Novel divertors and NHTX simulations*

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in collaboration with

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Divertor discussion

PPPL

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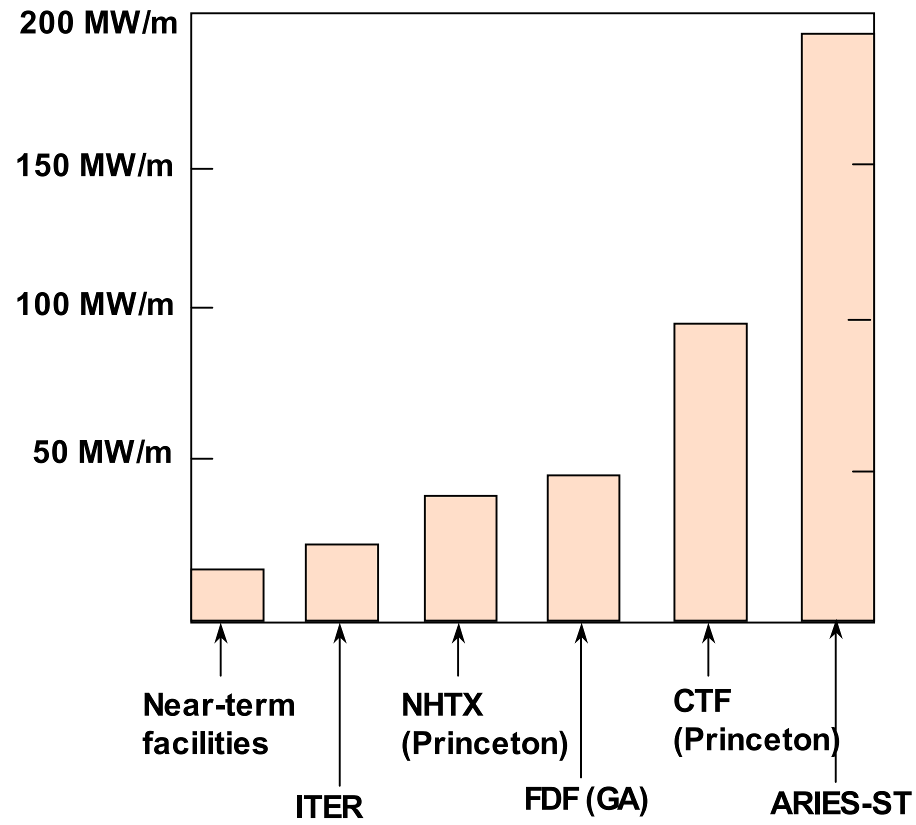
Outline

- **Heat load problem**
- **Some NHTX-specific results for orientation**
- **Divertor options**
  - Plate tilting
  - Radiation
  - Flux-surface expansion
    - Snowflake divertor (1 VG; full discussion from Ryutov)
    - X-divertor
  - Lithium (NSTX results and prospects; kinetic edge models)
- **Discussion**

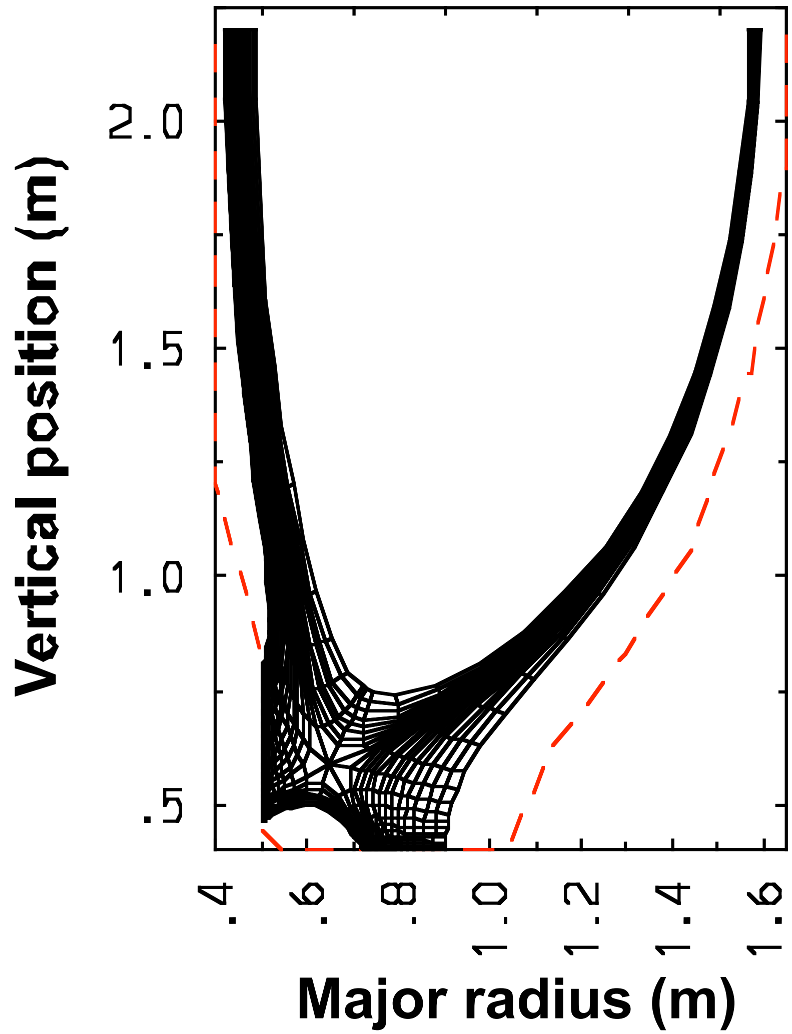
Future tokamaks have a major heat load problem

- **For NHTX, consider max. approx. area available on divertors and walls**
  - outer div. ~1 m^2 each
  - inner div. ~0.6 m^2 each
  - outer wall ~ 10 m^2
- **For 50 MW input, 25 to upper/lower divertors gives ~16 MW/m^2**
- **Or, if all goes to walls, ~5 MW/m^2**
- **However, heat-flux profiles will likely be much more peaked**



