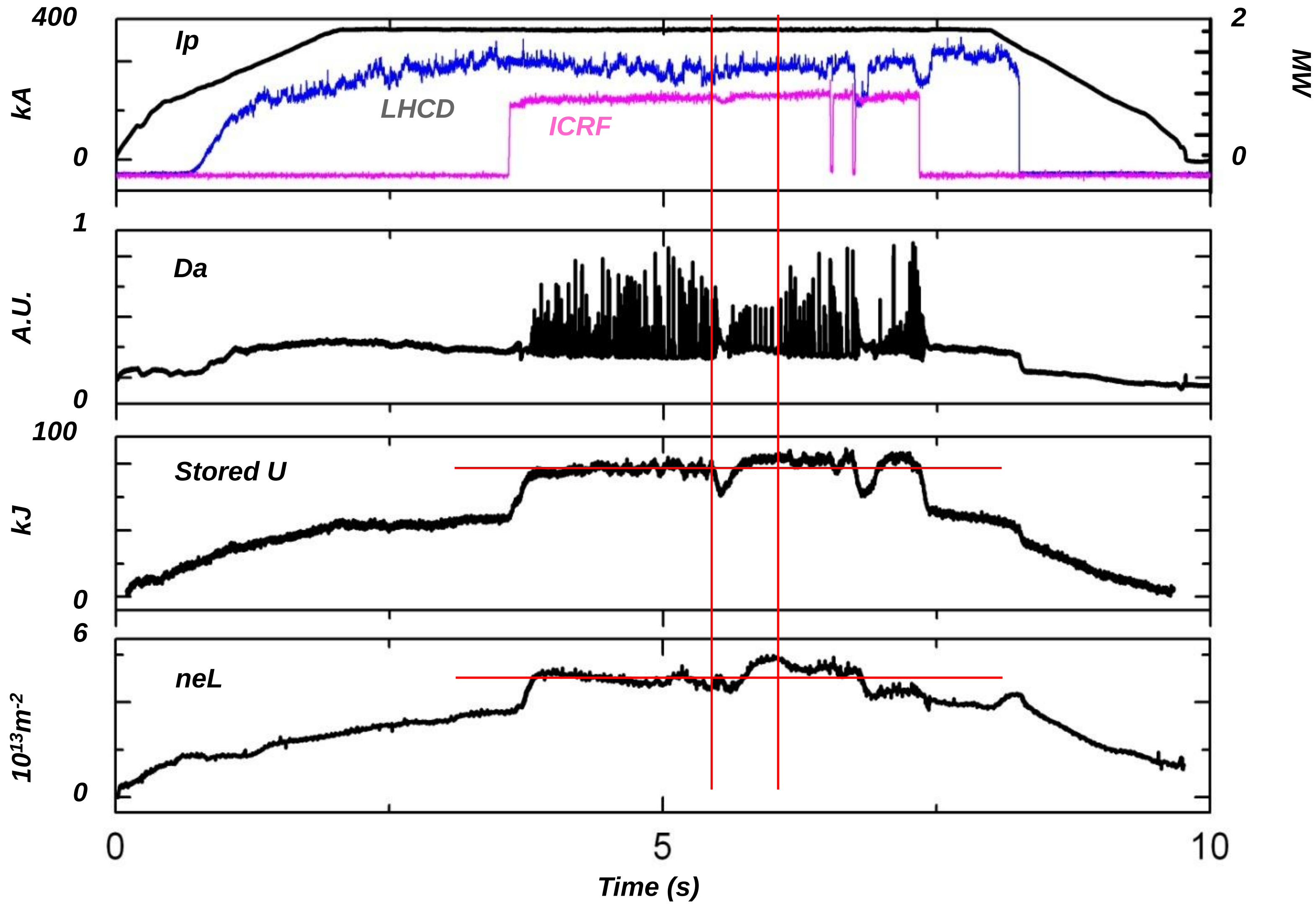
Ti(0) ~ Te(0) ~ 1 keV



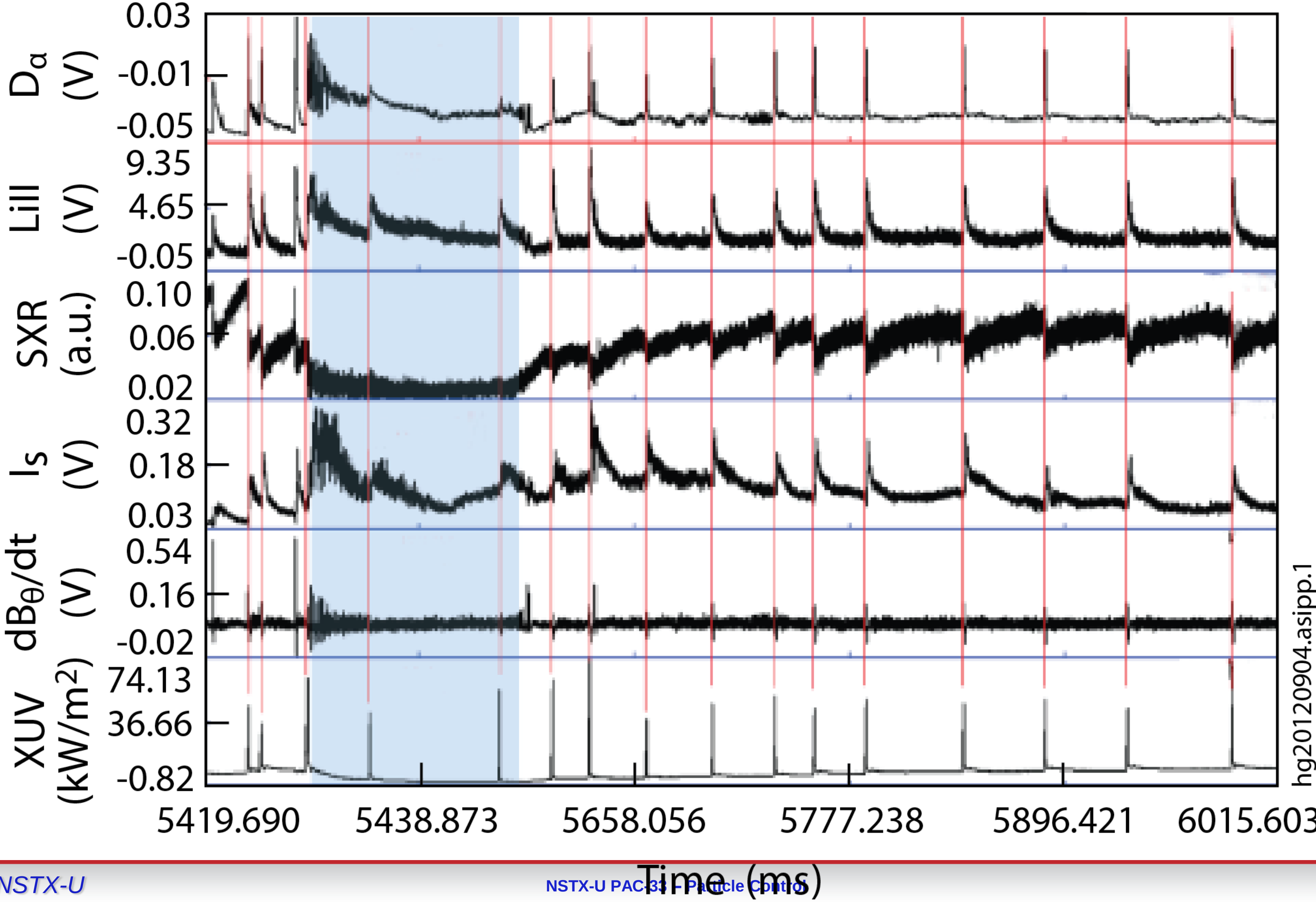
One sec injection @ 25 Hz of 0.7 mm Li granules at 52 m/s - shot 42477

