NSTX-U 5 Year Plan for Pedestal, Scrape-off Layer and Divertor Physics

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NSTX-U 5 Year Plan Review
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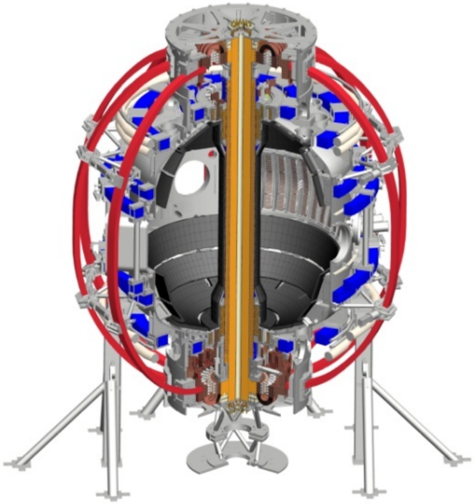

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Boundary Physics Program provides broad support for the NSTX-U 5 year plan goals

1. Demonstrate 100% non-inductive sustainment at performance that extrapolates to ≥ 1MW/m^2 neutron wall loading in FNSF
2. Access reduced ν^* and high-β combined with ability to vary q and rotation to dramatically extend ST physics understanding
3. Develop and understand non-inductive start-up and ramp-up (overdrive) to project to ST-FNSF with small/no solenoid
4. **Develop and utilize high-flux-expansion snowflake divertor and radiative detachment for mitigating high heat fluxes**
5. Begin to assess high-Z PFCs + liquid lithium to develop high-duty-factor integrated PMI solutions for next-steps

Longer-term (5-10 year) goal:

Integrate 100% non-inductive + high β and τ_E + divertor solution + metal walls

Boundary Physics program in NSTX-U contributes to critical research areas for FNSF and ITER

Boundary Physics Thrusts (and outline of the talk)

- **BP-1: Assess and control pedestal structure, edge transport and stability**
  - Pedestal structure, transport and turbulence studies
  - ELM characterization and control

- **BP-2: Assess and control divertor heat and particle fluxes**
  - SOL transport and turbulence, impurity transport
  - Divertor heat flux mitigation with impurity seeding and divertor geometry

- **BP-3: Establish and compare long-pulse particle control methods**
  - Validate cryo-pump physics design, assess density control and recycling
  - Compare cryo to lithium coatings for particle (collisionality) control

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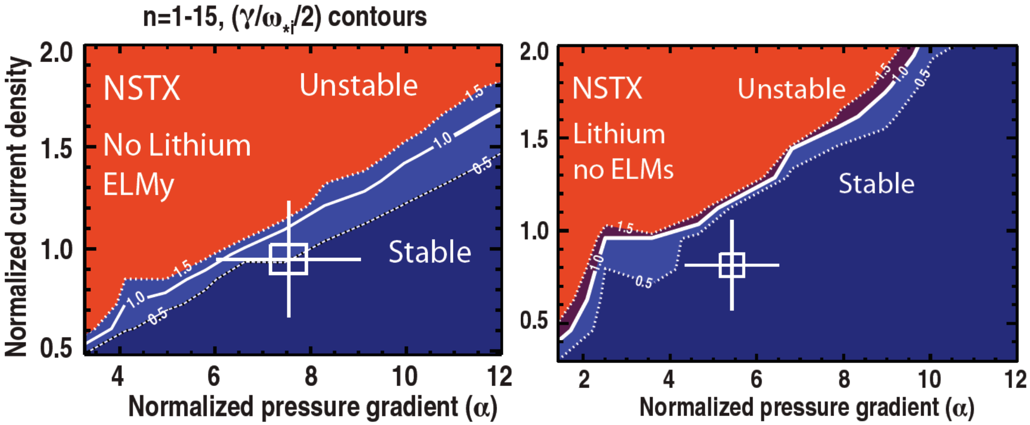
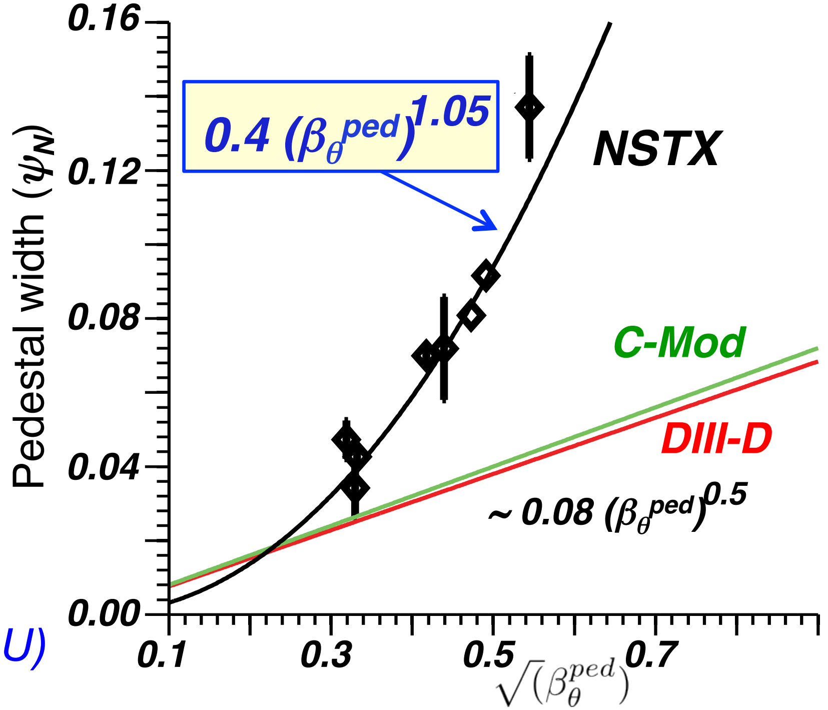
BP-1

Pedestal studies focus on instabilities and turbulence that limit pedestal heights, widths, and gradients

- Peeling ballooning limits on pedestal height and width consistent with ELMy/ELM-free operation
  - Lithium and 3-D fields used to manipulate profiles



- Kinetic ballooning mode (KBM) being tested as a mechanism to limit pressure gradient (width and height)
  - Scaling with β_{pol}^{ped} stronger in STs than higher R/a
  - No evidence yet of KBM fluctuation



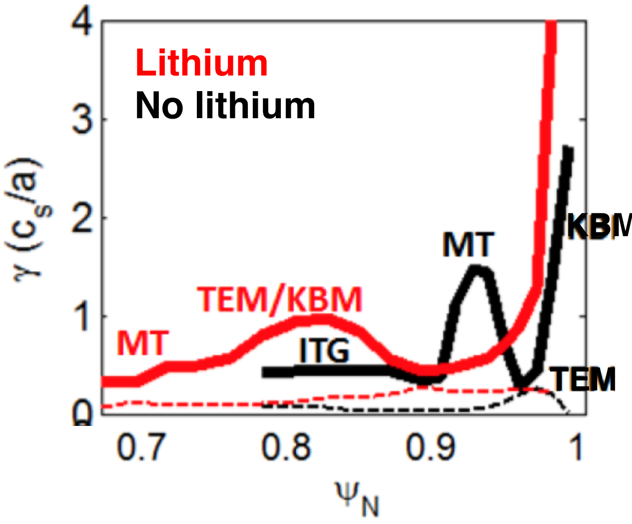
Diagnostics:

30 point core Thomson (NSTX) → 42 point (NSTX-U)

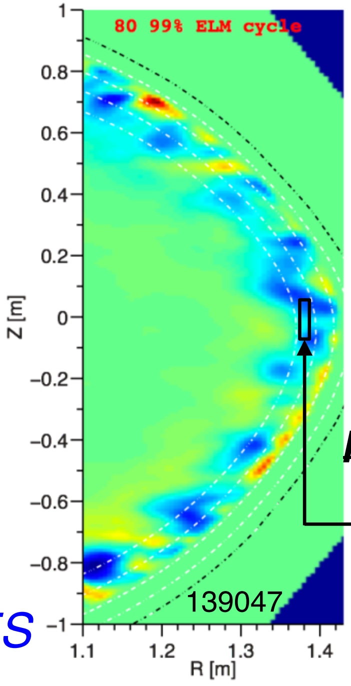
BP-1

NSTX-U will extend understanding of different microinstabilities and their role for pedestal control

- Flux-tube simulations provide indication of dominant edge instabilities
  - TEM / KBM modes dominant where pressure gradient is largest (GS2/GENE)
  - Microtearing unstable at pedestal top, stabilized with Li (GS2)
  - These studies will be extended to lower ν^* in NSTX-U



- Developing fuller-physics simulations needed for edge
  - XGC1 (full-f, global w/ separatrix, neutrals)
    - ITG simulations show correlation lengths consistent with measurements
  - Global, EM δf (GENE/GYRO)



R = 1.38m

	Theory (non-linear XGC1 code)	***Experiment***
radial	3 cm	2 – 4 cm (reflectometry)
poloidal	11 cm	10 – 14 cm (BES)

80% - 99% ELM cycle

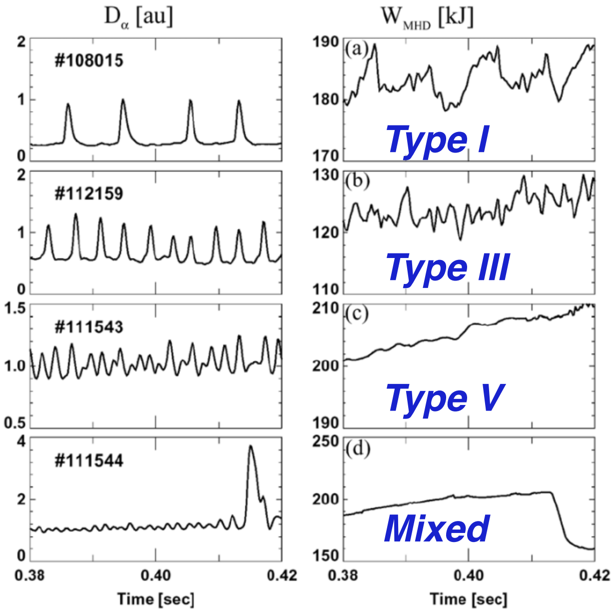
Diagnostics (NSTX-U):

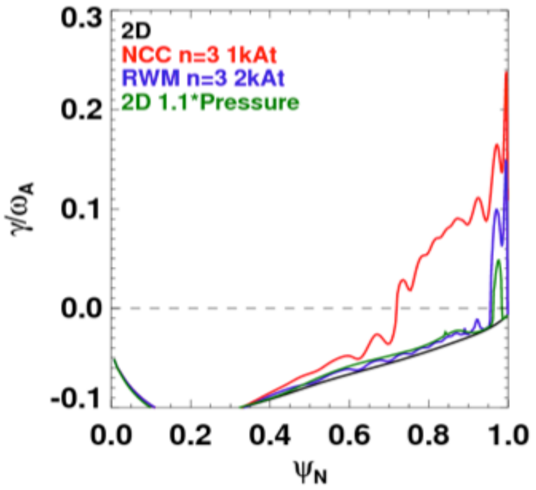
42 point MPTS, reflectometry, 48 point BES

NSTX-U will focus on developing small / acceptable ELM regimes, and active ELM and pedestal control

- Many ELM type regimes observed in NSTX: Type I, II, III, V, mixed
  - Phenomenology dependent on ν^*_{ped}, P_{SOL}, $I_{p,}$ shaping

- Pedestal and ELM control techniques
  - Lithium evaporation
    - In NSTX, reduced p' and edge bootstrap current
  - Lithium granule injector (tested at EAST)
  - Enhanced Pedestal (ELM-free) H-mode
  - 3-D fields
    - In NSTX, n=3 RMP destabilized ELMs (but weak impact on transport)
    - In NSTX-U, NCC coils
      - Wider spectrum, wider ballooning unstable edge region





Plans for pedestal transport, turbulence, and ELM control research

- Year 1 of 5 Year Plan
  - Continue cross-machine comparison of pedestal structure with DIII-D and Alcator C-Mod
  - Continue gyro-kinetic modeling of electromagnetic turbulence

- Years 2-3 of 5 Year Plan
  - Assess the L-H power threshold at higher I_p
  - Pedestal structure and turbulence vs engineering and physics parameters
  - ELM control with lithium coatings, lithium granule injector, and 3D fields
  - Access to new operational regimes (enhanced pedestal H-mode, I-mode)
  - Initiate assessment of SOL current generation and impact on ELM models and control
  - *Incremental: begin to design and construct power supplies to drive EHOs*

- Years 4-5 of 5 Year Plan
  - Compare effect of cryopumping and high-Z PFCs on pedestal structure and turbulence
  - Edge transport and ELM stability with NCC coils, comp. with gyro-kinetic calculations
  - Combine the new particle control tools (cryopump and LGI) to trigger ELMs

Diagnostics: MPTS, CHERS, BES, reflectometry, GPI

Boundary Physics program in NSTX-U contributes to critical research areas for FNSF and ITER

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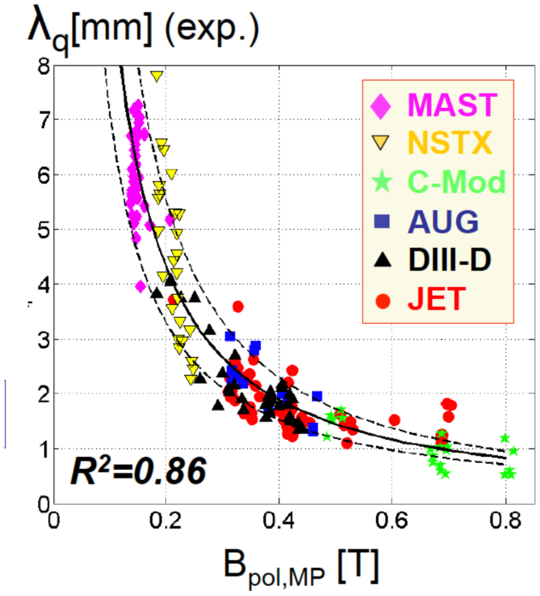
  - Validate cryo-pump physics design, assess density control and recycling
  - Compare cryo to lithium coatings for particle (collisionality) control