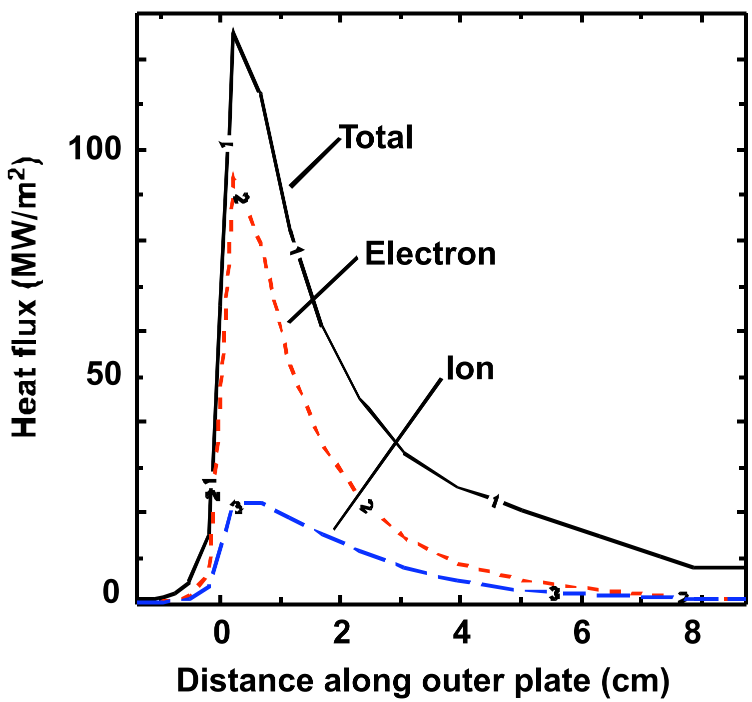
Nominal NHTX open divertor is symmetric double null

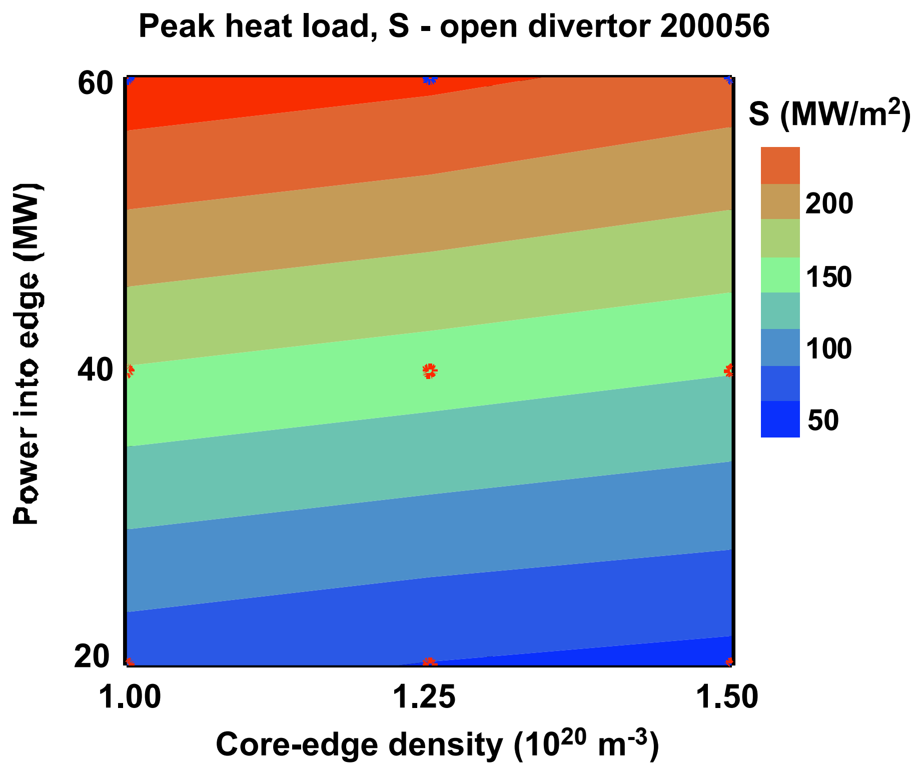
- Use UEDGE to model heat flux with "standard" D = 0.2 m^2/s and $\chi_{e,i}$ = 1 m^2/s
- High recyling: R_p= 0.99, R_w = 1.0
- Scan core-edge density and power input



Heat flux to outer divertor is very large in expected operating range (~50 MW)

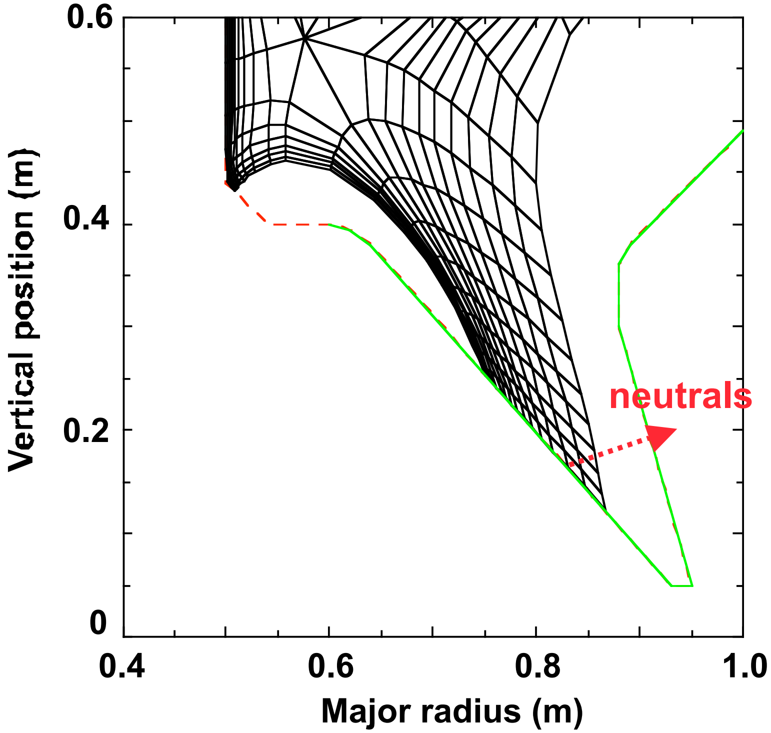
- Electrons carry most of energy
- Results similar to Canick, but need to be more closely compared
- 1% neon fixed-concentration shows only small heat-flux reduction