EAST

PPPL PRINCETON PLASMA PHYSICS LABORATORY

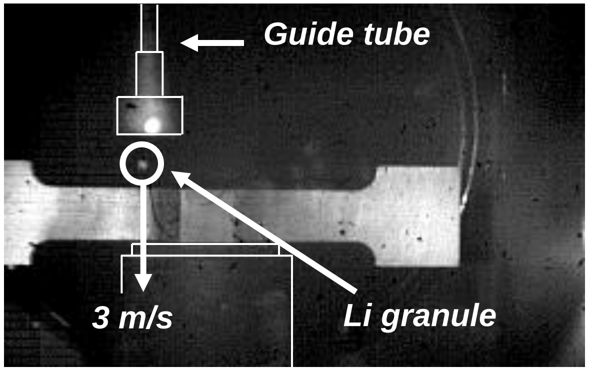


Examples of Triggered ELMs
Shot 42477



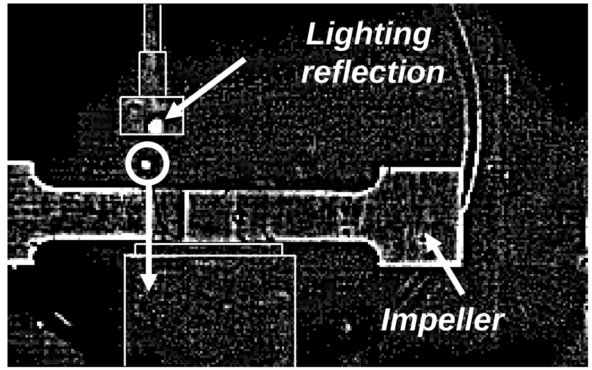
Video Images of Li granule Injection and ablation processes – shot 42477

Video camera image



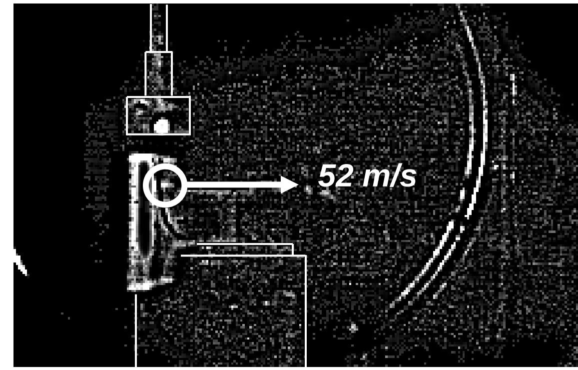
a) Granule exits tube

Same image filtered



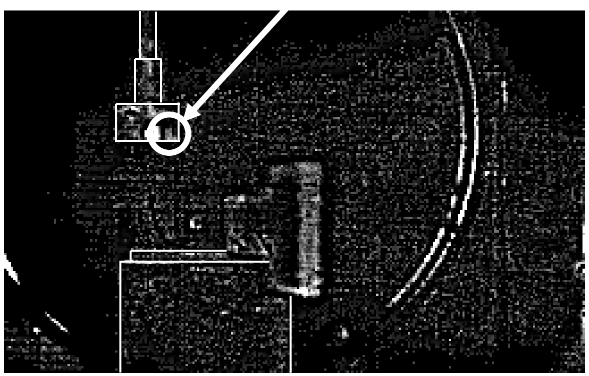
b) Granule exits tube

Granule impeller contact



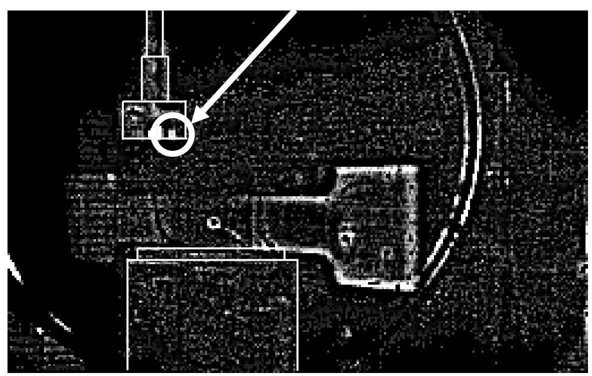
c) Impeller hits granule

38.06 ms after image c
First frame with ablation



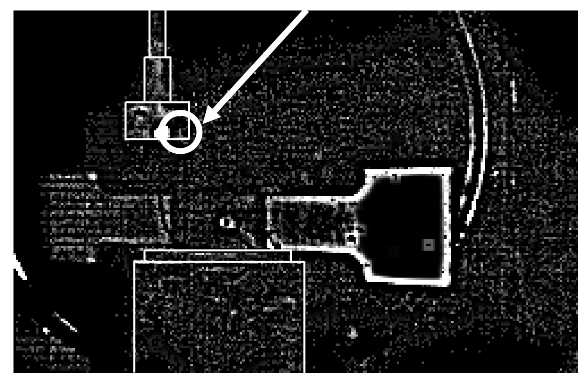
d) Rectangular “flash”

