*Analysis of alternative divertor designs for reducing peak heat-flux**

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Outline

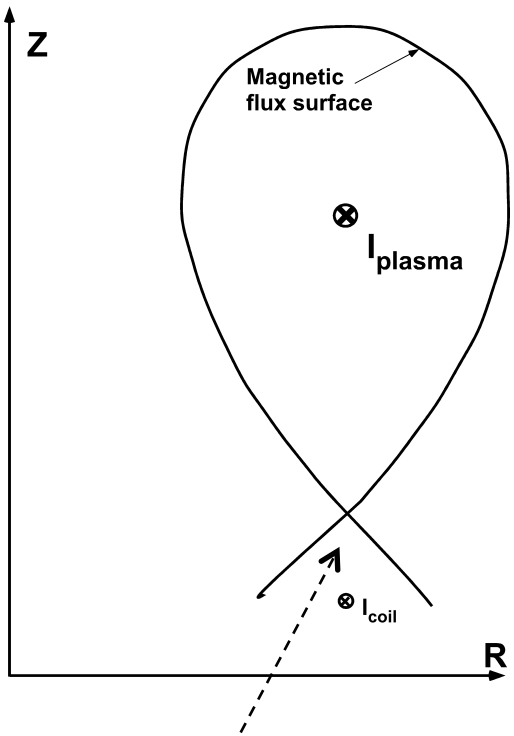
1. **Reduced average divertor heat load for snowflake divertor**

2. **Reduced ELM heat load for snowflake geometry**

3. **Other topics:**
   - Sheath potential modifications during ELMs
   - Radiative divertor for heat-load management in future devices

