National Spherical Torus eXperiment Upgrade

TO: PFC REQUIREMENTS WORKING GROUP
FROM: J. MENARD
SUBJECT: DESCRIPTION OF REDUCED MODEL FOR ESTIMATING NSTX-U DIVERTOR HEAT LOADS

The following slides outline the theoretical background and give examples for a distributed version of a code to calculate heat fluxes to NSTX-U plasma facing components.

The source code, scripts to define inputs and execute the code as well as the input equilibria are available at:
http://w3.pppl.gov/~jmenard/NSTXU/physics_design/divertor_heat_flux_scans/version_03/

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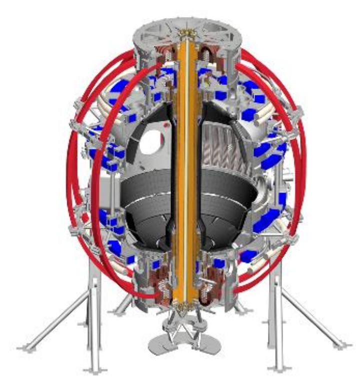
Fusion Energy Sciences

Description of reduced model for estimating NSTX-U divertor heat loads

J. Menard, PPPL

May 4, 2017
Version 3



Parametric fits to divertor heat flux

- T. Eich, et al., Nucl. Fusion **53** (2013) 093031, Eqn 1

$$q(\bar{s}) = \frac{q_0}{2} \cdot \exp\left(\left(\frac{S}{2\lambda_q}\right)^2 - \frac{\bar{s}}{\lambda_q \cdot f_x}\right) \cdot \mathrm{erf}c\left(\frac{S}{2\lambda_q} - \frac{\bar{s}}{S \cdot f_x}\right) + q_{\mathrm{BG}}$$

$$\bar{s} = s - s_0 = (R_{\mathrm{sep}} - R) \cdot f_x$$

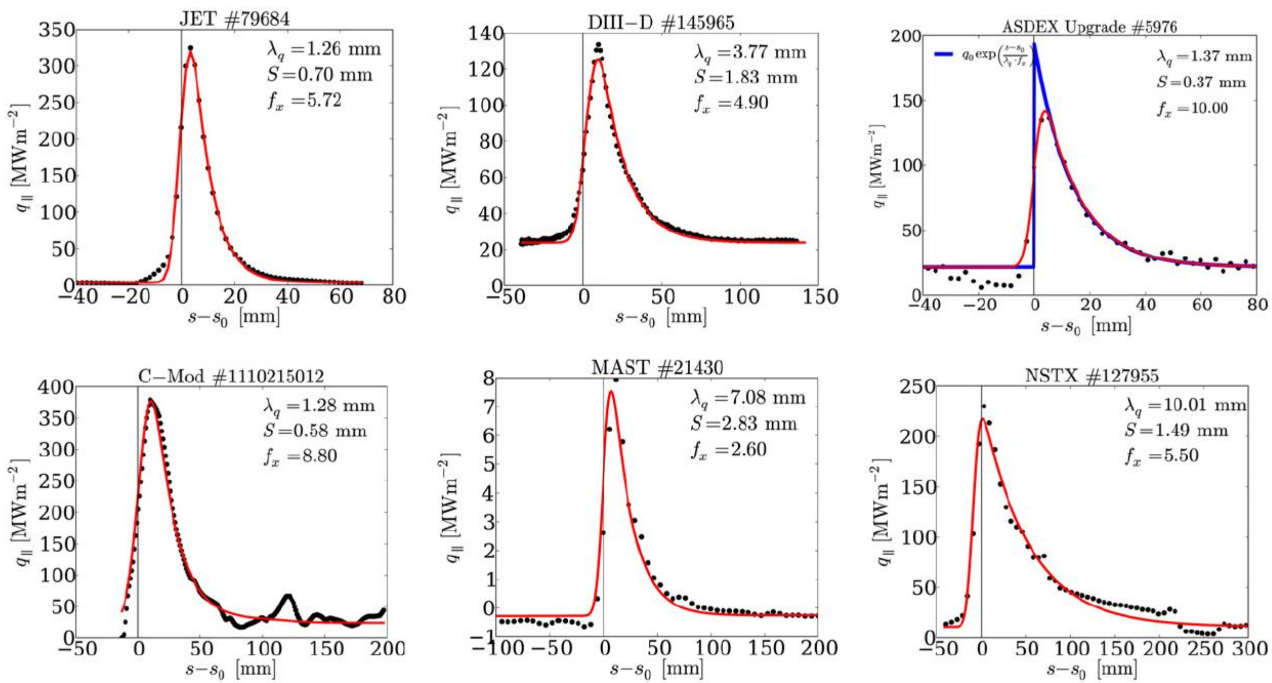


Figure 1. Typical outer target power parallel heat flux for each machine and result of fitting equation (1).