NSTX-U will help reduce SOL width scaling uncertainties for next-steps and assess relative importance of turbulent and drift-based transport

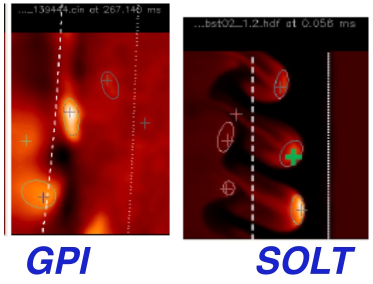
BP-2

- SOL width scaling critical for divertor projections
  - In NSTX: $\lambda_q^{mid} \sim I_p^{-1.6}$, independent of P_{SOL} and B_t
    - For NSTX-U (2 MA): $\lambda_q^{mid} = 3 \pm 0.5$ mm
  - Multi-machine database (Eich IAEA FEC 2012): ⟶

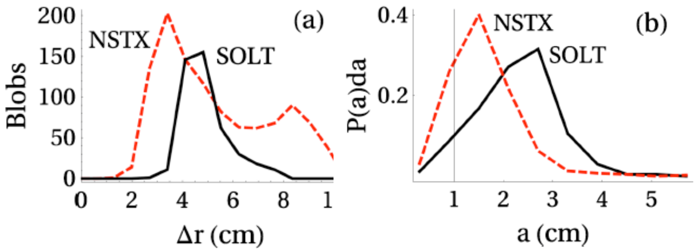
    λ_q^{mid} (mm) = (0.63+/-0.08) x $B_{pol,MP}^{-1.19}$
    - For NSTX-U (B_p~0.55 T): $\lambda_q^{mid} \sim 1.3$ mm



- Comparison of λ_{SOL} with SOL models
  - Parallel transport: conductive/convective, cross-field : collisional / turbulent / drift
  - Goldston heuristic drift-based model
    - $\lambda_{SOL} \sim (2a/R)\,\rho_{\theta},$ for NSTX-U: $\lambda_q^{mid} \sim 6$ mm
  - XGC0 (drift-kinetic): $\lambda_q^{mid} \sim I_p^{-1.0}$ at lower I_p
  - SOLT (fluid turbulence): I_p scaling is weaker than observed

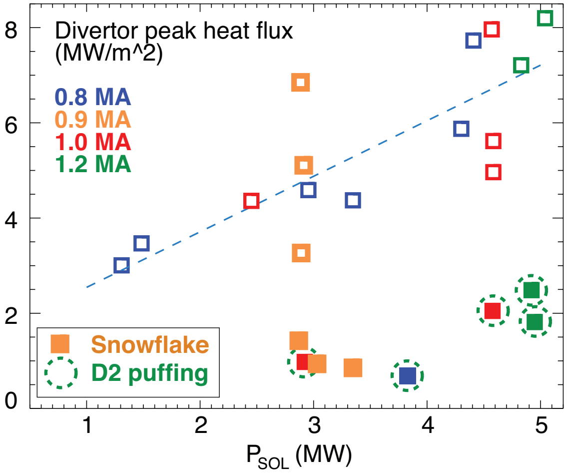


- Comparison of GPI, BES data and SOL transport and turbulence simulations
  - Blob formation, motion, interaction with sheared flows
  - Role of magnetic X-point geometry and finite ion gyro width
  - Effects of 3-D fields on turbulence

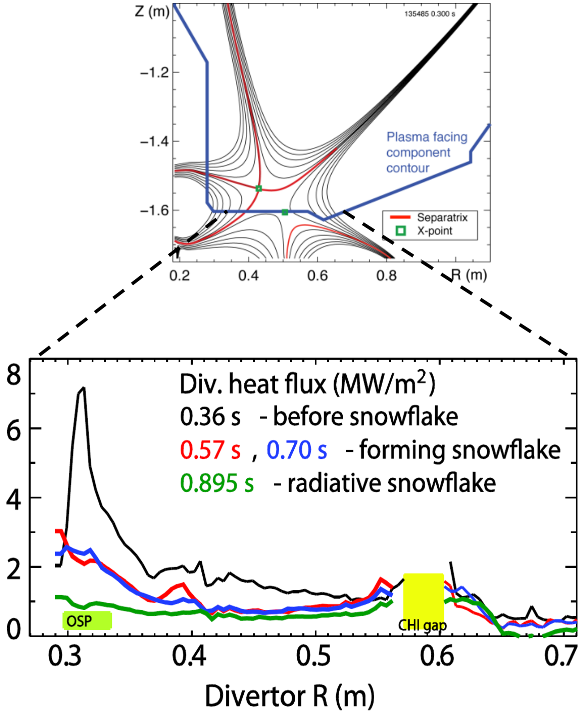


Standard and snowflake divertor geometries will be combined with radiation for heat flux mitigation and detachment studies

BP-2

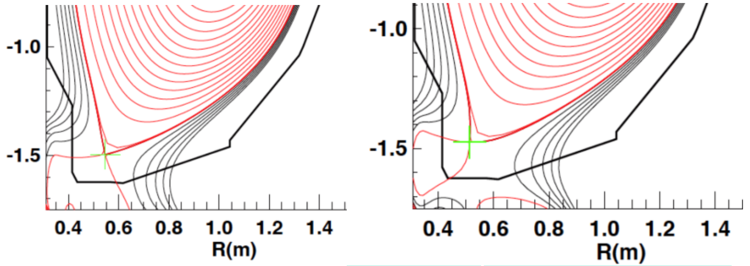


- Radiative divertor and snowflake geometry successfully applied in NSTX for heat flux mitigation in high-performance H-modes
  - Peak divertor heat flux reduced from 6-12 MW/m^2 to 1-2 MW/m^2 while maintaining H98(y,2)~1
  - In snowflake geometry, heat flux reduced during Type I ELMs
- Snowflake divertor configuration
  - Second-order null (B_p ~ 0 and grad B_p ~ 0)
  - Predicted divertor and pedestal properties confirmed in TCV, NSTX, and DIII-D
- Outstanding questions
  - Real-time magnetic control
    - Snowflake variants, up-down symmetric snowflake
  - Pedestal and ELM stability
  - SOL transport and turbulence
    - Flux tube squeezing effects, X-point transport and drifts
    - β-dependent heat transport
    - Compatibility with particle control and high-Z PFCs
    - Fluid turbulence and gyro-kinetic code validation

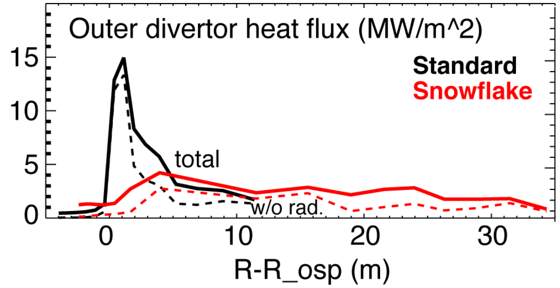


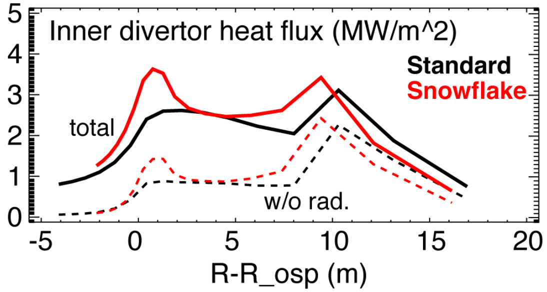
Simulations of snowflake divertor configuration for NSTX-U yield favorable projections