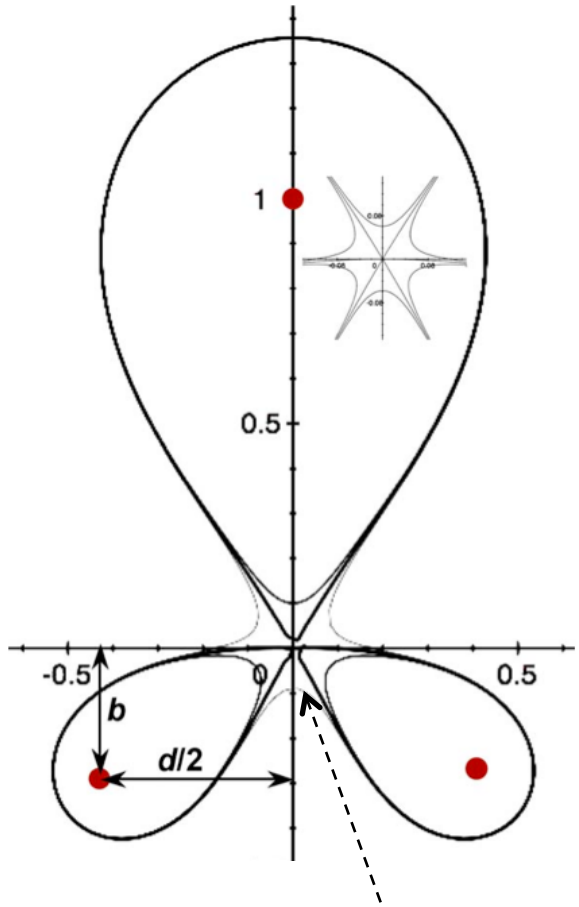
Alternate divertor geometries

Standard X-point



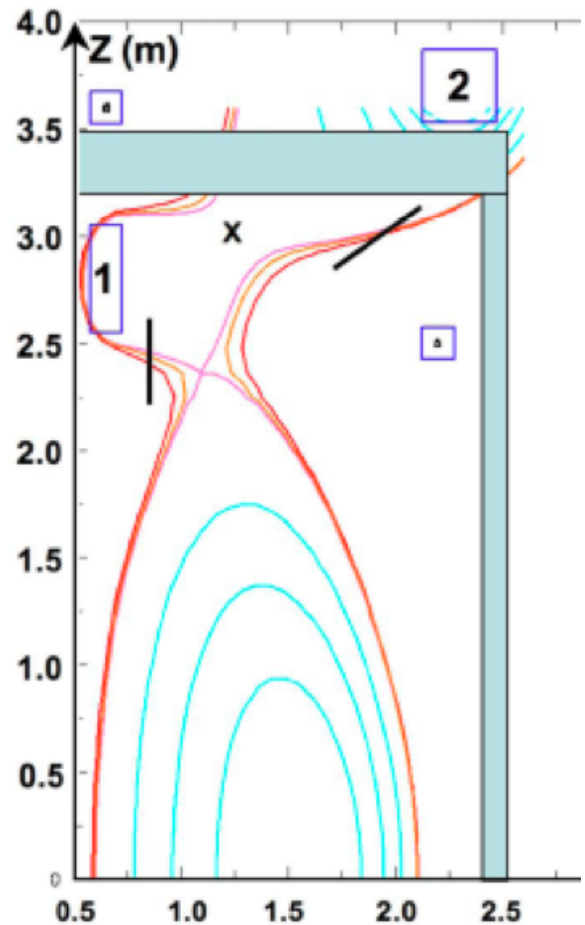
$B_{pol} \sim (r-r_x)$

Snowflake



$B_{pol} \sim (r-r_x)^2$

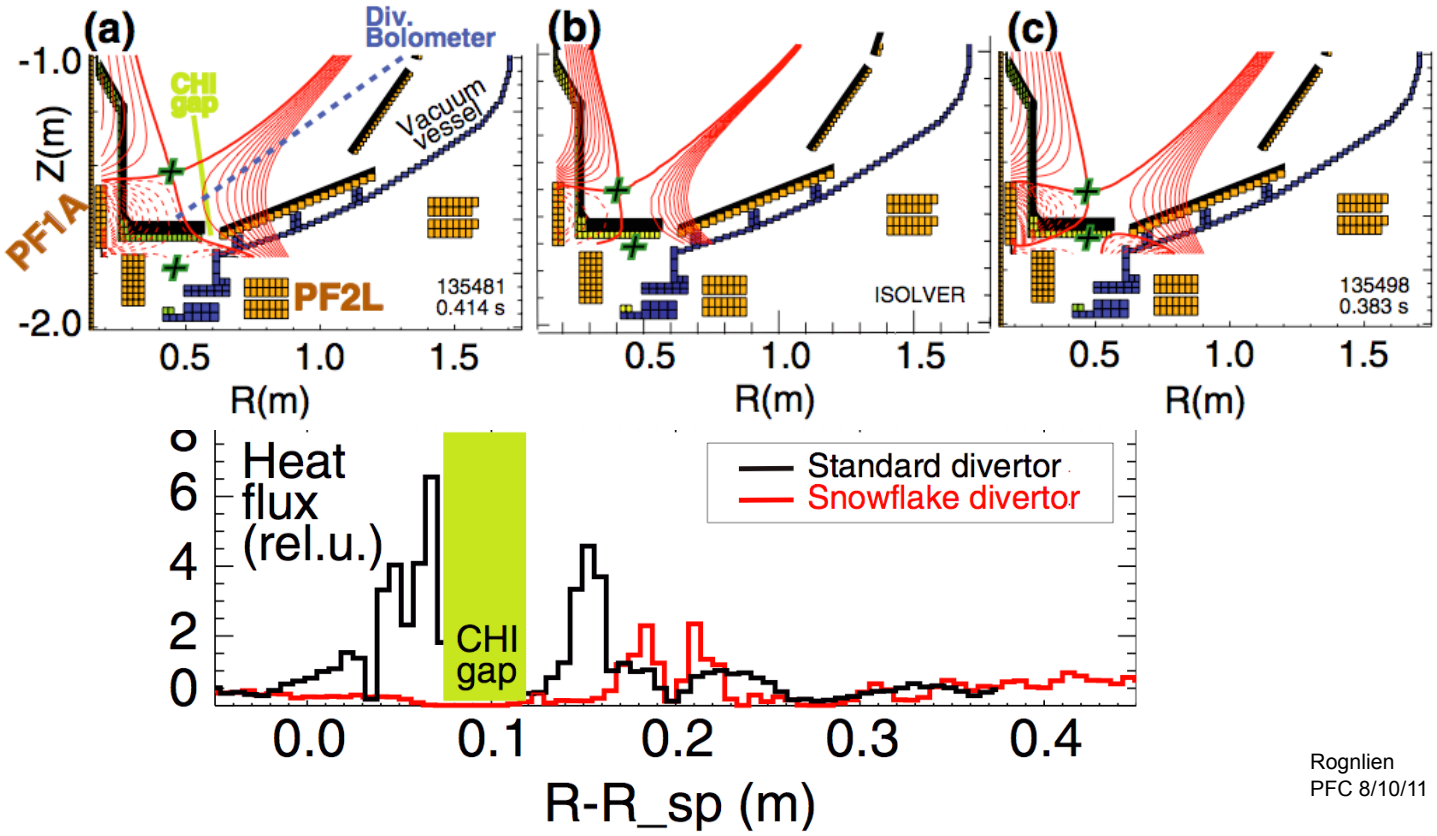
Super-X



Snowflake configuration yields strong peak heat-flux reduction in NSTX

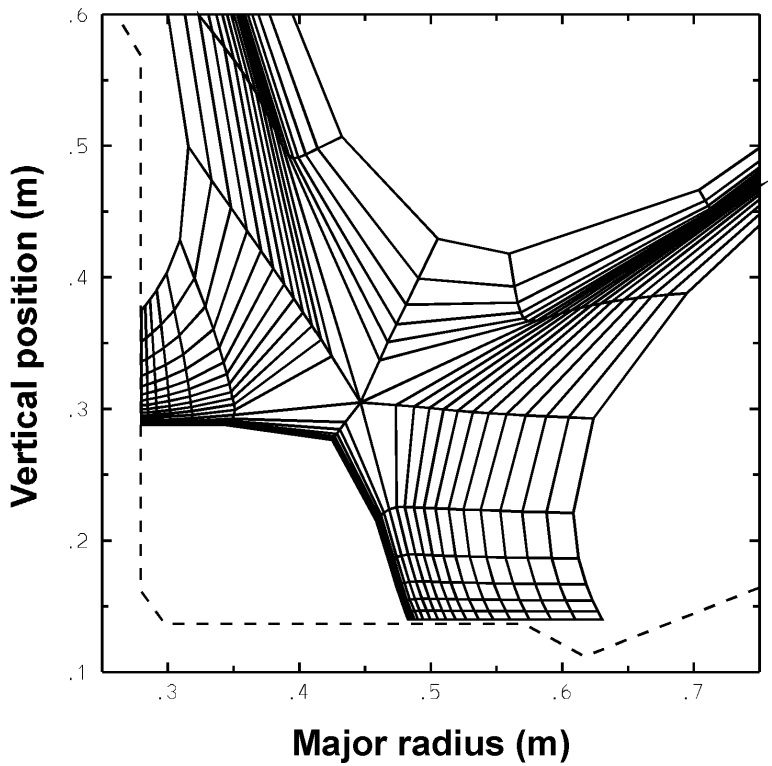
NSTX: factor of 3 heat-flux reduction on the divertor plate (V.A. Soukhanovskii et al, Nucl. Fusion, **51**, 012001, 2011)

- Easier detachment (no need in gas puff)
- Carbon content in the core down by a factor ~ 2
- Radiation from the core down by a factor ~ 2
- Radiation from divertor up by a factor of a few
- No noticeable adverse effect on core