Model for SOL heat flux width λ_q

- T. Eich, et al., Phys. Rev. Lett. **107** (2011) 215001
  - Equations 5, 7-10 → Goldston heuristic drift model for λ_q

Map λ_m to outer midplane: $\lambda_m^* = \frac{R_{\text{geo}}}{(R_{\text{geo}} + a)} \frac{B_p}{B_p^{mp}} \lambda_m$

$$B_p = \frac{\mu_0 I_p}{2\pi a \sqrt{(1+\kappa^2)/2}}$$

$$\lambda_m = 2.02 \frac{f_{\text{AZ}}}{\sqrt{(1+\kappa^2)}\epsilon^{1/8}} B_T^{-7/8} q_{\text{cyl}}^{9/8} P_{\text{SOL}}^{1/8}$$

$$q_{\text{cyl}} = \frac{2\pi a \epsilon B_T}{\mu_0 I_p} \frac{(1+\kappa^2)}{2}$$

with λ_m in [mm], P_{SOL} in [MW], B_T in [T]

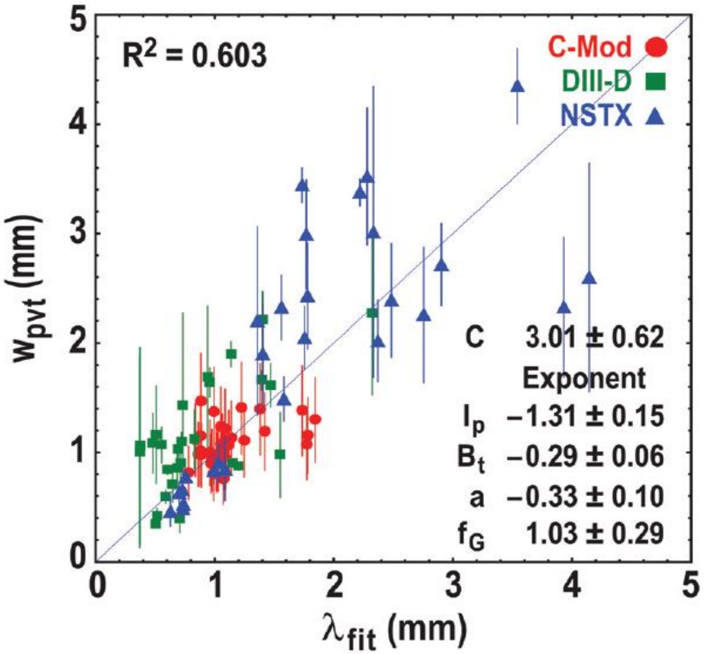
$$f_{\text{AZ}} = \left(\frac{2\bar{A}}{1+\bar{Z}}\right)^{7/16} \left(\frac{Z_{\text{eff}}+4}{5}\right)^{1/8}$$

$$\bar{Z} = \sum_i Z_i n_i / \sum_i n_i \qquad \bar{A} = \sum_i n_i A_i / \sum_i n_i$$

Use $\lambda_q = \lambda_m^*$

Data for private flux region width w_{pvt}=S

- M. Makowski et al., Phys. Plasma **19**, 056122 (2012)
- T. Eich, et al., Nucl. Fusion **53** (2013) 093031



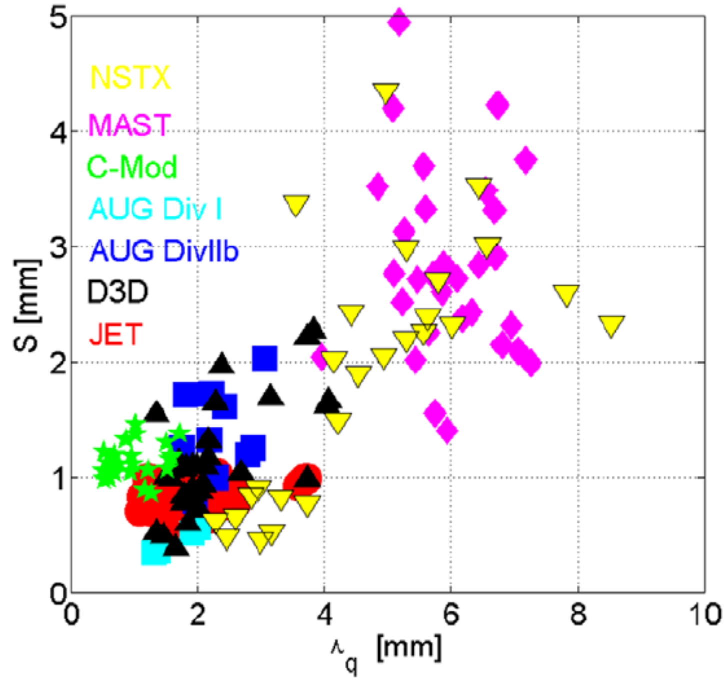


Table 5. Variation of mean power spreading factor, S and S/λ_q for the various devices.