Consider case 200058 with strike-point on outward-facing plate

- Here $n_{core} = 1.5x10^{20}$ and P_{core} = 30 MW again
- Heat flux broadens and is reduced by ~x3
- Divertor density lower, T_e is high; far from detachement



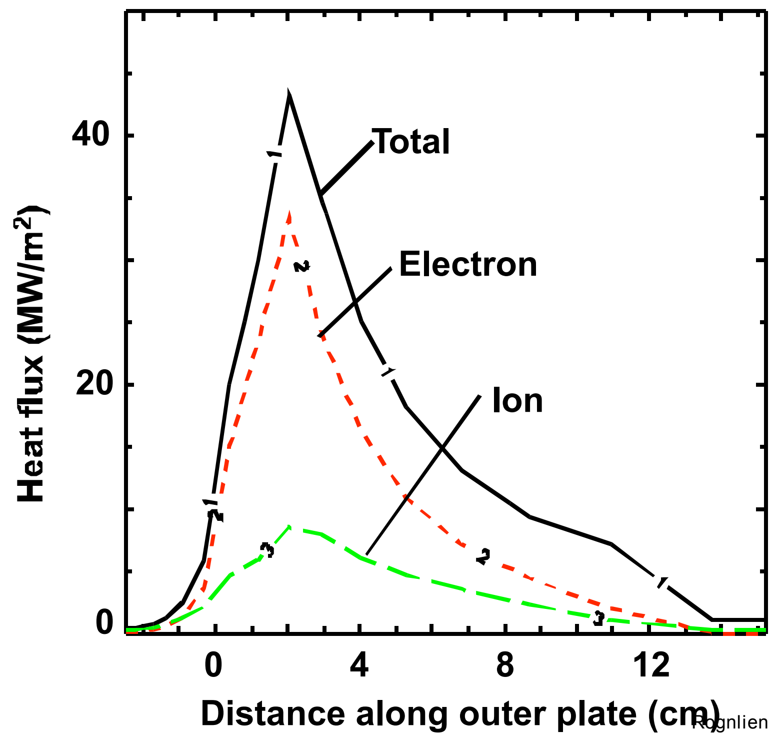
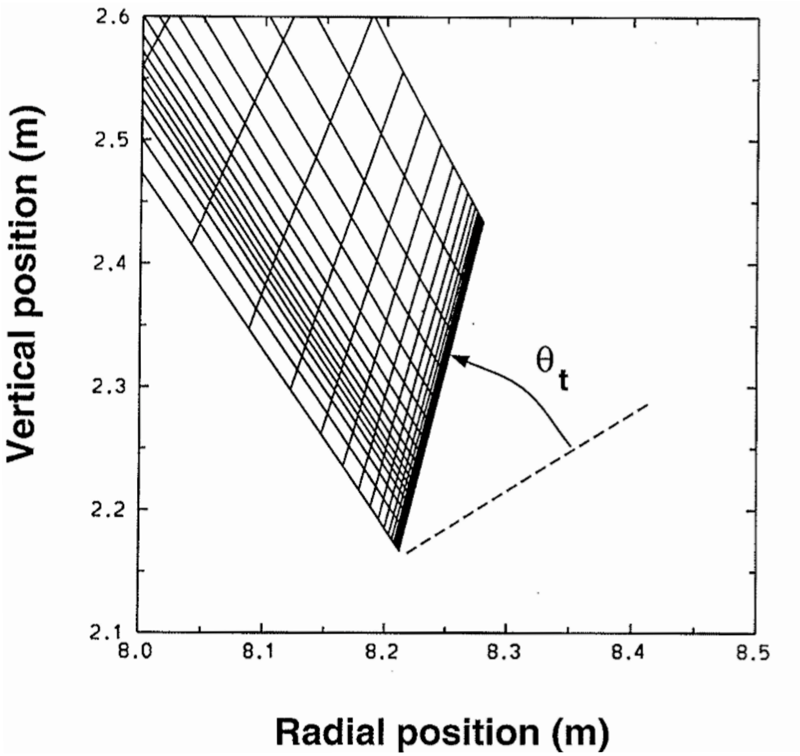
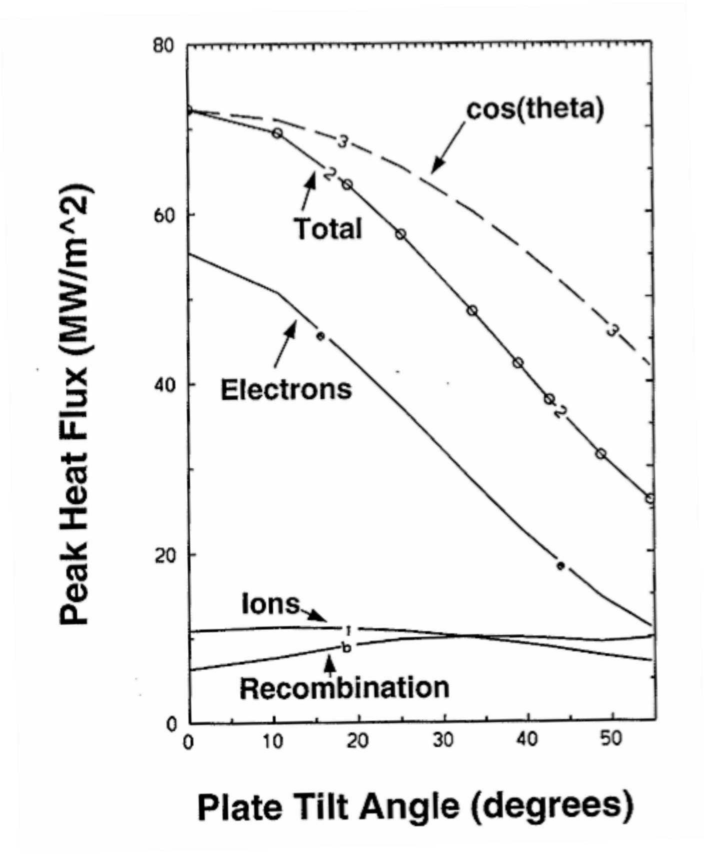


Plate rotation "toward" strike-point can induce detachment - the ITER solution

- Neutrals are roughly directed normal to plate
- Pushing neutrals toward separatrix increases plasma density, recycling
- Reduction of heat flux larger than cos(theta)