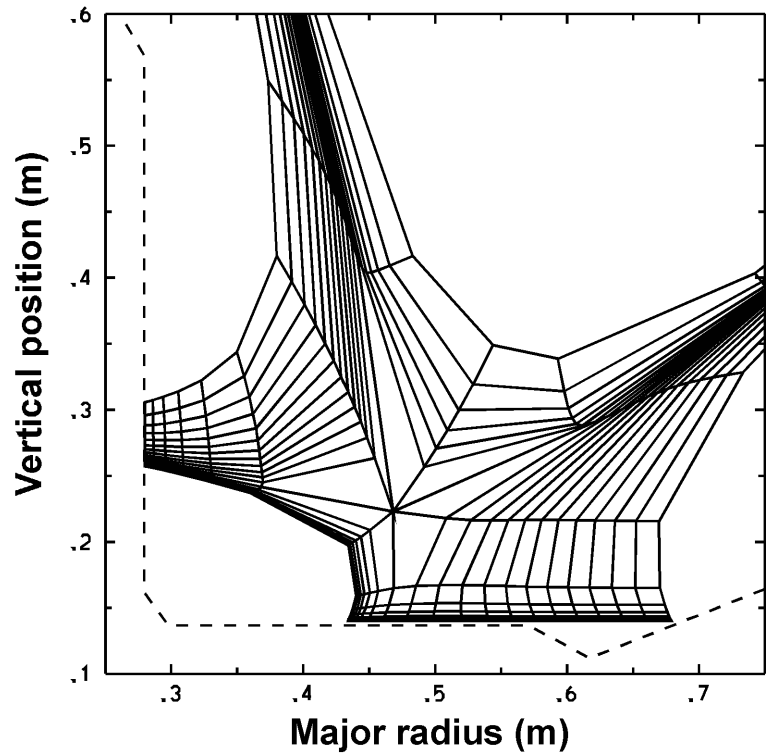


UEDGE is used to model snowflake geometry in NSTX

Standard: shot 135481

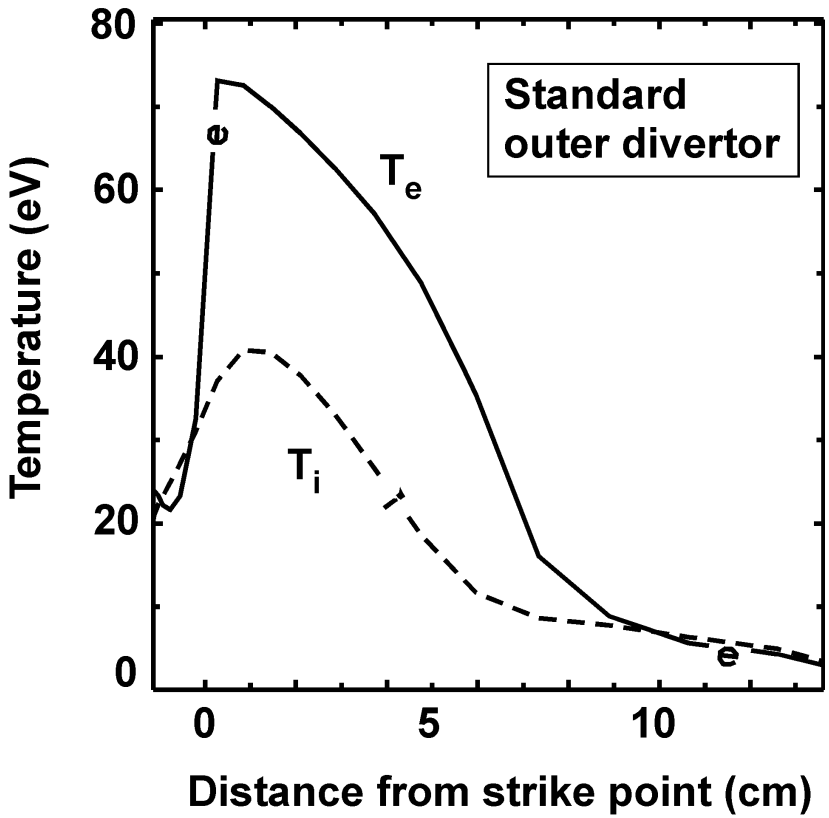


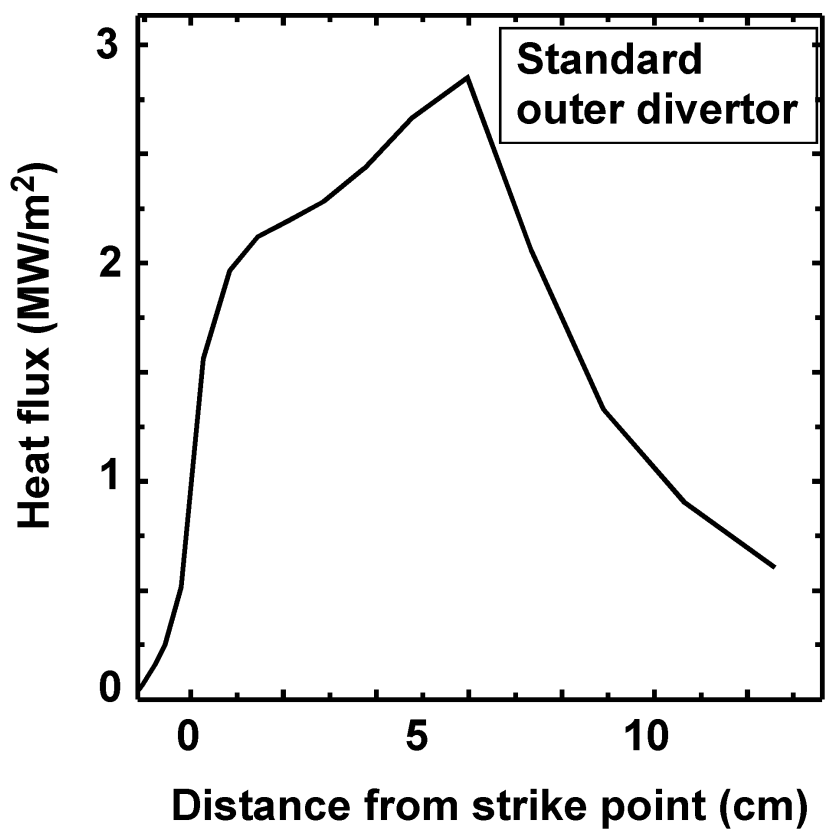
Snowflake: shot 135498



Modeling of standard divertor shows high divertor temperature and heat flux

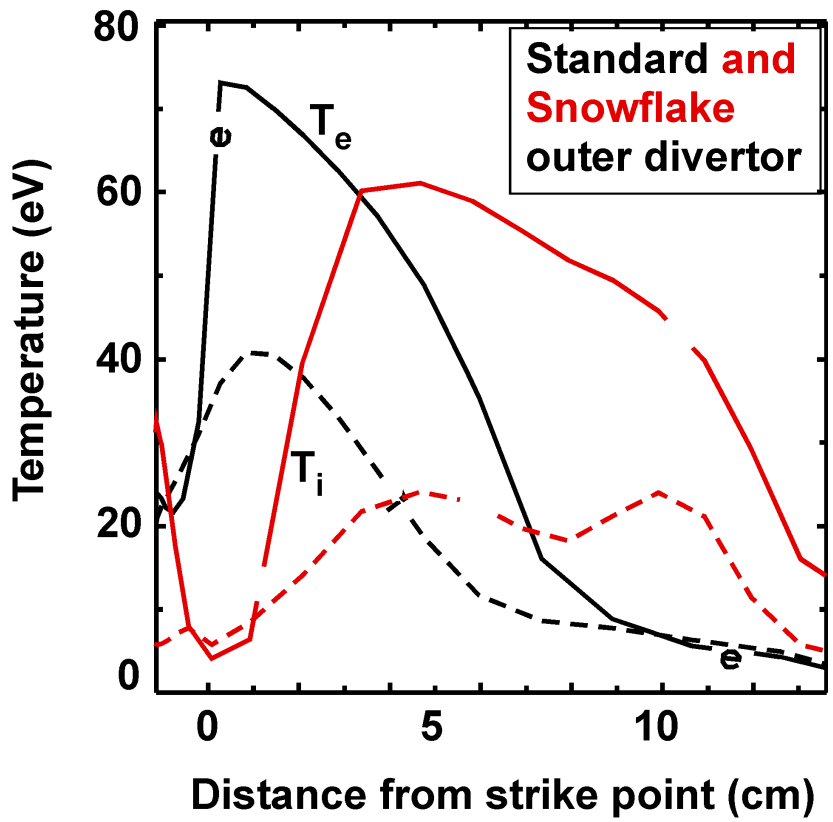