	JET	DIII-D	AUG DivI	AUG DivII	C-Mod	MAST	NSTX
S (mm)	0.59–1.04	0.39–2.27	0.35–0.56	0.79–2.02	0.86–1.46	1.11–4.95	0.46–4.35
S / λ_q	0.26–0.81	0.24–1.14	0.26–0.28	0.40–0.94	0.67–2.32	0.17–0.95	0.15–0.95

Generalized divertor heat-flux model consistent with Eich parametric fitting

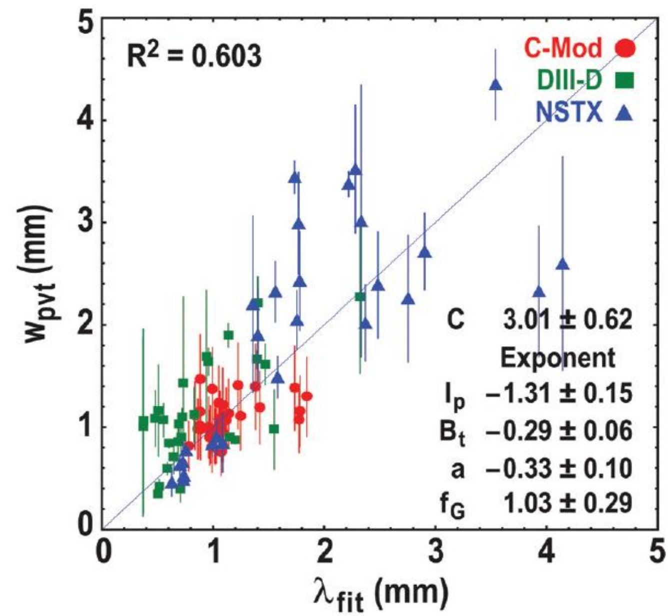
- SOL heat flux approximately field-aligned $\Rightarrow \vec{q} \approx \vec{q}_{||} = q_{||}\hat{b} = q_{||}\vec{B}/B$
- No SOL heat source $\Rightarrow \nabla \cdot \vec{q} = \vec{B} \cdot \nabla(q_{||}/B) = 0 \Rightarrow q_{||} = f(\psi)B$
- $q_{||} \equiv q_{||0} B \hat{q}(\hat{\psi})$ $\qquad \hat{q}(\hat{\psi}) \equiv 0.5 \exp(\sigma_0^2 - \sigma)\text{erfc}(\sigma_0 - \sigma/2\sigma_0)$
- $\sigma_0 \equiv S/2\lambda_q$ $\qquad \sigma \equiv \hat{s}/\hat{\lambda}_q$ $\qquad \hat{s} \equiv \hat{\psi} - 1$ $\qquad \hat{\psi} \equiv (\psi - \psi_{axis})/\Delta\psi$
- $\hat{\lambda}_q \equiv \lambda_q |\nabla\psi|_{omp}/\Delta\psi$ $\qquad \Delta\psi \equiv (\psi_{edge} - \psi_{axis})$
- Note: $q_{||0} \approx P_{div}/(2\pi|\nabla\psi|_{omp}\lambda_q)$ for $\sigma_0 \rightarrow 0$
- Divertor surface normal unit vector $\equiv \hat{n} \Rightarrow q_{divertor} = (\hat{n} \cdot \hat{b}) q_{||0} B \hat{q}(\hat{\psi})$
- Define total B-field angle of incidence $\theta_B \Rightarrow \hat{n} \cdot \hat{b} = \sin(\theta_B)$
- For $q_{divertor} =$ Eich $q(\bar{s}) = q_0 \hat{q}(\bar{s}) \Rightarrow q_0 = \sin(\theta_B) q_{||0} B$

$$\boxed{q_{divertor} = q_{||0} \sin(\theta_B) B \hat{q}(\hat{\psi})}$$

Choice of S for NSTX-U calculations

- Options:
  - S_{Mak} = S from Makowski scaling
  - S_{rel} = MIN(S / λ_q) × λ_q = 0.15 × λ_q
    - MIN(S / λ_q) = 0.15, 0.17 for NSTX, MAST
  - S_{fix} = fixed / constant value of S
- NSTX-U model uses combination of all these options as follows:
  - First set S = MIN([S_{Mak}, S_{rel}])
  - Then enforce $S_{min} \leq S \leq S_{max}$
    - S_{min} = 0.1mm, S_{max} = 0.5mm
  - S typically set by S = S_{rel} ≈ 0.2-0.3mm
  - S = 0.15 × λ_q ≈ S_{mak}(f_G = 0.4, 2MA, 1T)

  ➔ **Consistent w/ physics/ops goal f_G ≥ 0.5**



Model for power conducted to divertor target

- P_{heat} = total heating power (ohmic + auxiliary + alpha)
- f_{rad} = fraction of heating power radiated from core
  - For NSTX-U projections assume f_{rad} = 0.3
- $P_{rad} = f_{rad} \times P_{heat}$ = power radiated from core
- $P_{sol} = P_{heat} \times (1-f_{rad})$ = power into SOL
- N_{div} = Number of in/out divertor legs connected to target
  - N_{div} = 1 for single null (SN), N_{div} = 2 for double null (DN)
- f_{obl} = fraction of power to outboard divertor leg(s)
  - For NSTX-U projections assume f_{obl} = 0.8 for DN, 0.65 for SN
- $f_{ibl} = (1-f_{obl})$ = fraction of power to inboard divertor leg
- $f_{leg} = f_{obl}$ or f_{ibl} = fraction of power to chosen divertor leg