Maximum ablation



e) Max “flash” intensity

Last frame with ablation

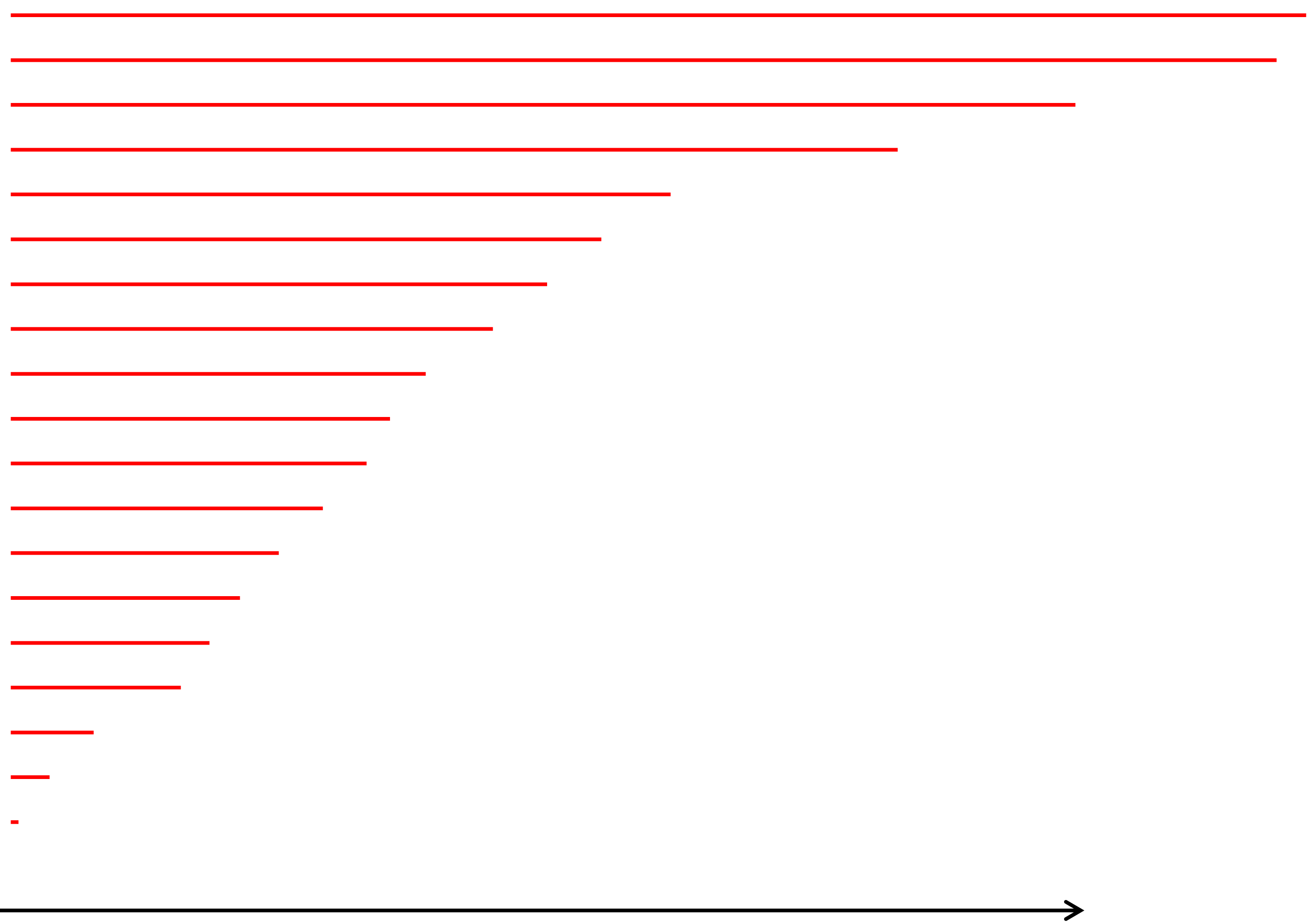


f) Ablation “flash”ends

Images (d – f) ablation duration Δt = 469 μs

Video timing of Li granule injections with respect to 1st Granule

Granule #	Δt (ms)
20	1071
19	1045
18	879
17	732
16	546
15	487
14	442
13	397
12	342
11	313
10	293
9	258
8	222
7	189
6	163
5	141
4	68.7
3	32.7
2	6.5



Li granule injection timing on video versus edge XUV signal