Standard: shot 135481

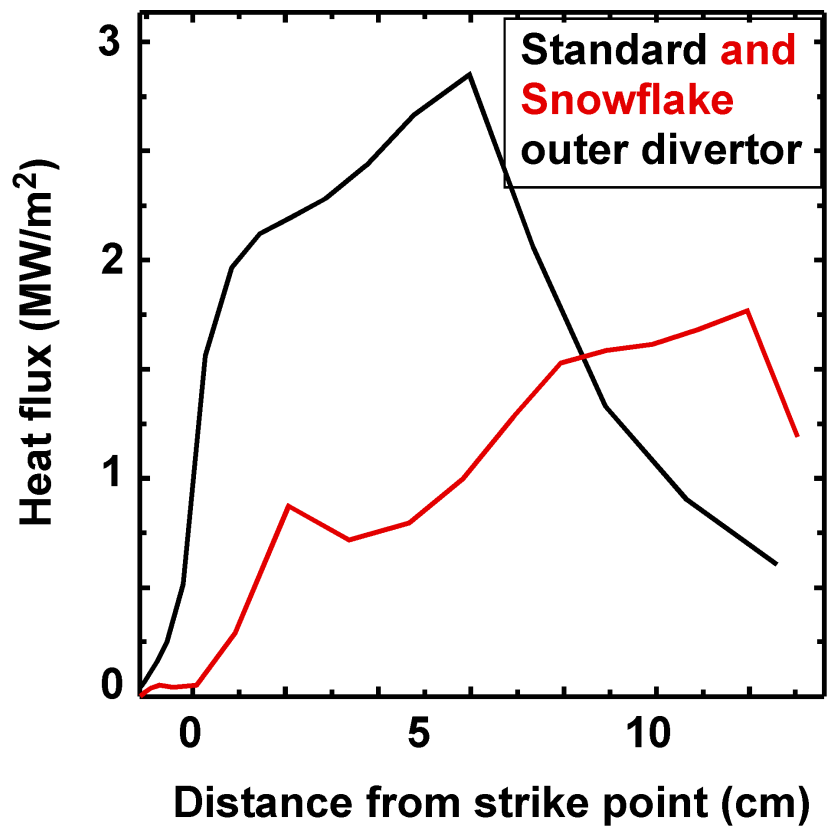




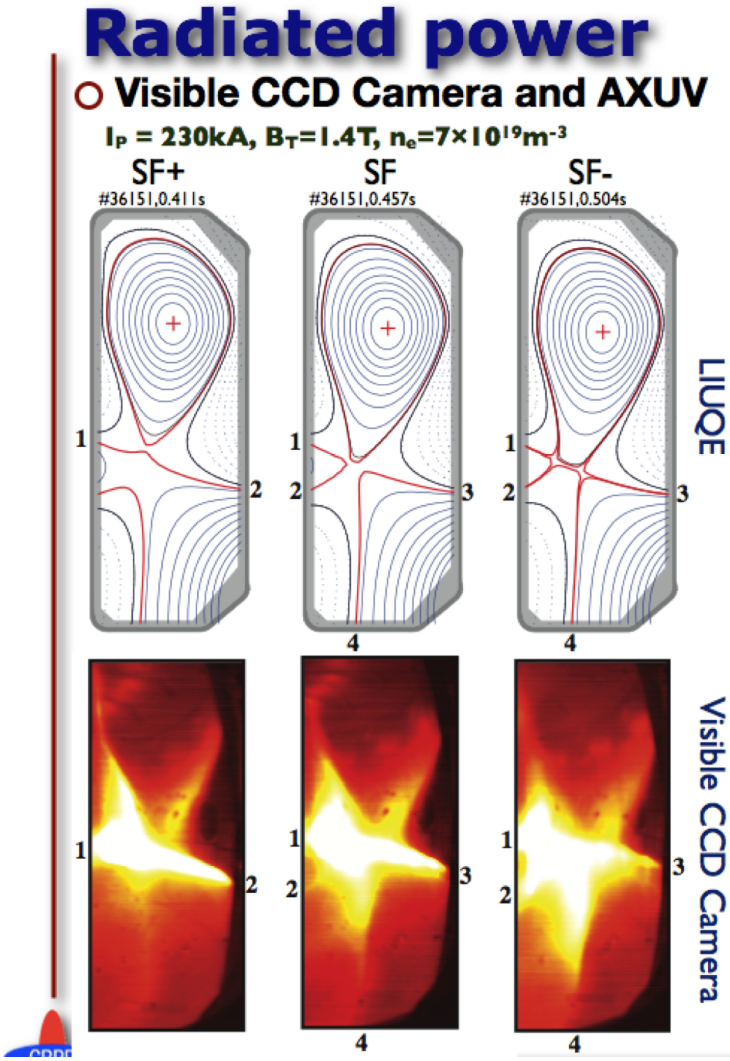
In comparison, the snowflake configuration for similar parameters shows substantial reduction

Shots 135481 and 135498





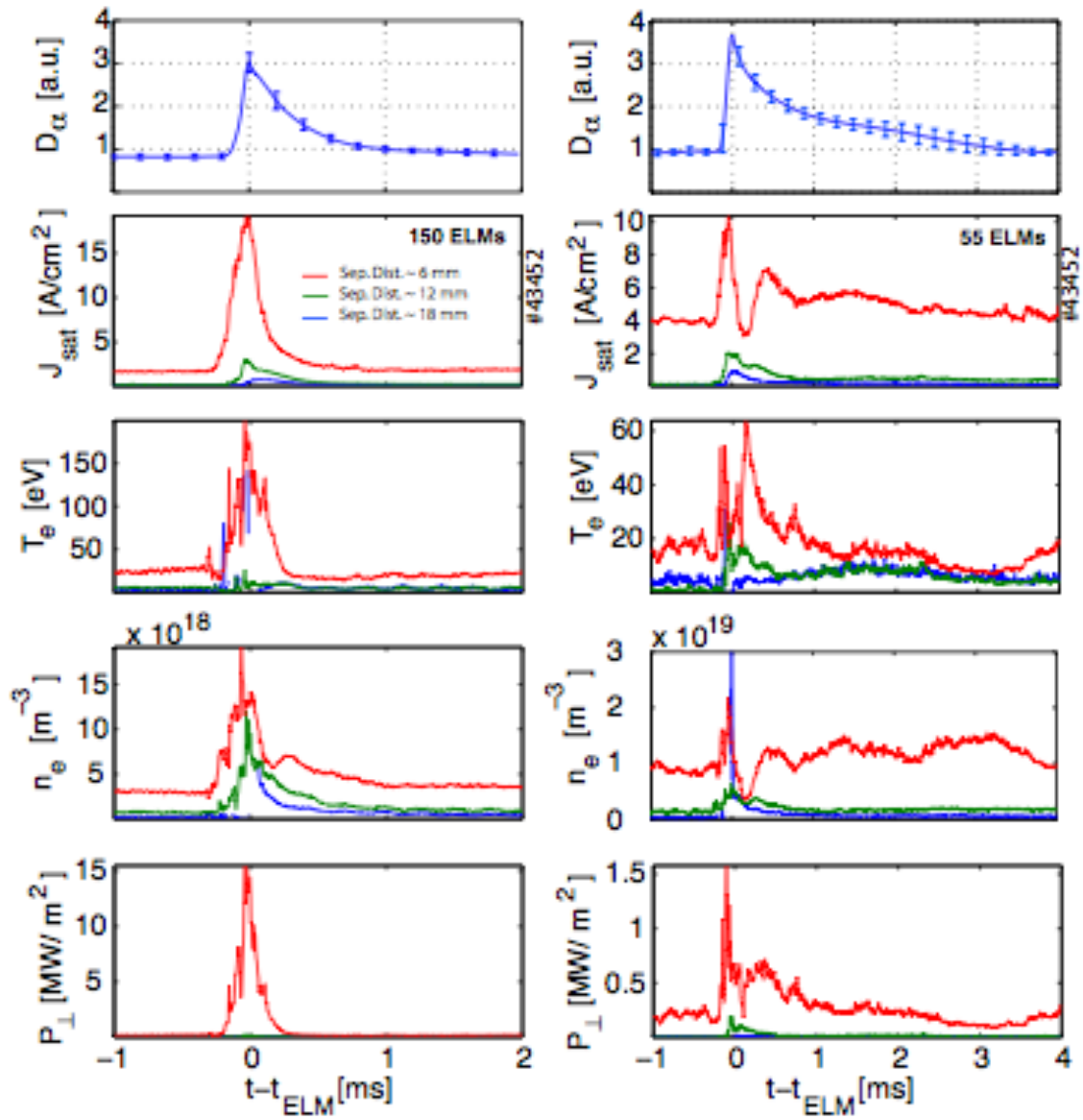
TCV tokamak in Lausanne has also studied the snowflake