$P_{div} = P_{sol}\, f_{leg} / N_{div}$ = power conducted to divertor target

NSTX example: low δ, I_P = 0.8MA

D. Gates *et al.* Phys. Plasmas 13 (2006) 056122

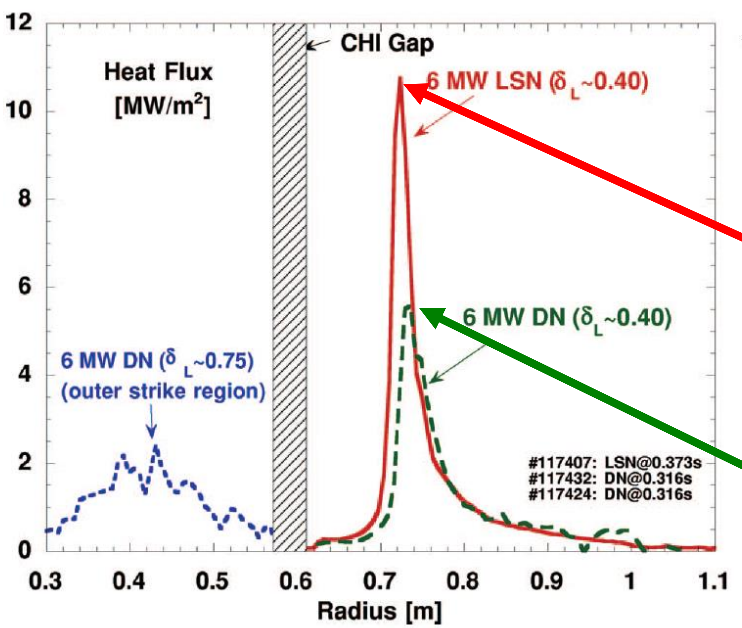
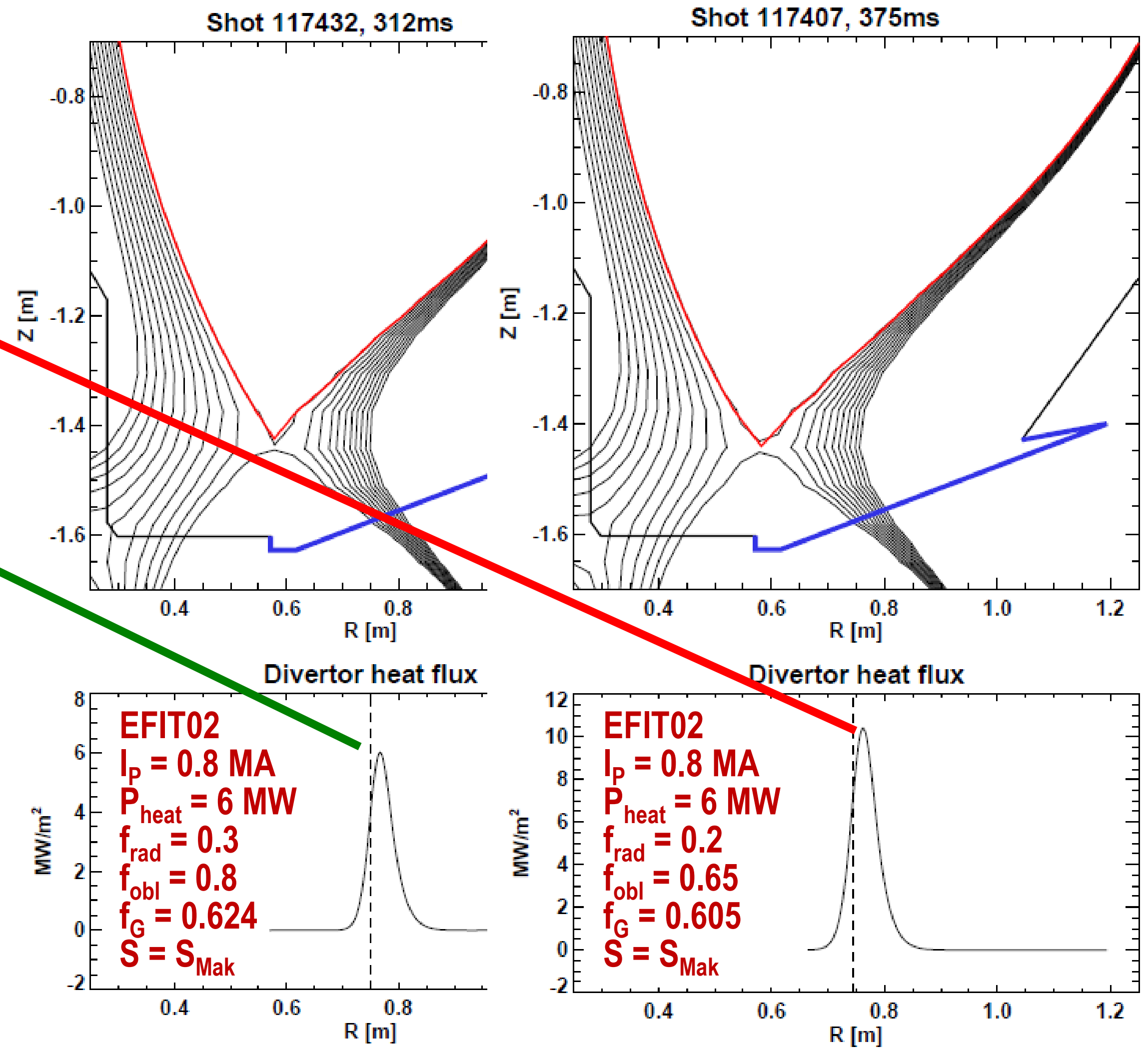


FIG. 13. (Color) The peak heat flux vs major radius for three different divertor configurations: (1) low δ lower single null, (2) low δ double null, and (3) high δ double null. All three configurations had identical heating power. The peak heat flux reduces by a factor of ~5.