- Significant geometry effects affecting plasma-wetted area, heat transport and radiation
- Significant heat flux reduction compatible with cryopump operation
  - Multi-fluid edge transport model UEDGE with 4 % carbon
  - for P_{NBI}=12 MW case, peak outer divertor heat flux reduction from 15 MW/m^2 to 4 MW/m^2
    - Due to increased plasma-wetted area, heat flux diffusion across longer flux tube length, and radiation
  - Inner divertor detached
  - Particle removal by cryopump results in reduced radiation
    - But still significant heat flux reduction due to geometry



	Standard	**Snowflake**
L_X (m)	**5**	**17**
f_{exp}	**20**	**60-100**
V_{div} (m^3)	**0.070**	**0.128**

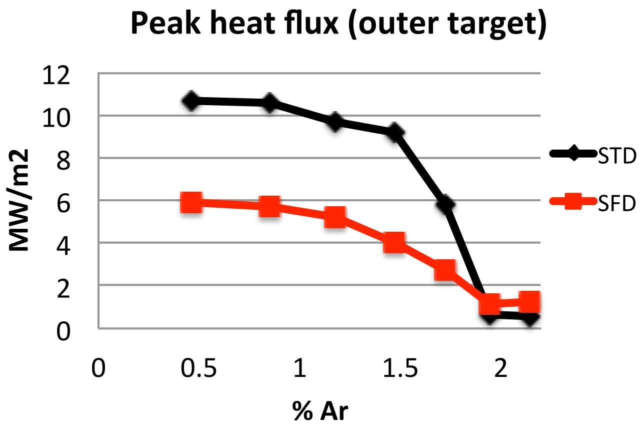


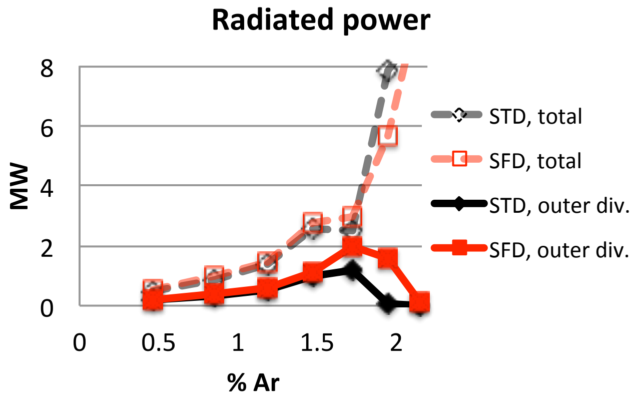


BP-2

Impurity-seeded radiative divertor with feedback control is planned for NSTX-U

- Detachment studies and validation of multi-fluid and gyro-kinetic models
  - Single, double null and snowflake divertors will be combined with gas seeding
- Seeding gas choice dictated by Z_{imp} and PFC
  - Li/C PFCs compatible with D_2, CD_4, Ne, Ar seeding
  - UEDGE simulations show Ar most effective
    - Too much argon causes radiation collapse of pedestal
- Feedback control of divertor detachment via impurity particle balance control
  - Cryopump for particle removal
  - Divertor gas injectors as actuators
  - Real-time control sensors being identified
    - PFC temperature via IR thermography or thermocouple
    - Thermoelectric current between inner and outer divertor
    - Impurity VUV spectroscopy or bolometry
    - Neutral gas pressure
    - Balmer / Paschen series spectroscopy





Plan for SOL and divertor research

BP-2

- Year 1 of 5 Year Plan
  - Continue analysis of SOL width database and comparison with models
  - Collaboration with DIII-D on snowflake and radiative divertor experiments
- Years 2-3 of 5 Year Plan
  - Establish SOL width and divertor database vs. engineering and physics parameters
  - Re-establish edge turbulence measurements (GPI, BES, cameras, probes)
  - Initial radiative divertor experiments with D_2, CD_4 and Ar seeding and lithium
  - Develop snowflake divertor magnetic control and assess pedestal stability, divertor power balance, turbulence, 3D fields as functions of engineering parameters
  - Comparison with multi-fluid and gyro-kinetic models
- Years 4-5 of 5 Year Plan
  - Compare SOL width data with theoretical models and in the presence of 3D perturbations of various types, e.g. RMP coils, HHFW heating, NBI injection
  - Combine snowflake configurations with pedestal control scenarios and tools, cryo
  - Implement radiative divertor control, demonstrate long-pulse H-mode scenario
  - Develop experiment-based model projections for ST-FNSF

Diagnostics: MPTS, CHERS, BES, GPI, IR cameras, Langmuir probes, spectroscopy

Incremental: divertor Thomson Scattering to provide critical data for model validation for snowflake and radiative detachment studies

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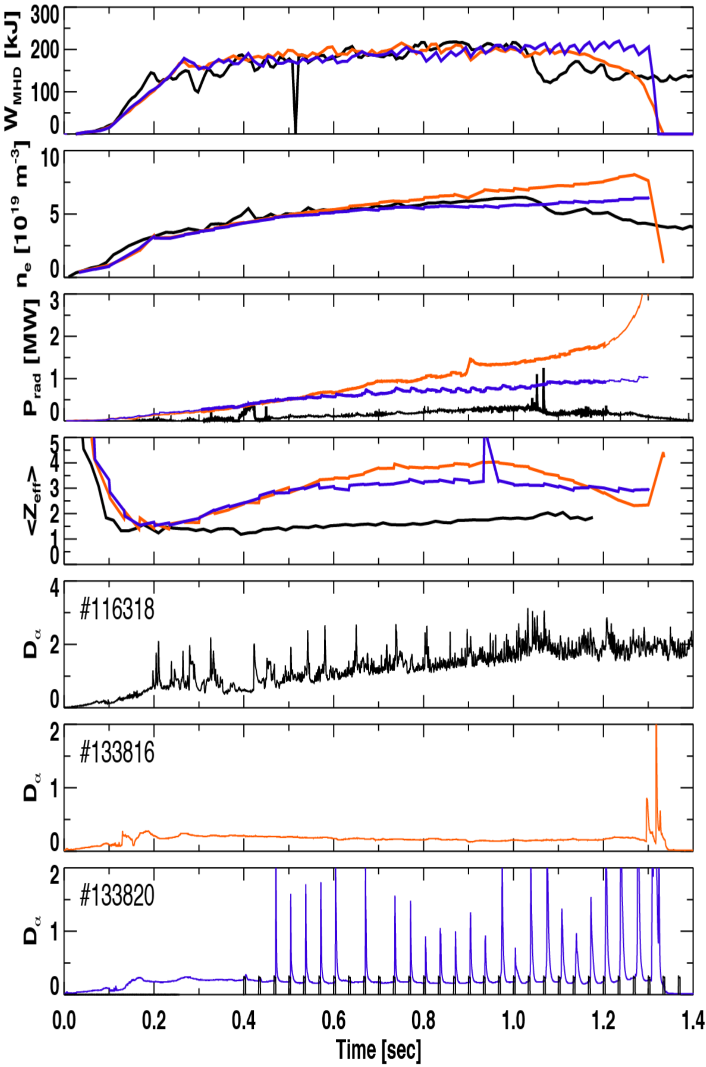
  - Compare cryo to lithium coatings for particle (collisionality) control