Piras F, Coda S, Furno I, Moret JM, Pitts RA, Sauter O, Tal B, Turri G, Bencze A, Duval BP, Felici F, Pochelon A, Zucca. "Snowflake divertor plasmas on TCV", *Plasma Physics Controlled Fusion* **51 (2009)** 055009, 2009,

TCV data shows that ELM peak heat load is reduced with a snowflake geometry

During ELMy H-mode, estimate that peak ELM heat load is reduced by ~10 compared to standard divertor geometry, Labit et al., EPS Conf., 2011



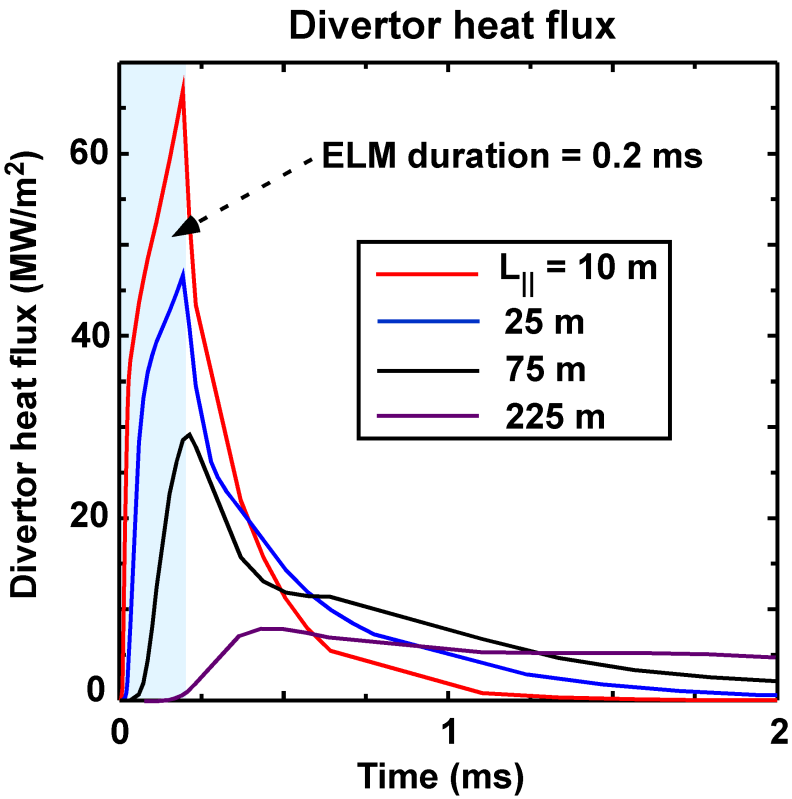
Snowflake geometry can reduce surface temperature rise from ELMs

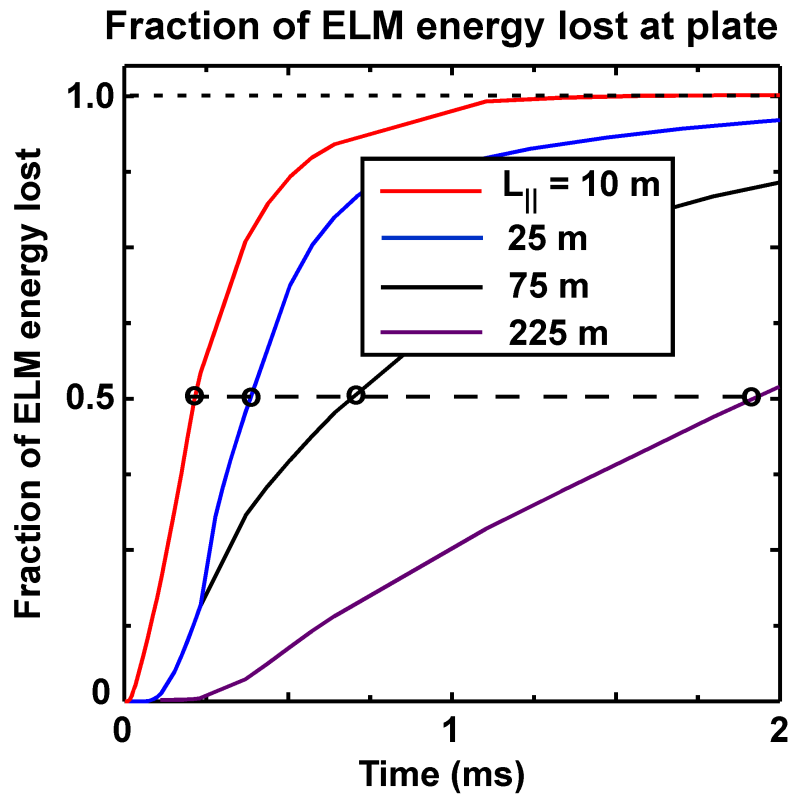
- **Surface temperature rise scales as**

$$T_{surf} \propto \frac{\mathcal{E}_E}{\kappa_m A_E \tau_E^{1/2}}$$

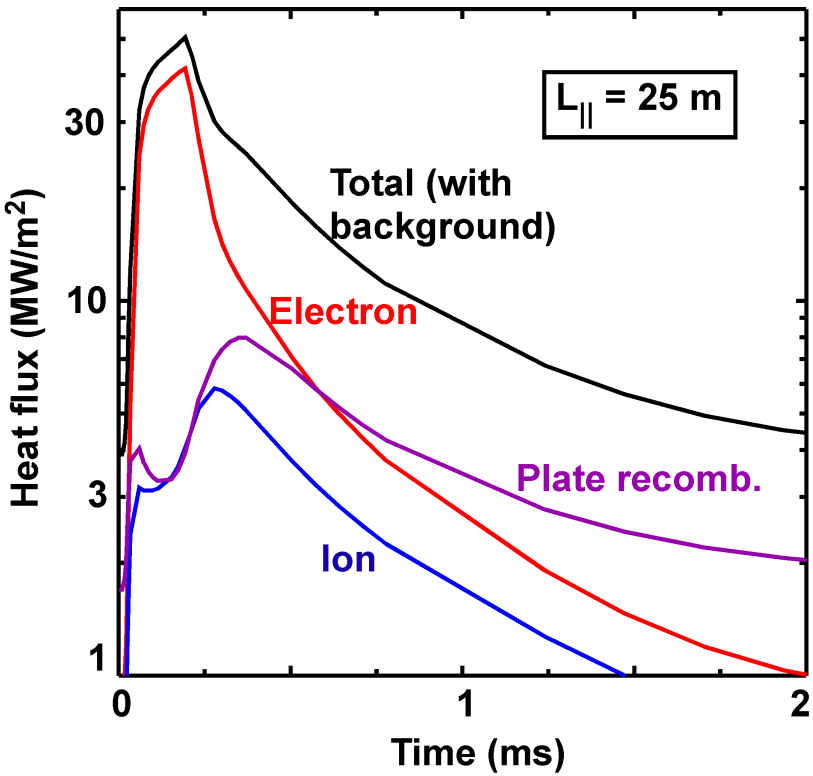
- **Snowflake geometry provides mechanisms to reduce T_{surf}**
  - Longer distance along magnetic field **B** between midplane ejection region and divertor plates: $S_{||} \sim \text{Int}\,(B/B_{pol})\,dx_{pol}$
  - Magnetic flux expansion of divertor heat footprint
  - Enhanced radial transport of energy near null-point region
  - Feedback on ELM growth