NSTX example: high δ, I_P= 1.2MA

V.A. Soukhanovskii et al Nucl. Fusion 49 (2009) 095025

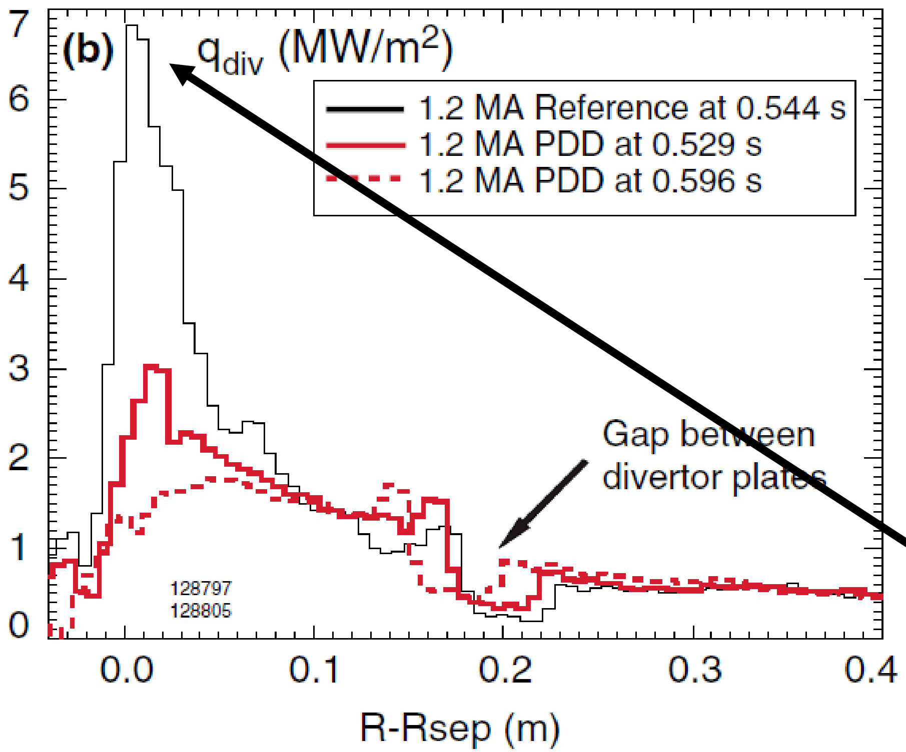
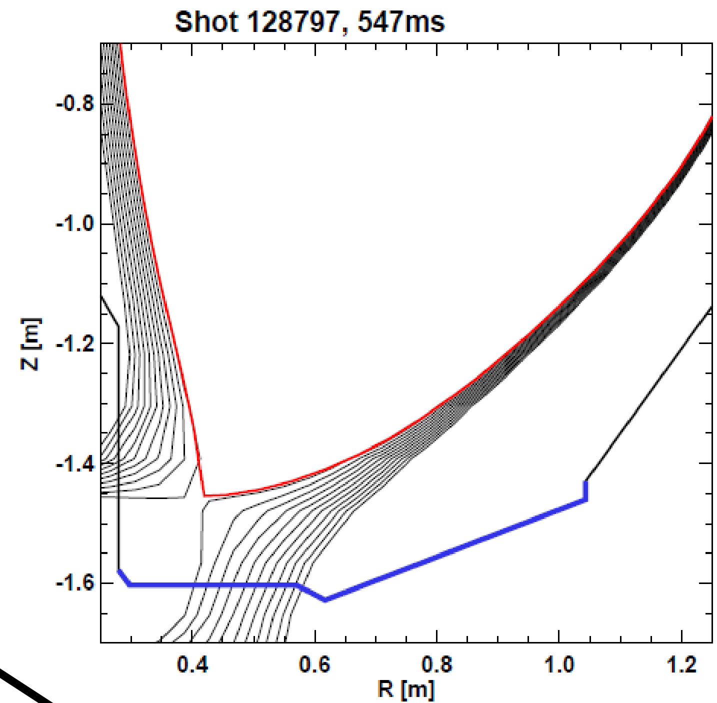
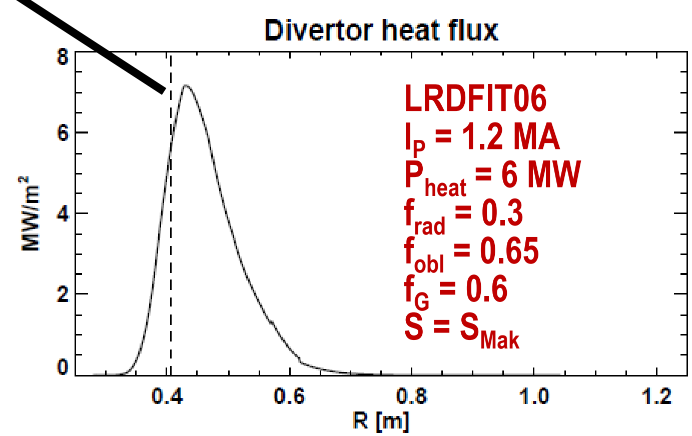


Figure 4. Divertor heat flux profiles in the reference and PDD discharges: (*a*) 1.0 MA and (*b*) 1.2 MA.