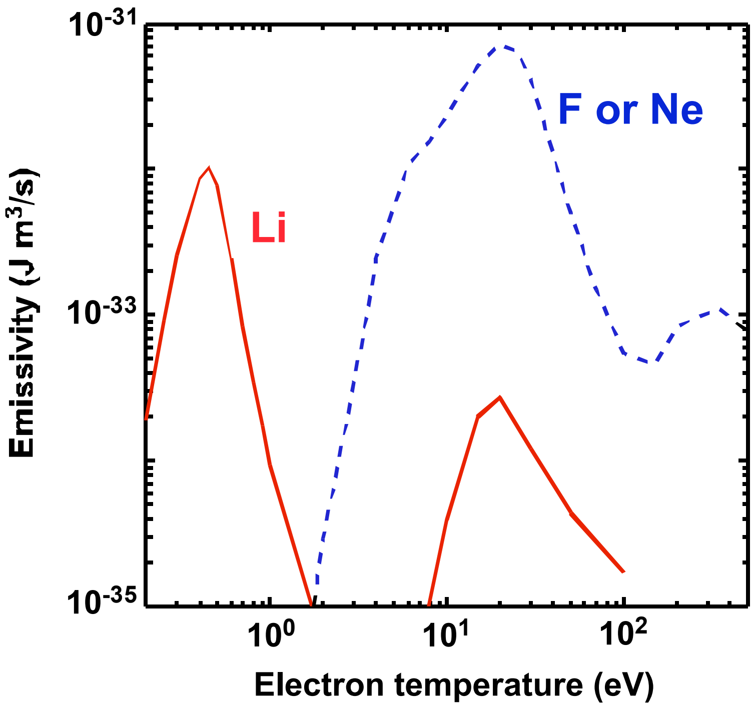




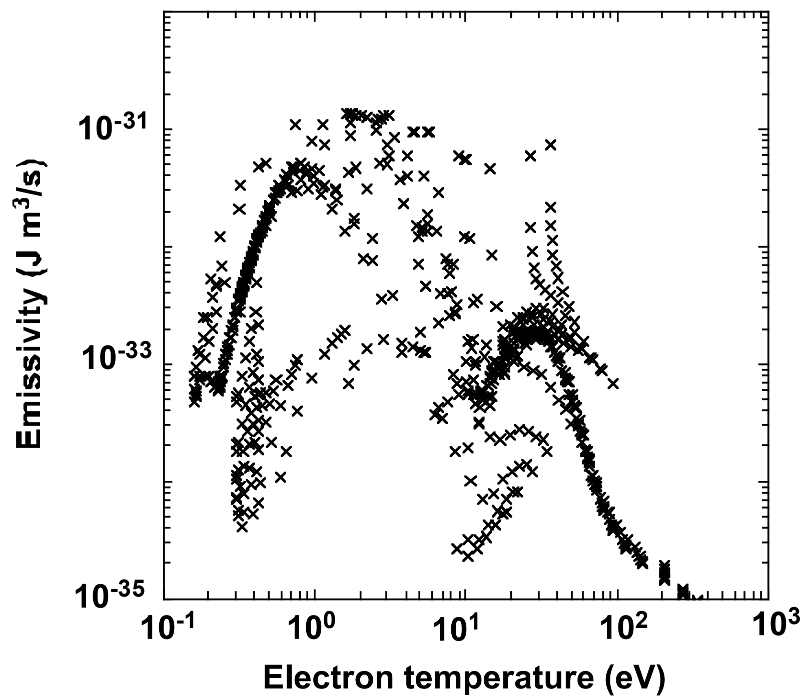
Radiation efficiency requires high density; transport effects can increase radiation

- Even lithium can give substantial radiation in a “detached-like” regime
- BUT high recycling Li plate doesn’t give high enough density

No transport (MIST)

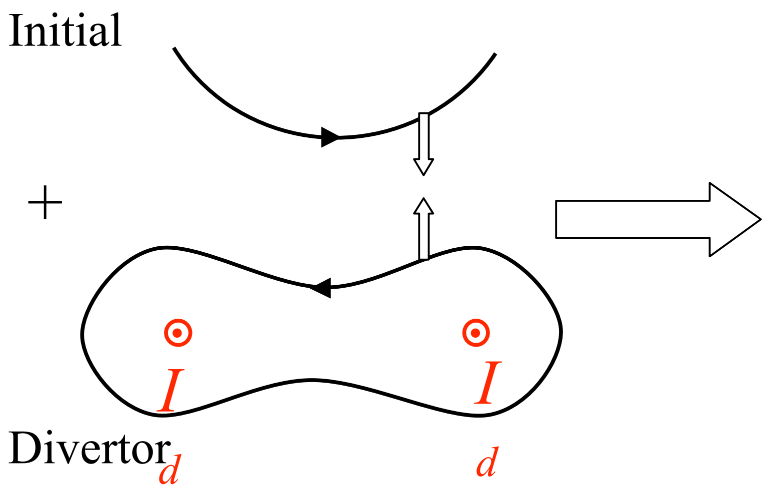


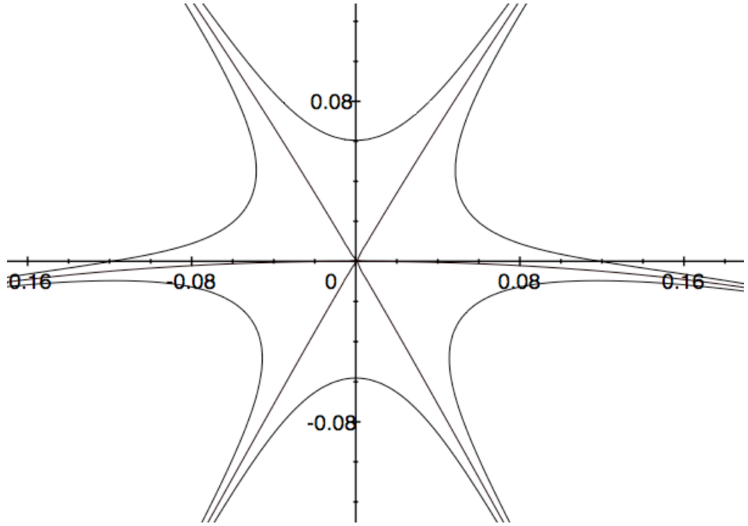
Li multi-species with transport; wall is Li, but plate high recycling