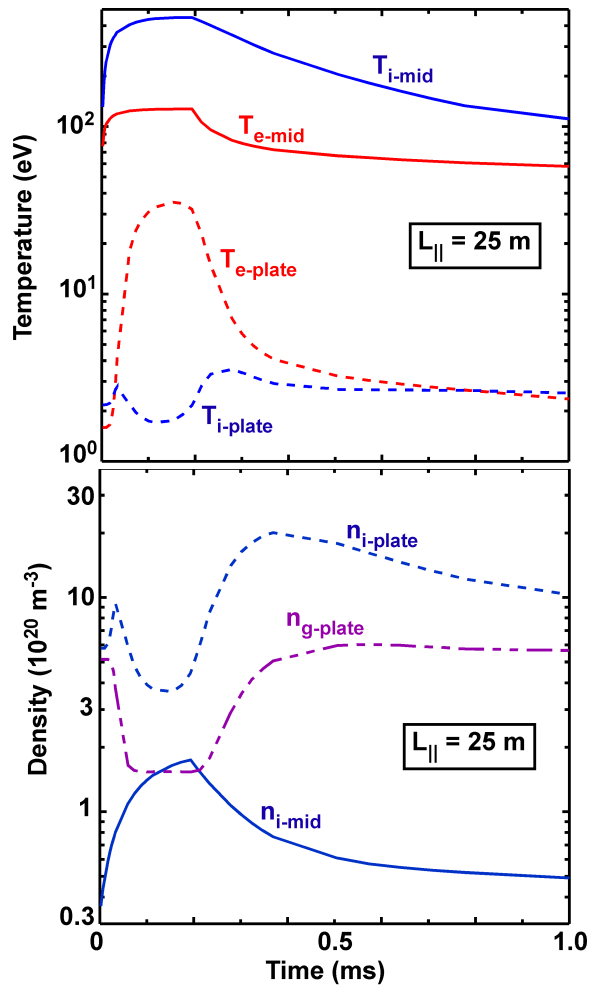
UEDGE modeling shows how ELM deposition time increases with larger $L_{||}$





Divertor heat flux is made up of a number of components



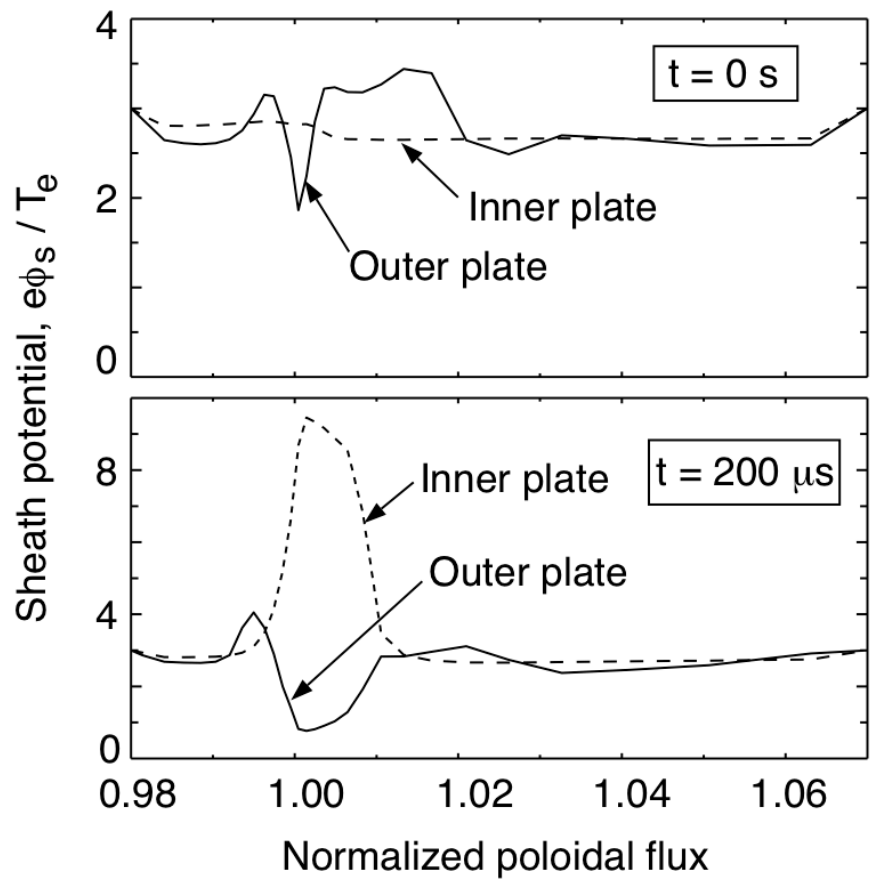


Summary of other topics:

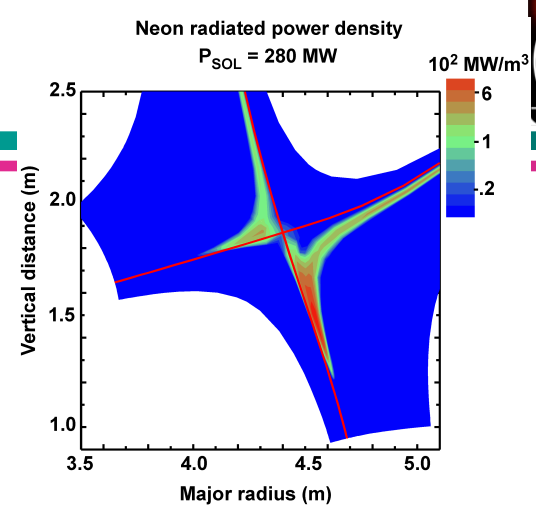
- plasma sheath currents
- radiative divertor