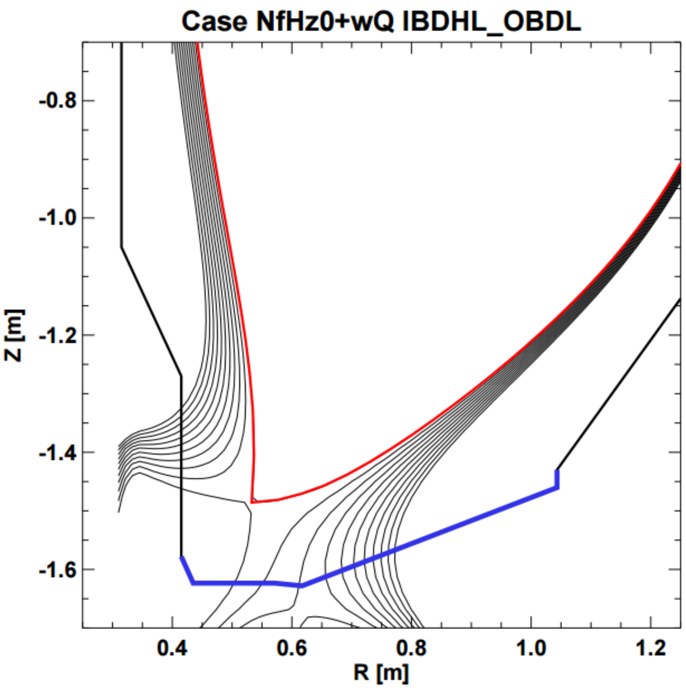


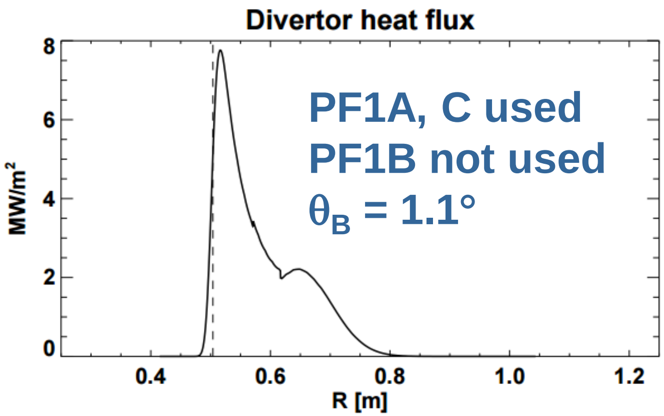


Comments on comparison to NSTX and extrapolation to NSTX-U

- Have looked at very limited number of NSTX cases
  - f_{rad} = 0.2-0.3 and S = S_{Mak} ***might*** be reasonable scaling assumption for NSTX / NSTX-U
    - Peak heat fluxes can match, but exact profile shapes differ
    - There is substantial uncertainty in both f_{rad} and S_{Mak}
  - Need DIVSOL TSG to identify more cases for comparison
  - More detailed analysis of NSTX S-scaling would be valuable
- For scaling to NSTX-U, use more conservative (i.e. smaller) $S = S_{rel} = 0.15 \times \lambda_q$
- Detachment is option for reducing NSTX-U heat-flux
  - Showed reduction of $q_\perp$ by ~50-70% in NSTX
  - Prefer not to rely on detachment for NSTX-U scenarios
    - Beneficial to have more operating margin if PFCs will allow