Snowflake divertor produces a (near) 2nd order field null for flux expansion (Ryutov, PoP '07)

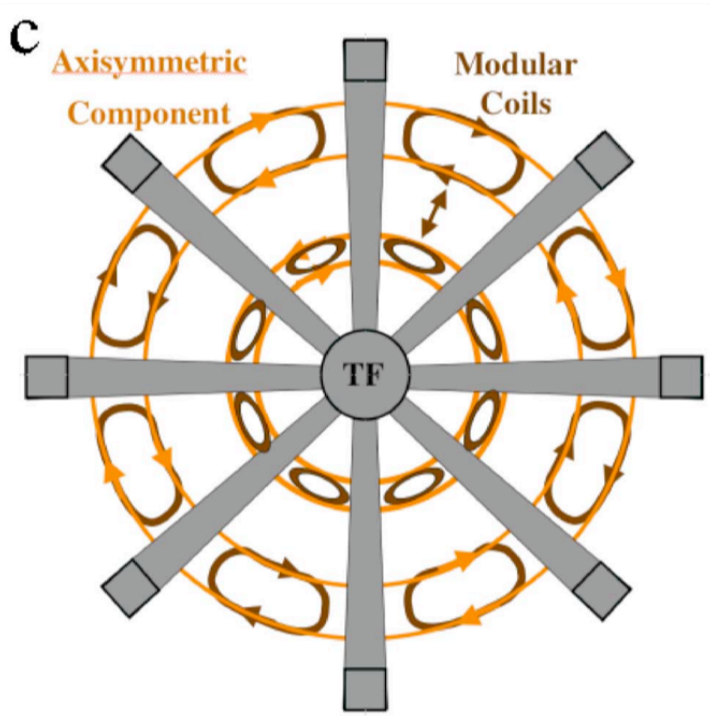
- Simple two-wire X-point model generalized by adding another divertor wire
- Stability of configuration obtained by operating off perfect snowflake - see Ryutov

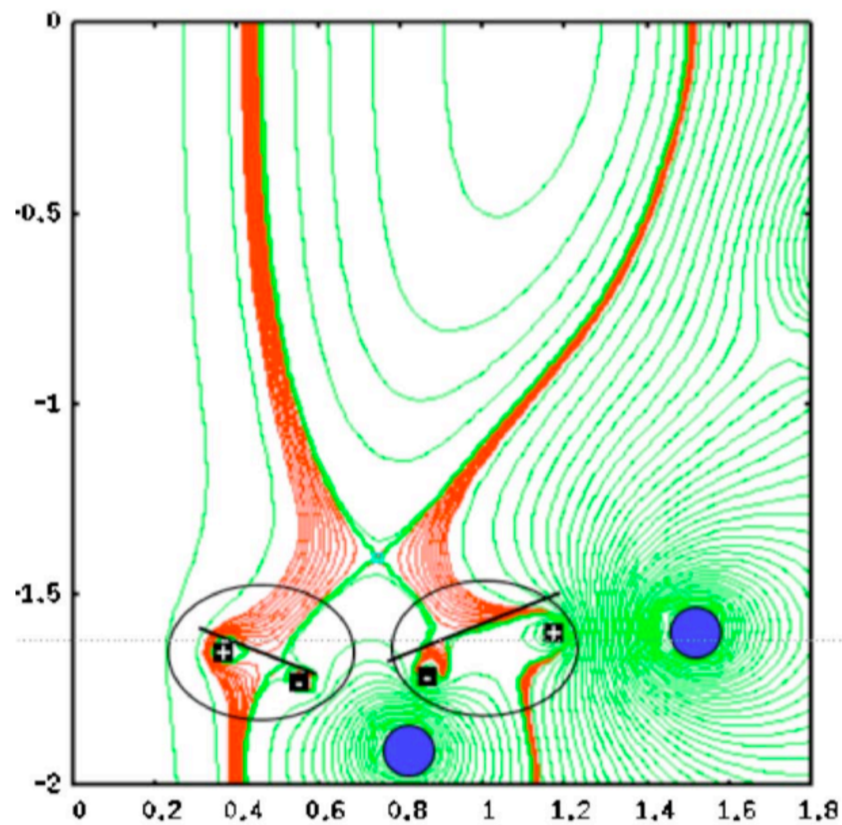




X-divertor utilizes multiple divertor coils to produce a nearby flux expansion (Kotchenreuther, PoP '07)

- Technology may be more complicated
- Offers possibility of stabilizing MARFE formation away from X-point and core plasma
- 1/2 radiation still localized near plates