Thermoelectric currents in SOL during ELM can impact surface heat flux

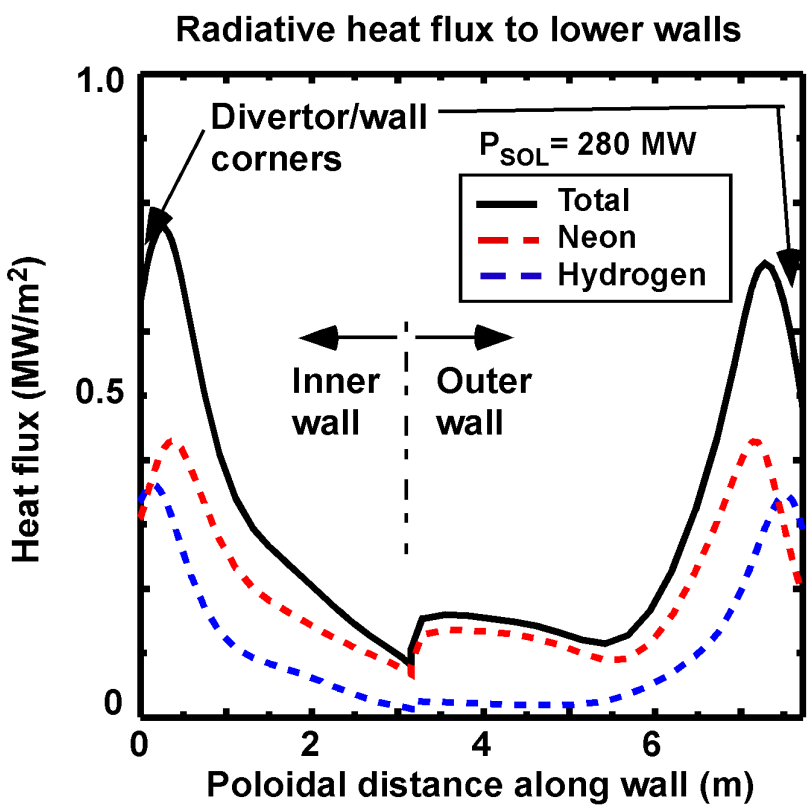
- Plasma temperature differences between inner/ outer divertor surfaces can drive large currents
- Such currents can substantially change the sheath potential from zero-current condition of $\phi \approx 3T_e$
- 2D ELM simulation result for DIII-D ELM conditions

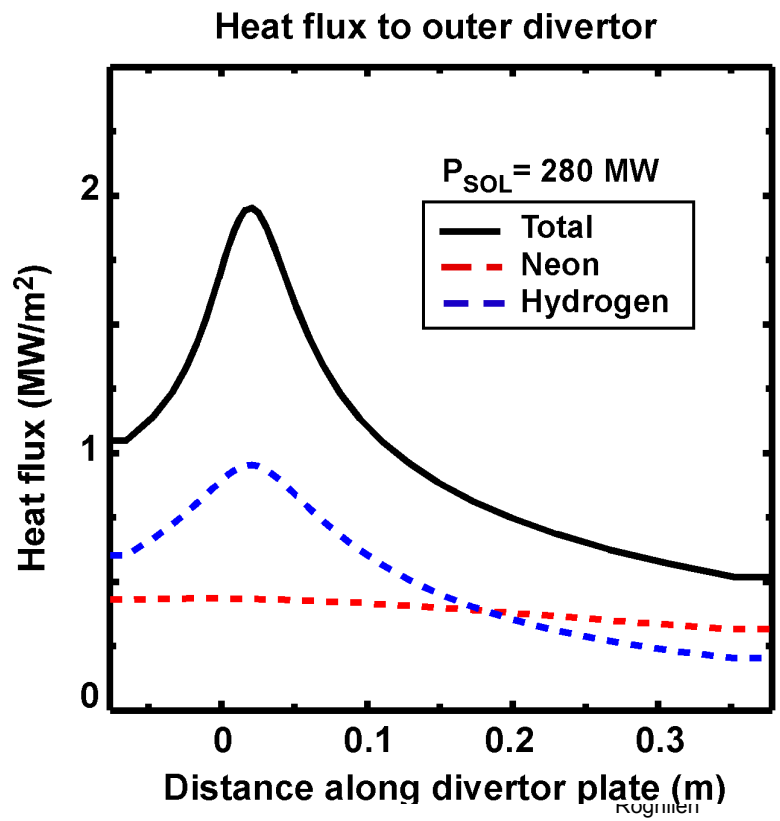


Radiating neon in SOL for ARIES ACT1 at high density



- can high density edge exist?
- is core impurity level acceptable?



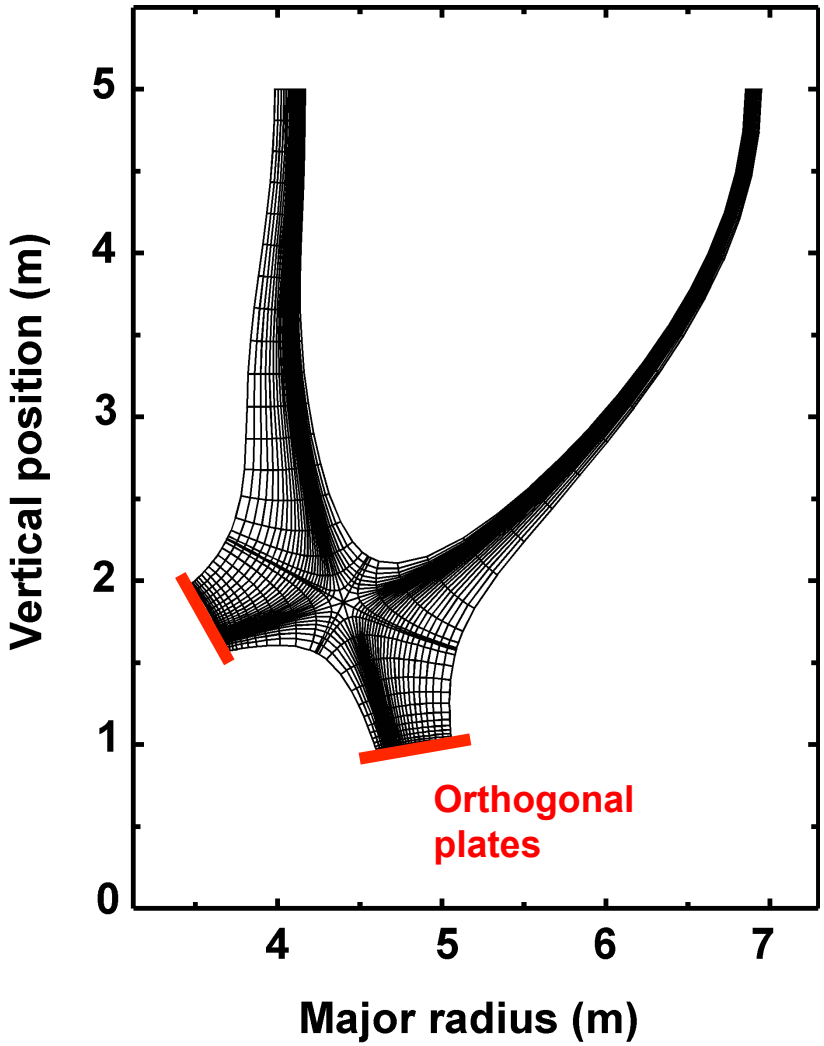


Summary

- **NSTX snowflake divertor reduces average divertor heat load**
  - A large decrease in peak heat flux
  - UEDGE modeling shows that power detachment results
  - Preliminary results with Carbon show stronger effect
  - Need to include lithium and couple to WBC
- **TCV reduction in peak ELM heat-load, surface temperature rise with snowflake configuration**
  - Experimental results reported at EPS in June, 2011; ~10 times reduction in peak ELM heat load
  - UEDGE modeling shows how deposition time lengthens for the snowflake
  - Area of deposition increase from magnetic flux expansion
- **Other topics**
  - SOL currents during ELMs substantial change sheath potential
  - Radiative SOL compatibility of high density and core Zeff