NSTX-U projection example: high δ, I_P = 2MA with high flux expansion divertor

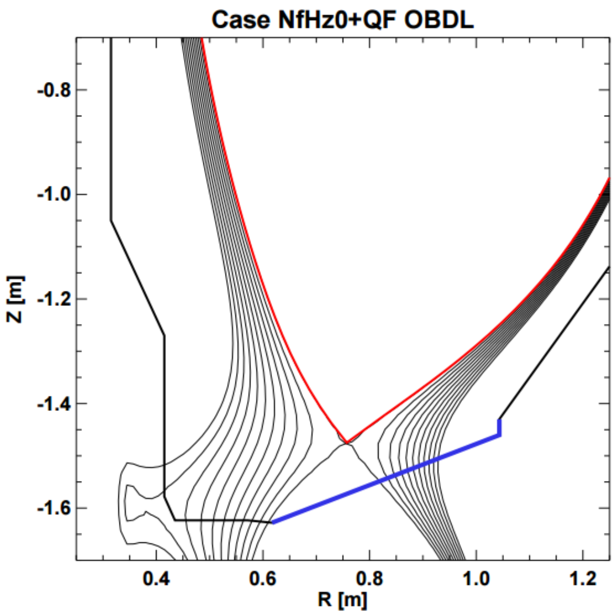


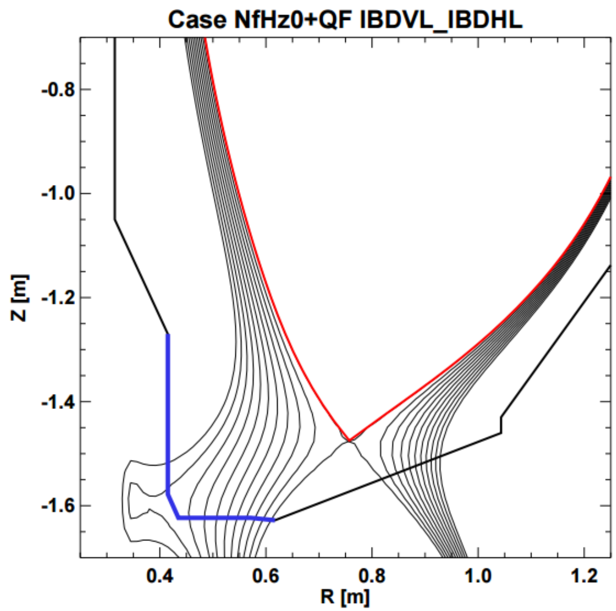


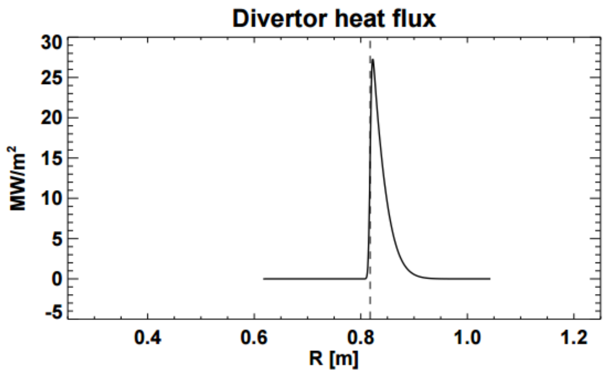
- A = 1.75, κ = 2.74, balanced DN
- I_P = 2MA, B_T = 1T, P_{heat} = 10MW
- $\lambda_{q\text{-}mid}$ =1.97mm, S/λ_q = 0.15
- Poloidal flux expansion = 36
  - Also assume B-field angle of incidence θ_B must be ≥ 1° (tile alignment / leading edge tolerance)
- Radiation fraction = 30%
- 80% of power to outboard
- 50-50 split between upper/lower
- P_{div} ~ 2.8MW to divertor target
- $q_{div\text{-}peak}$ = 7.8 MW/m^2

Example case from 96 with high I_{PF1A}

- **A=1.84, κ=2.5, $\delta_{U,L}$ = 0.193, 0.375, I_{OH}=0, $I_{PF1AU,L}$ = 15, 7kA**