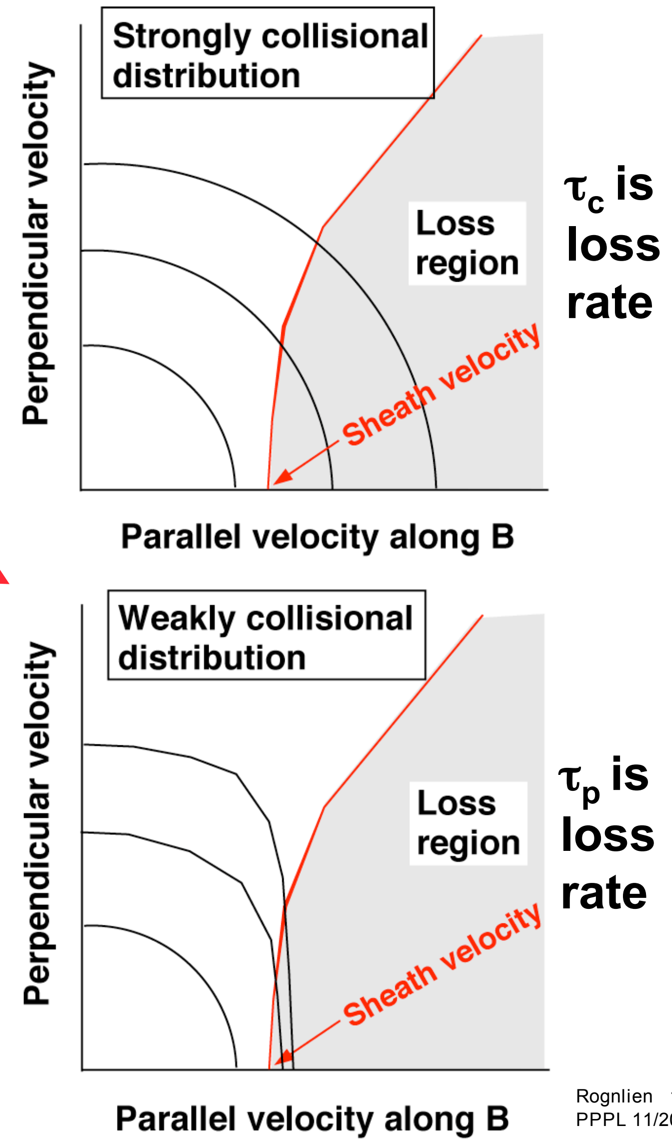


Three main points

- **Kinetic modifications needed for edge-plasma transport**
- **Low-recycling (lithium) divertor (NSTX example)**
  - higher edge temperatures
  - plate heat flux about the same
- **Core contamination by lithium appears acceptable**
- **Developing kinetic transport codes (e.g., TEMPEST and XGC) with be very useful here**

Parallel plasma transport is modified for a hot, low-density edge plasma

- Mean-free-path $\lambda \propto T^2 / n_e$ and $L_{||}$ is B-field-line length
- When $\lambda \sim L_{||}$, the velocity-space distribution is non-Maxwellian
- Plasma heat and momentum transport coefficients change
- Sheath boundary conditions are modified & normalized potential $e\phi/T_e$ can decrease



Viscosity, thermal conduction, and thermal force are limited for long mean-free paths

- Flux-limiting of transport coefficients have the form

$$q_c = -\kappa_e \frac{\partial T_e}{\partial s_{\|}} \rightarrow -\kappa_e [1 + (q_c/q_f)^2]^{-1/2} \frac{\partial T_e}{\partial s_{\|}},$$

where κ_e is the classical heat conductivity, $s_{\|}$ is the distance along B, and $q_f = c_e n T_e (2T_e/m_e)^{1/2}$ with $c_e \approx 0.15$.

- Thermal force term has kinetic correction of the form

$$0.71 n \nabla_{\|} T_e \rightarrow \frac{0.71 n \nabla_{\|} T_e}{(1 + \lambda_{mfp}/L_{\|})}$$

For l > $L_{||}$, boundary electron loss rate is determined by velocity-space scattering

- Electron kinetic energy lost at the collisional sheath is

$$2T_e\Gamma_e = 2T_e\frac{n\bar{v}_e}{4}\exp(e\phi_s/T_e)$$

- Monte Carlo simulations show that long mean-free-path regime can be treated by the extended formula

$$2T_e\Gamma_e \rightarrow 2T_e\frac{n\bar{v}_e}{4}\frac{\exp(e\phi_s/T_e)}{\boxed{(1+\tau_p/\tau_c)}}$$

where τ_p is long mean-free path Pastukhov confinement time, and τ_c is the confinement time for the collisional (full velocity loss-cone) sheath-limited regime. Here the correction factor is

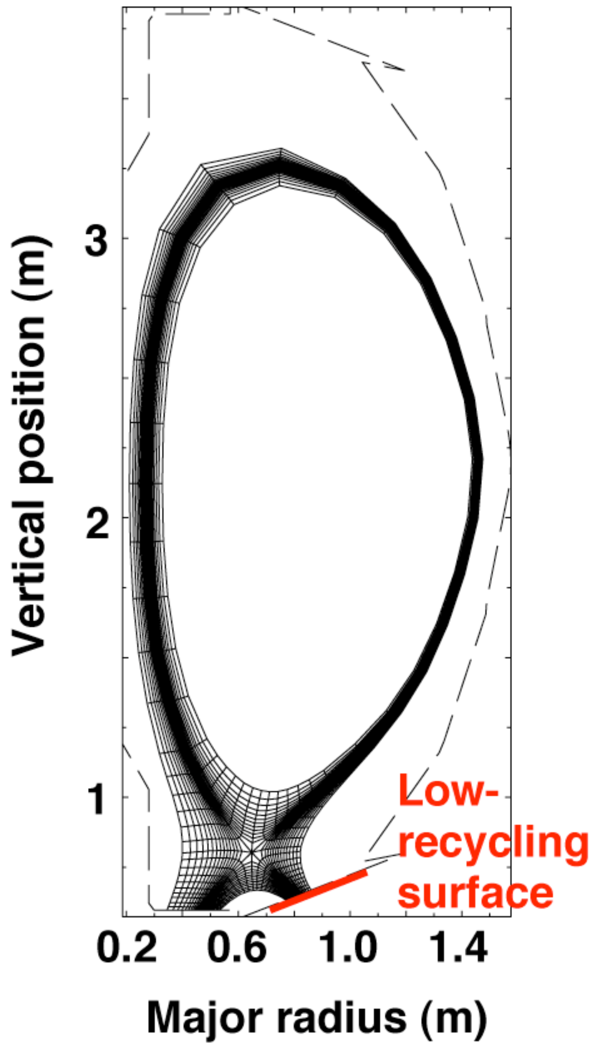
$$1/\boxed{(1+\tau_p/\tau_c)} \approx 1/\boxed{[1+\alpha_c(\lambda_{mfp}/L_{||})(e\phi_s/T_e)]}$$

Effect of low-recycling is illustrated for an NSTX case

- **Use 2D UEDGE fluid transport with kinetic corrections**

- **Begin with a base-case with high recycling (shot 109034, Porter)**
  - P_{core} = 2 MW
  - $D = 0.5\ m^2/s$, $c = 1.5\ m^2/s$
  - R = 1.0
  - Wall gas albedo = 0.95
  - Carbon impurity