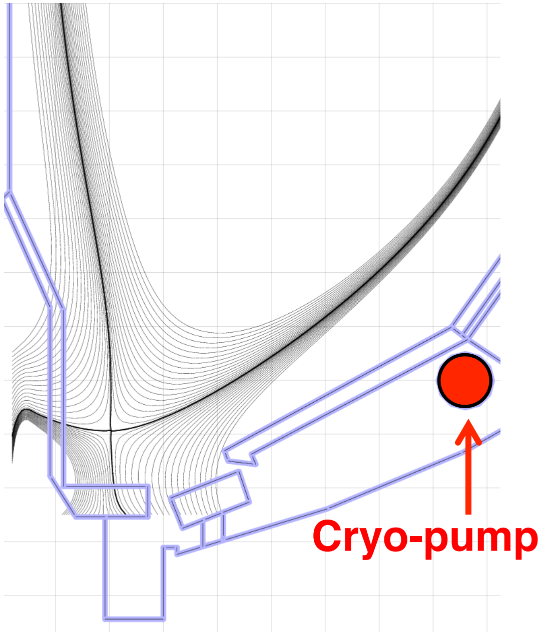
Particle control in NSTX-U will be accomplished with variety of fueling and exhaust techniques

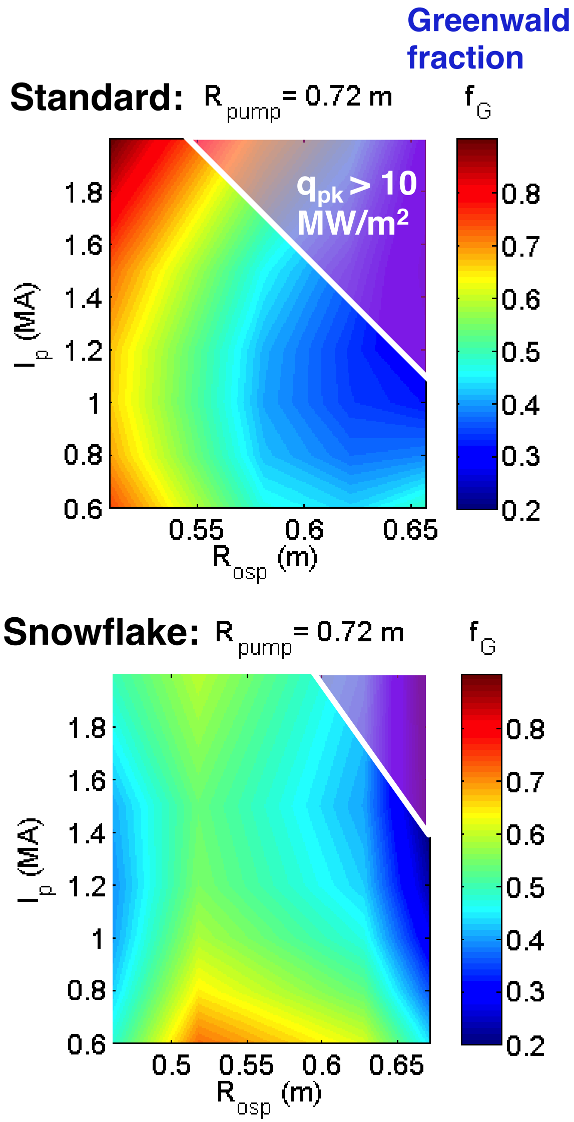
- Density control goals for NSTX-U:
  - Lower density to access reduced collisionality
    - As low as f_G~0.3-0.5 desired
  - Need to avoid density limit in long-pulse shots
    - Greenwald fraction f_G~0.7-1.0 sufficient for non-inductive studies
  - Develop FNSF-relevant pumping scenarios
- Novel and conventional pumping and fueling techniques for density control
  - Lithium coatings for deuterium pumping
  - Cryopumping
  - Conventional and supersonic gas injectors
- Impurity control goal Z_{eff} ~ 2-2.5
  - ELMy H-modes with boronized carbon PFCs
  - ELM-triggering with 3D fields and lithium granules to expel impurities in H-modes with lithium



Cryo-pump will be key for density and collisionality control in Years 4-5

- Cryo-pump is proven technology for plasma density control
  - NSTX-U design is similar to DIII-D
  - Need plenum pressure of 0.6 mTorr to pump NBI input





- Pressures >1 mTorr can be reached over wide range of plasma shapes and SOL widths
  - Semi-analytic pumping model used to optimize plenum geometry
- Optimized plenum geometry can pump conventional and snowflake divertors over a range of R_{OSP}, I_p
  - Cannot sustain $f_G < 1$ at 2 MA with standard divertor
  - High snowflake flux expansion results in better pumping

Plan for particle control research

- Years 1-3 of 5 Year Plan
  - (Year 1) Complete cryopump physics design
  - Perform engineering design and installation
  - Validate cryopump physics design by comparing with initial experiments
  - Assess lithium conditioning for density and impurity control
  - Assess lithium coating lifetimes and interaction with ion fluxes
  - Compare boronized and lithium-coated graphite plasma-facing componenets
    - Perform local hydrogenic recycling and particle balance measurements in the upper and lower divertor areas, and main wall
- Years 4-5 of 5 Year Plan
  - Characterize performance of cryopump, compare with design calculations, and with lithium conditioning
  - Assess pump performance with metallic PFCs
  - Develop scenarios use the cryo-pump for deuterium control while maintaining ELMs for impurity flushing

Boundary program will advance pedestal physics and power and particle handling in NSTX-U for ST-FNSF, ITER

- Pedestal physics: test consistency with peeling ballooning, and test applicability of kinetic ballooning
  - Use lithium conditioning, granules, and 3D fields as a way to manipulate the density and pressure profile
- Power and particle handling: further develop snowflake and radiative divertors
  - Test key predictions of snowflake configuration, and evaluate synergy with radiative divertors, graphite and high-Z plasma facing components, and cryo-pumping
- Li and cryopump to achieve stationary density and low Z_{eff}
  - Up to an order of magnitude reduction in ν^* compared to NSTX