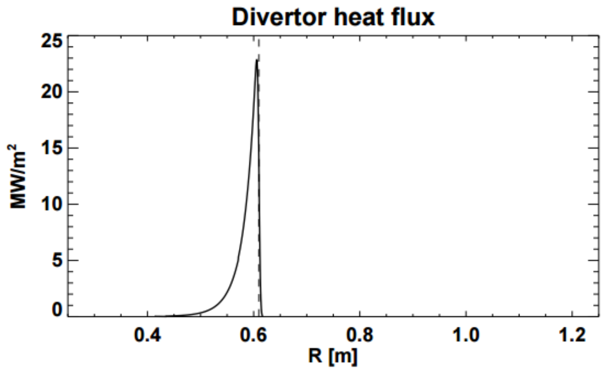




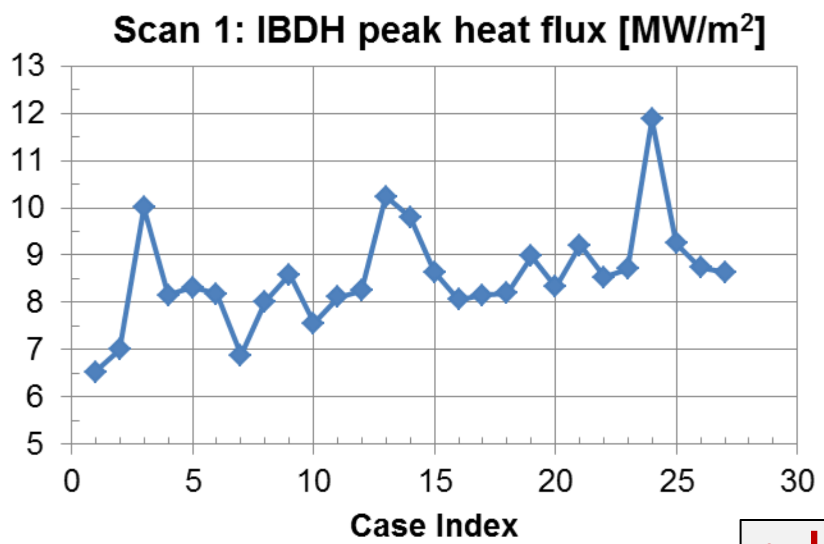


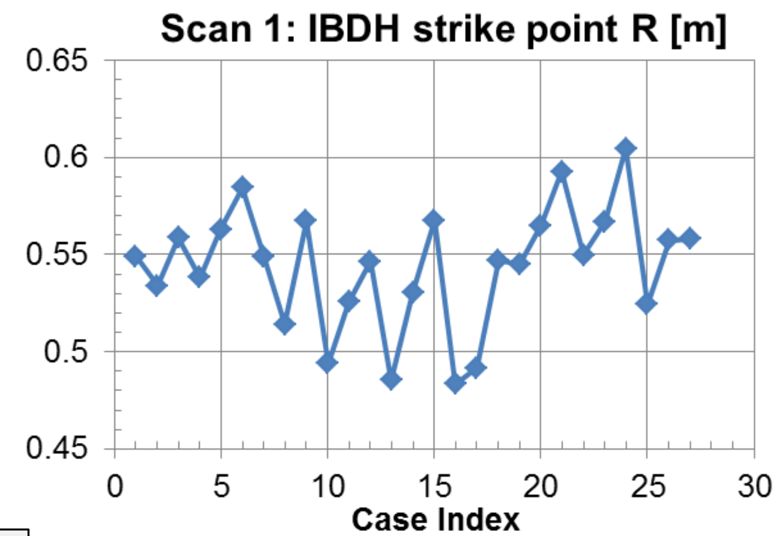
q_{peak} ~20-25MW/m^2

Δt_{flat} < 1s without sweeping or other mitigation

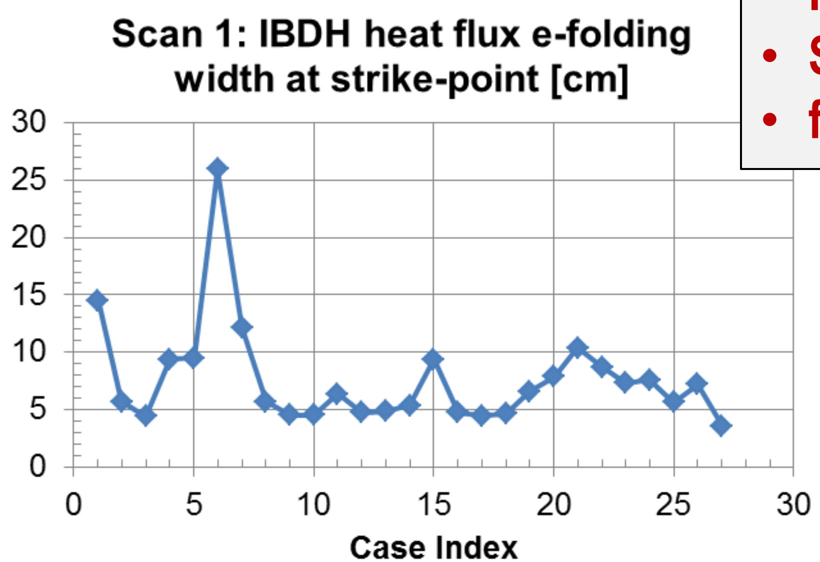


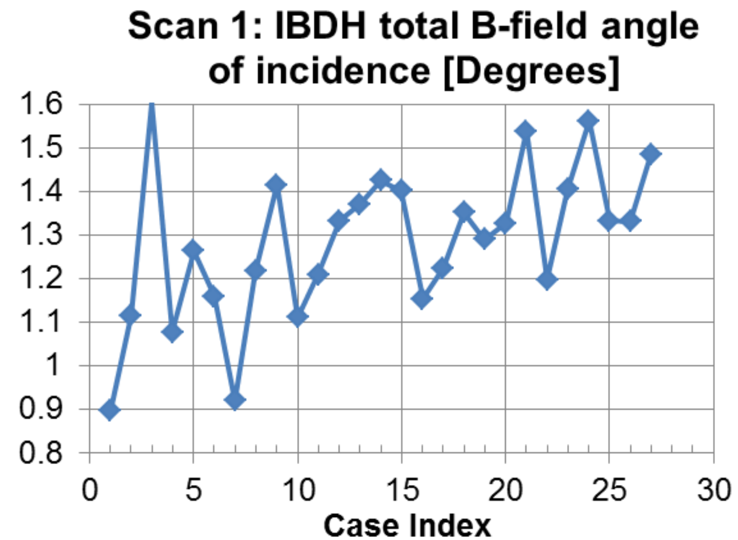
Example: Scan 1: No PF1B, use PF1C for high flux expansion
IBDH tile heat flux projections





- **HD model λ_q**
- **$S / \lambda_q = 0.15$**
- **$f_{rad} = 0.3$**





Possible next steps / future work

- Add simple core emission source to compute core radiation heat loads on first wall, divertor
- Generalize model to compute 2D incident $q_{||,\perp}$ and Γ_{rad} on entire limiter boundary
- Include 3D tile / boundary shapes?