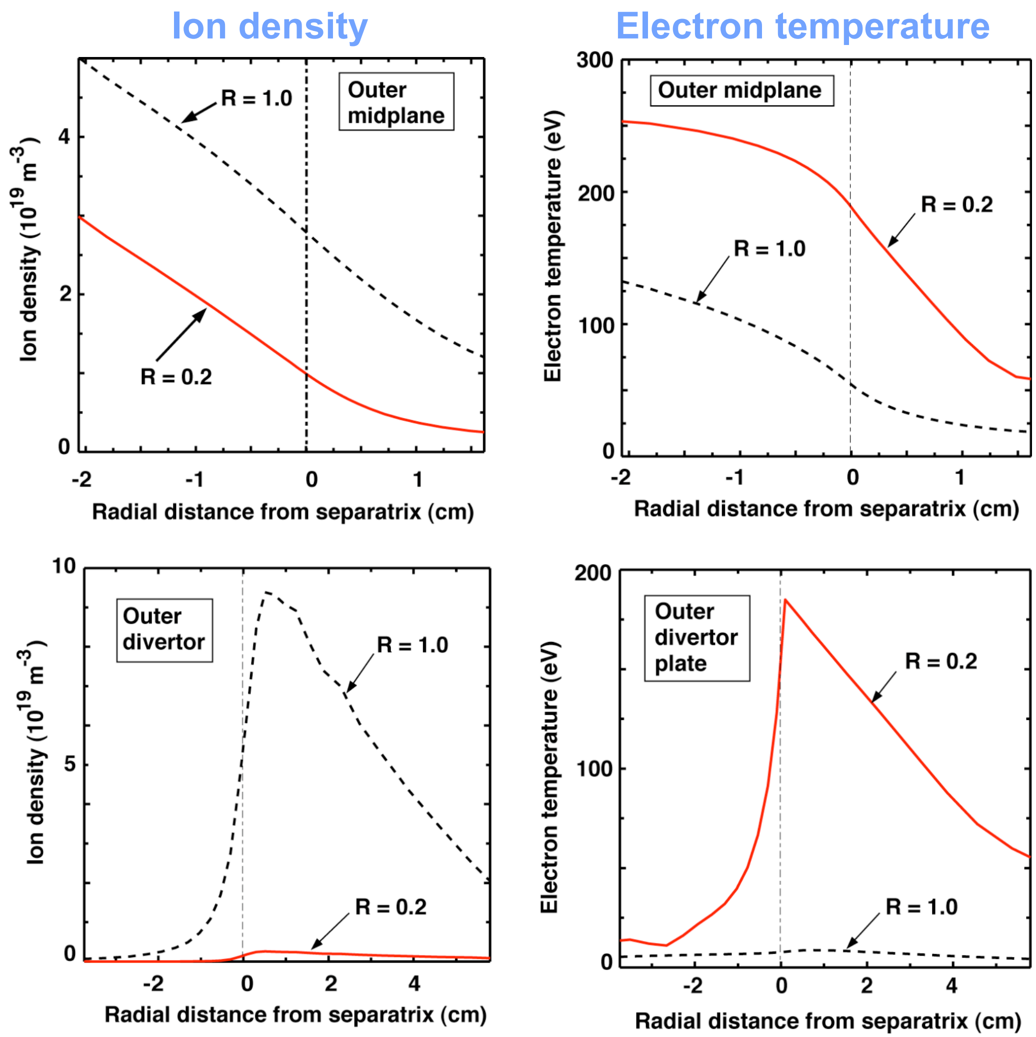
- **Solutions for R = 1.0, 0.9, 0.5, and 0.2 on outer divertor only**



Low recycling increases midplane temperatures by factor of ~2

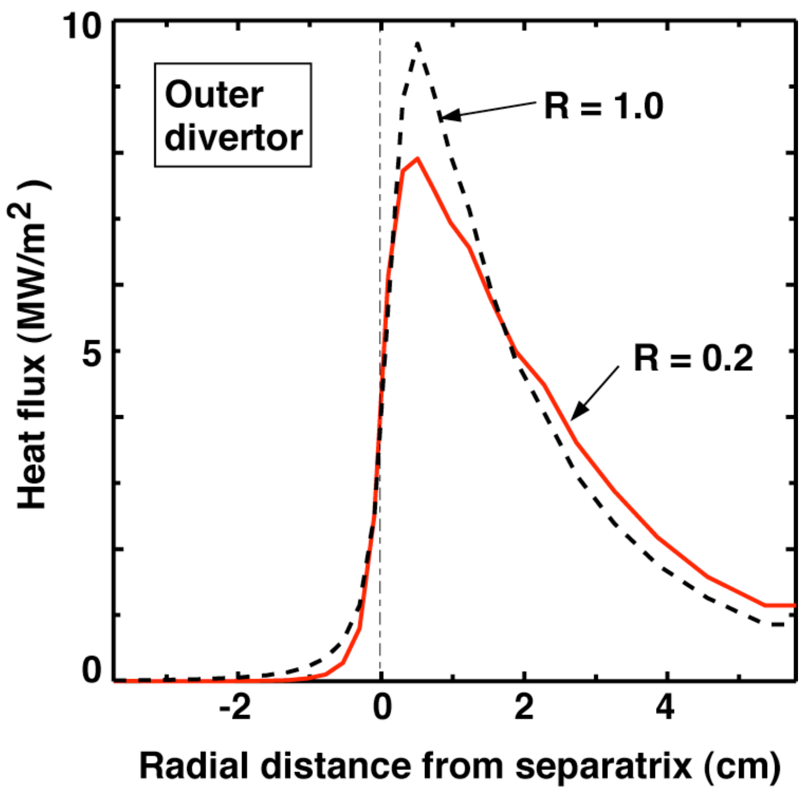
- Low recycling decreases edge density for fixed source
- For R=0.2, $\lambda \sim L_{||}$
- Sputtering increases for low recycling (high T_e)

Increased edge temperature may reduce core turbulence



Peak divertor heat flux largely unchanged by R

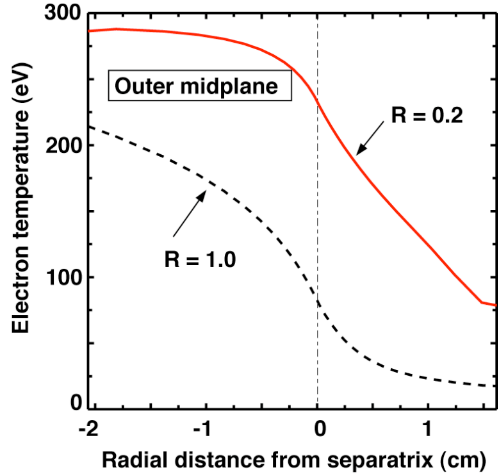
- **Direct energy loss from escaping particles scales as $nT\,T^{1/2} = nT^{3/2}$ at the divertor**
- **For high collisionality, nT ~ constant along B-field**
  - implies heat flux ~ $T^{1/2}$
- **However, for low recycling, $nT|_{midplane} \gg nT|_{divertor}$**