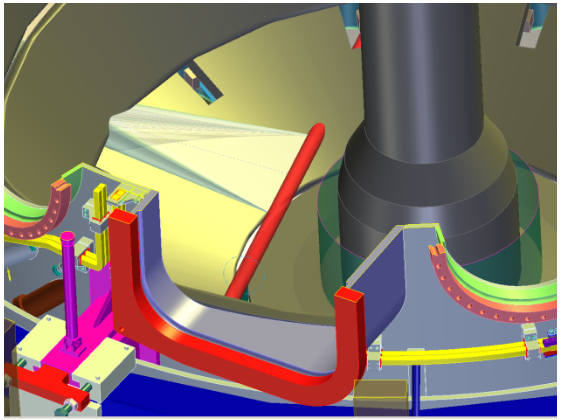
Backup

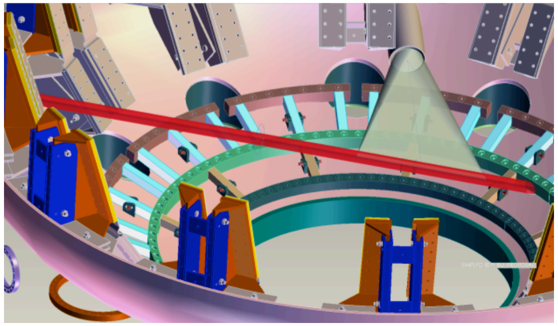
Planned NSTX-U facility upgrades enable access to new parameter space and unique capabilities

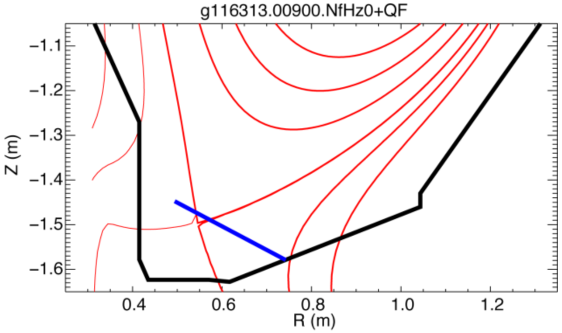
Planned upgrades (NSTX → NSTX-U)	**Operations year available**	**Boundary Physics area**
P_{NBI} = 5 → 12 MW (5 s) 7.5 →15 MW (1.5 s)	1-2	Pedestal structure and ELM stability, L-H, divertor heat flux (12 → 15-20 MW/m^2) P/R ~ 10 → 20 P/S ~ 0.2 → 0.4
I_p = 1.3 → 2 MA B_t = 0.5 → 1 T	1-2	L-H transition, pedestal structure and stability, SOL width, divertor heat flux
Pulse length 1.5 → 5-10 s	1-2	Steady-state divertor heat flux mitigation, density and impurity control
Axisymmetric PF (divertor) coils PF1A, 1B, 1C, 2L	1-3	Plasma shaping, L-H, divertor configuration control
High-Z plasma-facing components	2	Core and pedestal impurity transport, divertor transport
Non-axisymmetric control (NCC) coils	3	ELM control and pedestal transport
Divertor cryopump	3	Pedestal stability, density control, divertor transport and radiation control

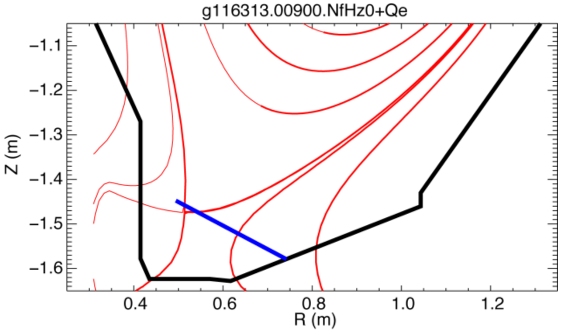
Divertor Thomson Scattering system would significantly enhance NSTX-U Boundary research capabilities

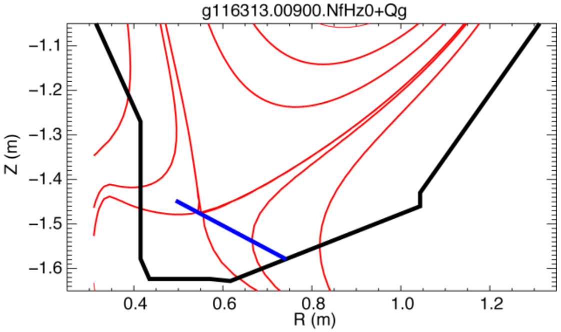
- Physics contributions
  - ELM and inter-ELM divertor transport
  - SOL width scaling, role of X-point heat transport
  - Radiative detachment model validation
  - Snowflake divertor properties, incl. X-pt β_p measurements
  - Divertor plasma-surface interaction and impurity transport studies, erosion rates via spectroscopy
- A conceptual geometry identified for NSTX-U
- Conceptual system design underway







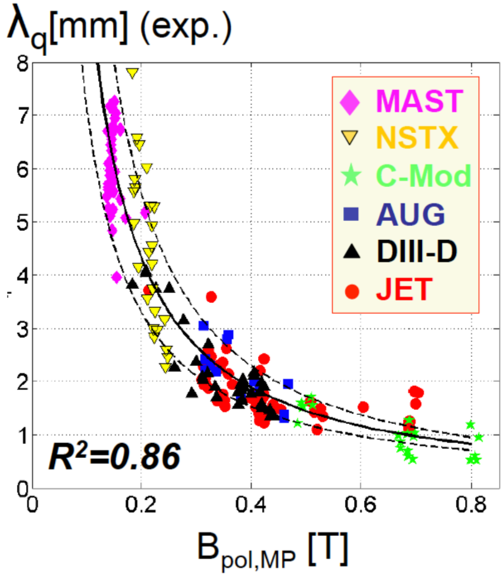


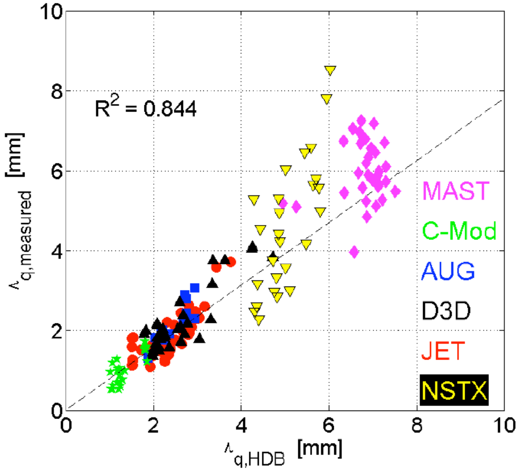


SOL width studies elucidate on heat flux scaling projections for NSTX-U, ST-FNSF and ITER

- Goal: compare SOL width scalings with models
- SOL width scaling
  - In NSTX: $\lambda_q^{mid} \sim I_p^{-1.6}$
    - For NSTX-U (2 MA): $\lambda_q^{mid} = 3\pm0.5$ mm
  - Multi-machine database (Eich IAEA FEC 2012):

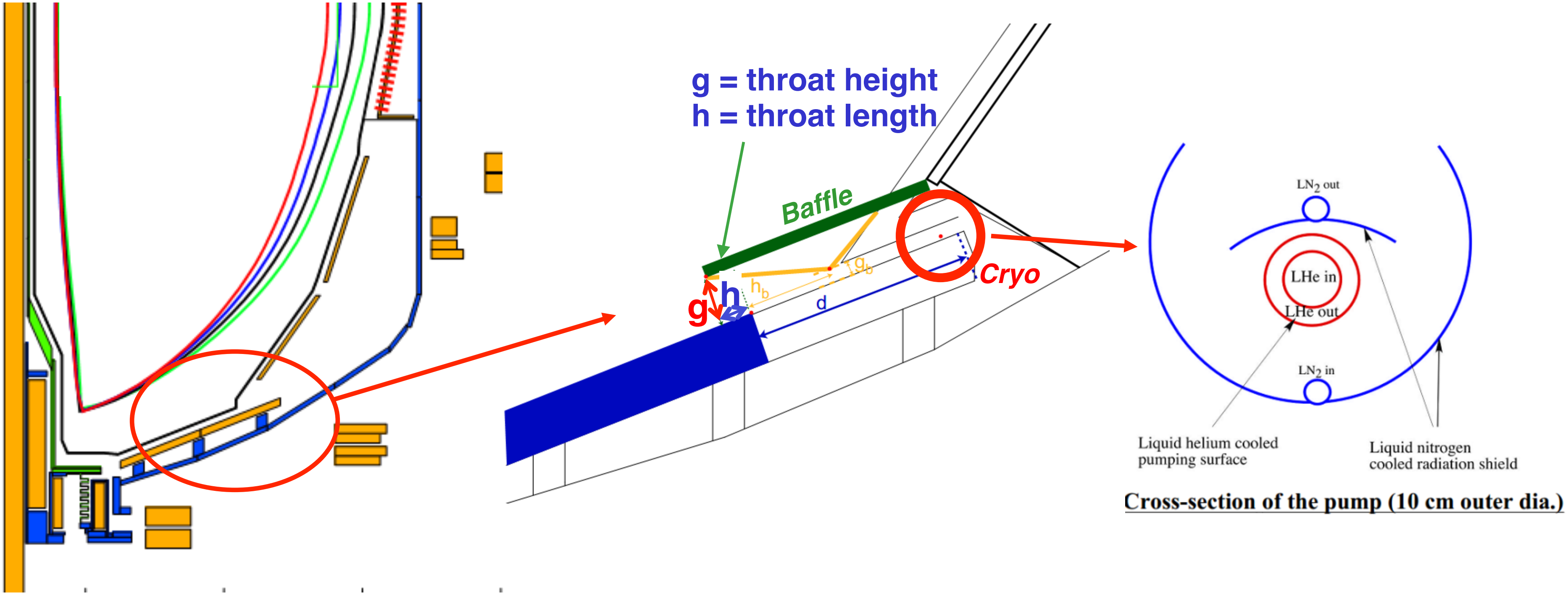
    λ_q^{mid} (mm) (0.63+/-0.08)x $B_{pol,MP}^{-1.19}$
    - For NSTX-U (B_p~0.55 T): $\lambda_q^{mid} \sim 1.3$ mm
  - Comparison with SOL models
    - Parallel transport: conductive/convective, cross-field : collisional / turbulent / drift
    - Goldston heuristic model: ∇B and curvature drift motion sets SOL width $\lambda_{SOL} \sim (2a/R)\ \rho_i$, Spitzer thermal conduction sets T_{sep}
      - For NSTX-U: $\lambda_q^{mid} \sim 6$ mm
- *Diagnostics: IR cameras, MPTS, Langmuir probes*
  - *Divertor Thomson scattering (incremental) desirable*





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

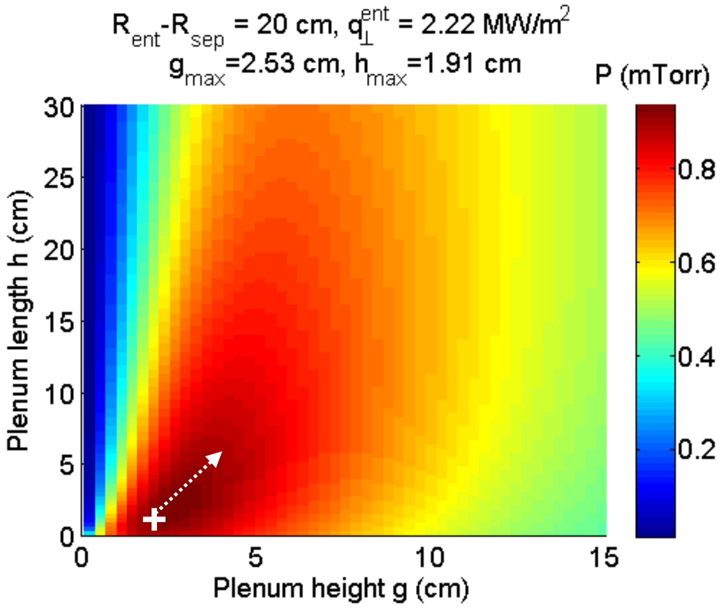
- Cryo-pump is proven technology for plasma density control
  - More conventional pumped ELMy H-mode scenario
- NSTX-U design is similar to DIII-D outer lower pump
  - Plenum located under new baffling structure near secondary passive plates
  - Pumping capacity of a toroidal liquid He cooled loop
    - 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)

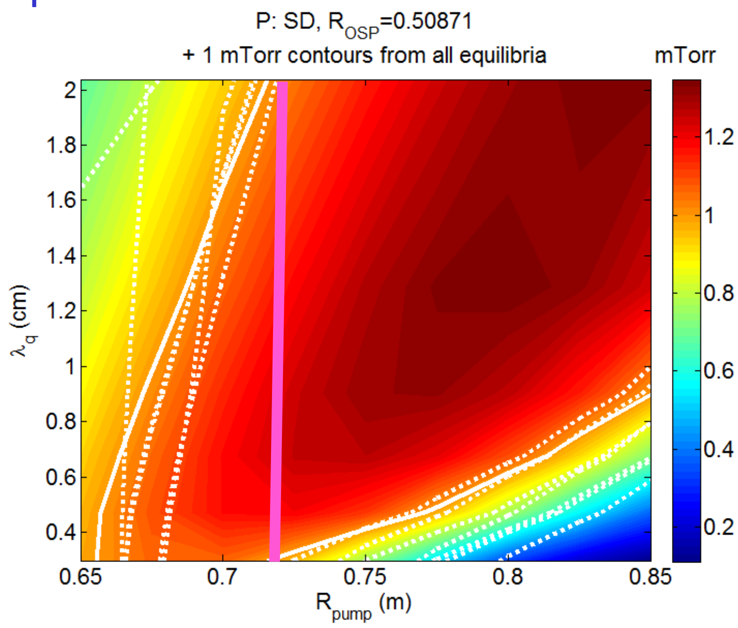


Cross-section of the pump (10 cm outer dia.)