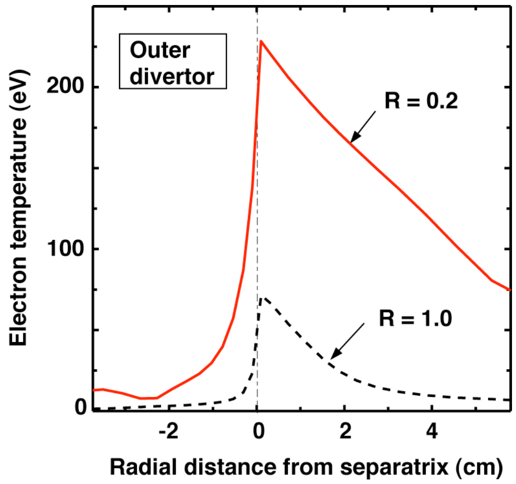


A substantial convective particle loss about the outer midplane can decrease effect of R

- **Add a radial convective velocity increasing from 10 m/s --> 100 m/s from core --> wall**
- **Increased wall flux gives increased pumping (albedo=0.95) - model dependent**
- **Effectiveness of divertor pumping is decreased**

Electron temperature

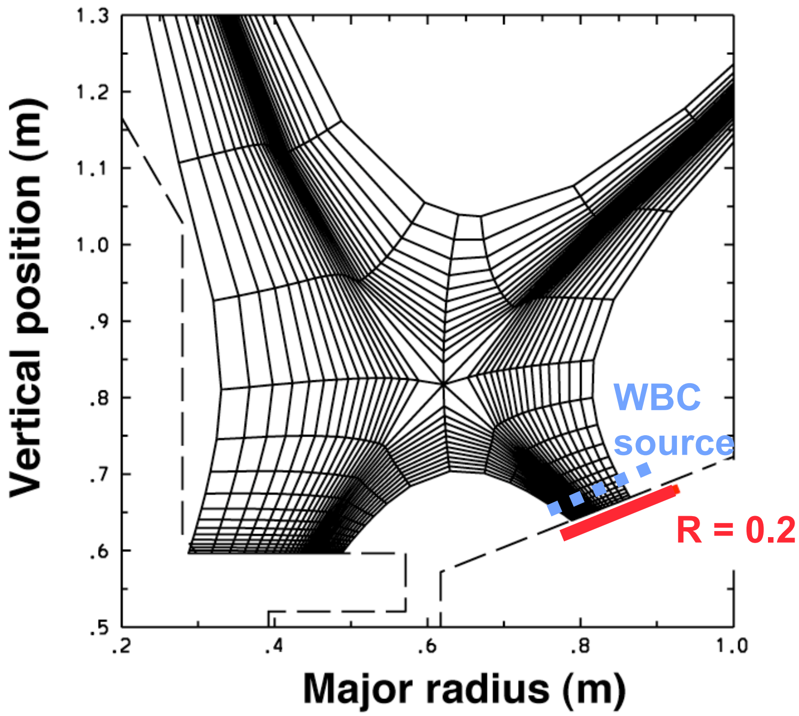




Contamination of core from lithium divertor being modeled by coupling UEDGE & WBC MC code

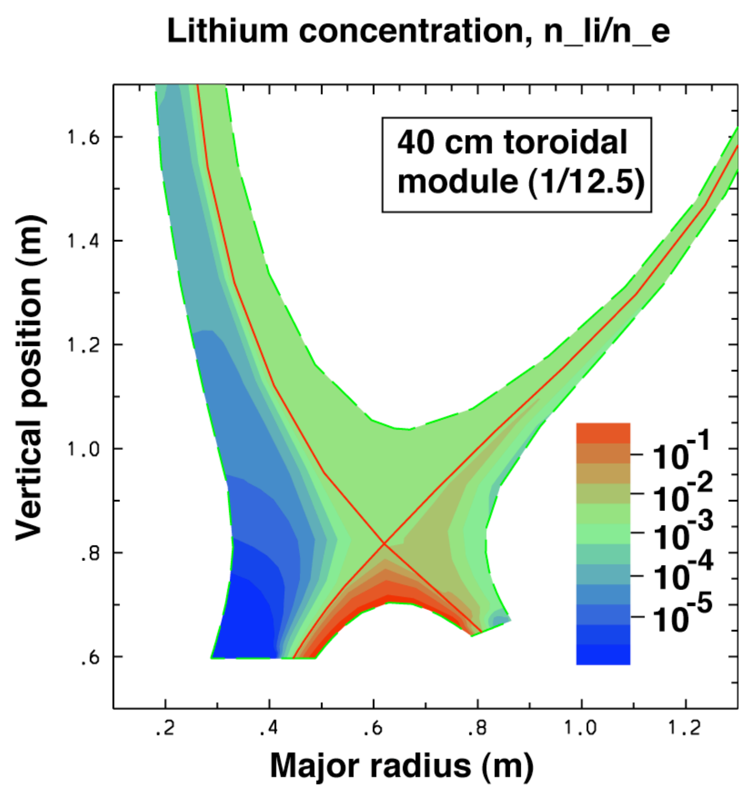
- Heat and particle flux to module computed by UEDGE
- Temperature rise of Li surface from heat transfer (Ulrickson)
- Sputtering of Li from U. Ill. composite model (Allain et al.)
- WBC calculates lithium source near the divertor plate (Brooks)
- UEDGE uses this Li source to calculate lithium density throughout the edge region

NSTX divertor region + Li module



Lithium flows throughout the SOL, but core boundary concentration appears low

- **Lithium concentration peaks in outer SOL and private-flux regions**
- **Primary forces keeping Li in divertor are E_p & hydrogen drag**
- **Lower recycling good because**
  - Lower sputtering hydrogen flux
  - Monotonic downward E_p ; R=0.2 much better than R=0.9
  - Higher sputtering rate is bad



Summary

- **Simulating low-recycling plasmas uses known modifications to fluid transport models**
- **Substantial increase in edge temperature is calculated**
- **Plasma convection shows some reduction of core-edge T increase**
- **Lithium contamination studies for NSTX begun**
  - Impurity screening at low R aided by E_p & downward hydrogen flow
  - Role of convection on Li must be included