Semi-analytic pumping model used to optimize plenum geometry

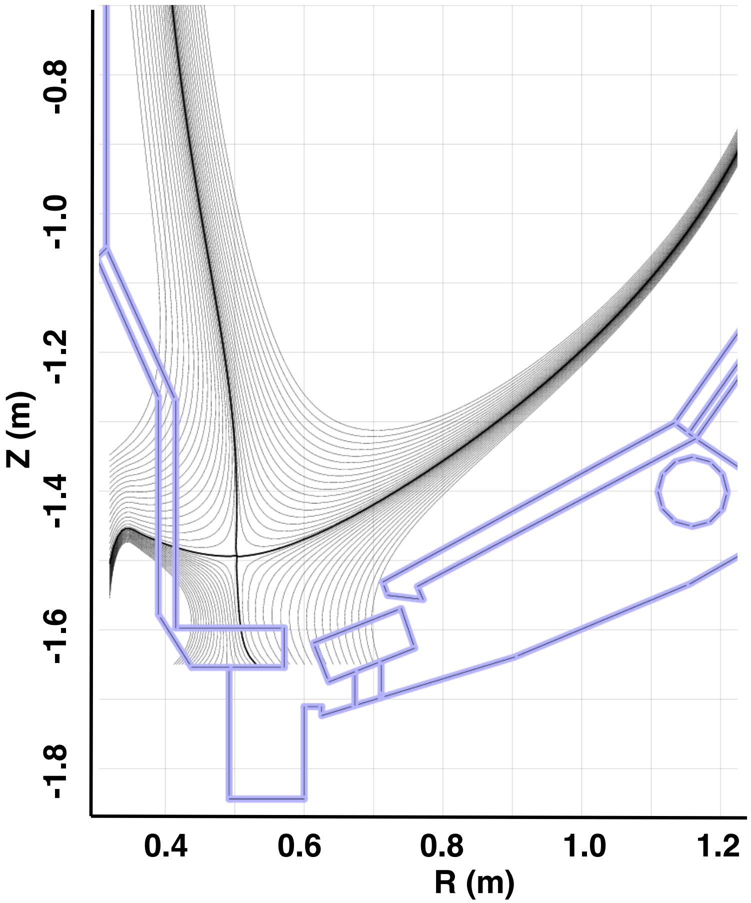
- Model developed for DIII-D pumping studies (Maingi, NF ‘99)
  - Predicts plenum pressure, validated with DIII-D data
  - Projected NSTX-U heat flux (I_p scaling) and divertor T_e (~15 eV) used as input
  - Uses first-flight neutral model (insufficient for detached divertor)
- Pressure is maximum for 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


R_{ent}-R_{sep} = 20 cm, $q_{\perp}^{ent}$ = 2.22 MW/m^2
g_{max}=2.53 cm, h_{max}=1.91 cm

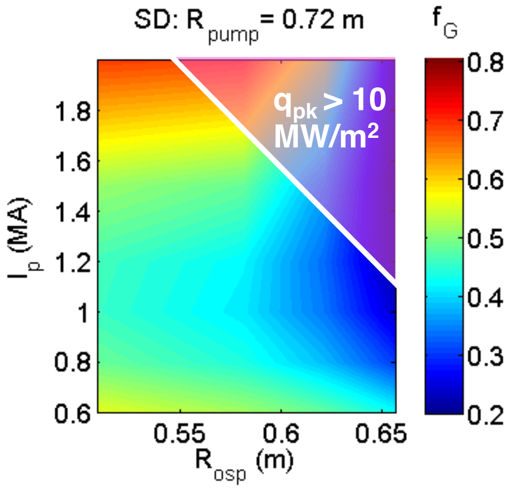

P: SD, R_{OSP}=0.50871
+ 1 mTorr contours from all equilibria

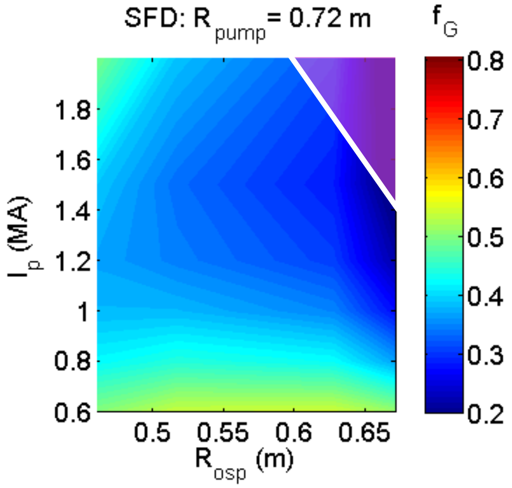
Optimized plenum geometry can pump to low density for conventional and snowflake divertors over a range of R_{OSP}, I_p

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



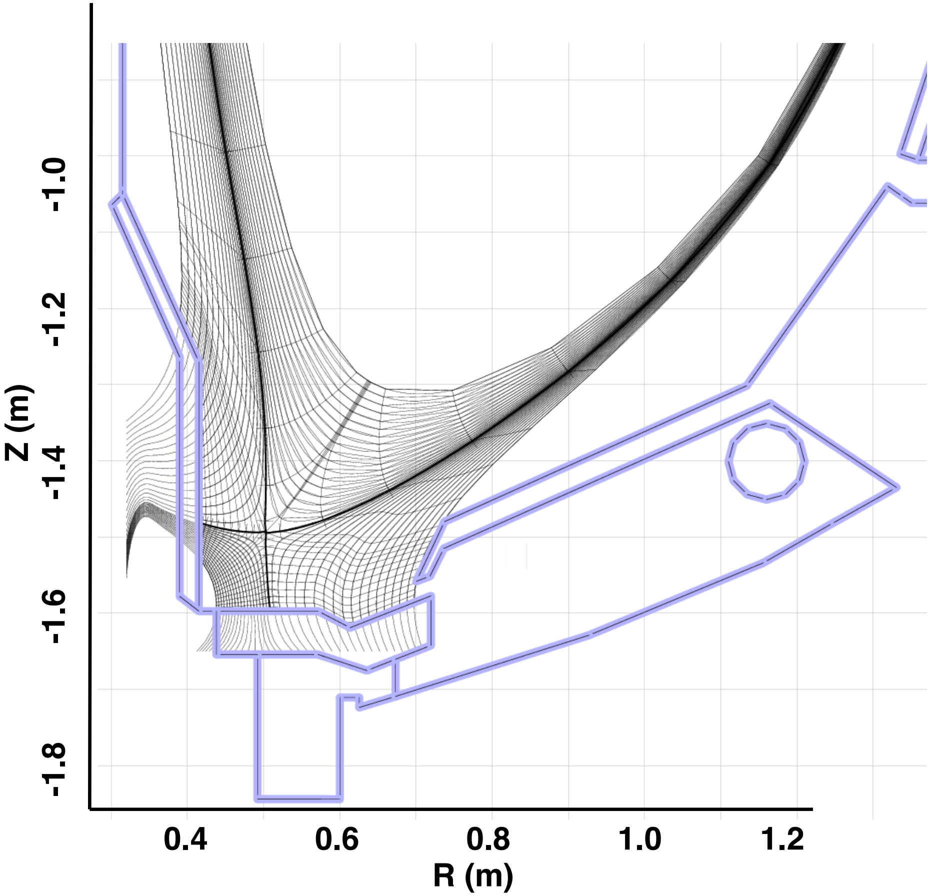
- Core density estimated assuming pumped flux=NBI input
  - 2-pt model used to estimate upstream density
  - Assume n_e/n_e^{sep}~3
- Can pump to f_G<0.5
  - f_G~0.7 desirable for all scenarios, lower provides more flexibility
  - Moving R_{OSP} closer to pump allows lower n_e, but limited by power handling
- High flux expansion in SFD gives *<u>better</u>* 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***