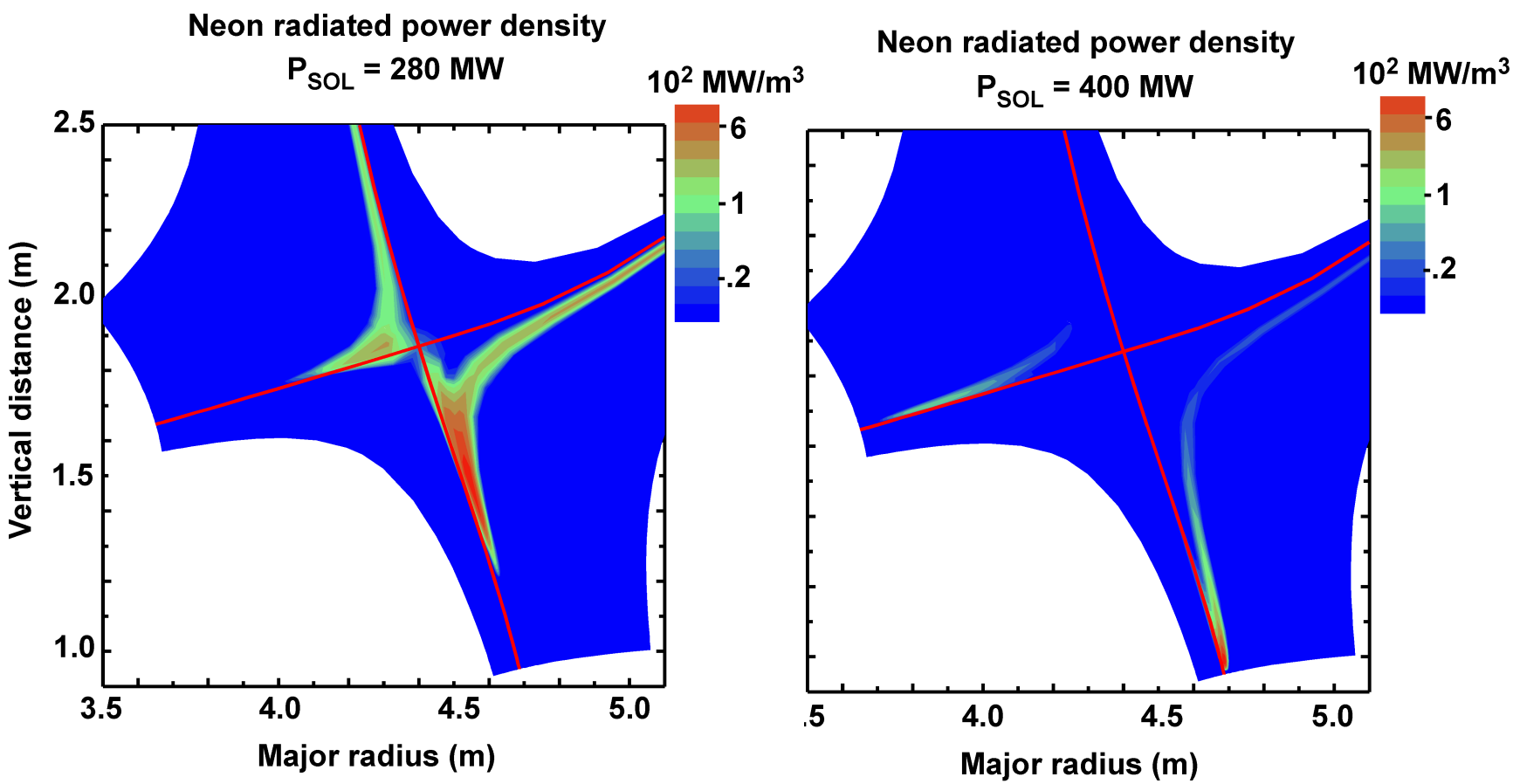
Back-up slides on radiative SOL

ACT-1 geometry (simple divertor) and parameters

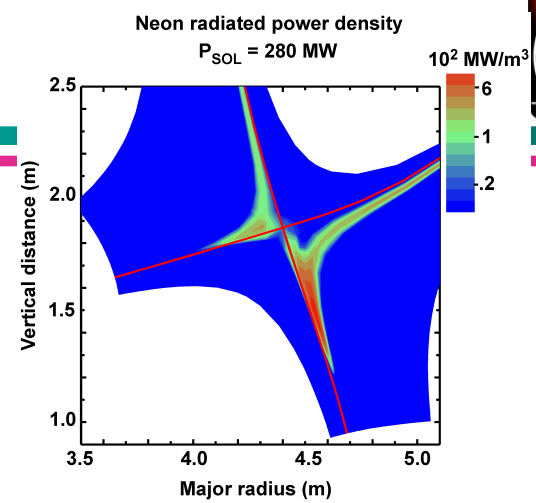


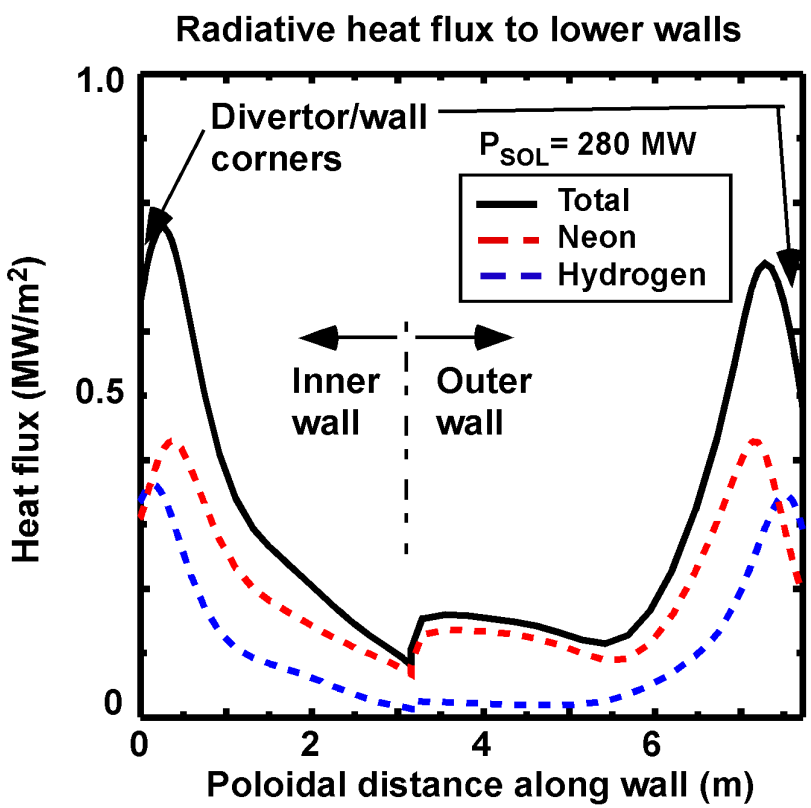
- **Magnetic equilibrium from Kessel**
- **Symmetric double null**
- **Power from pedestal**
  ~400 MW
- **Pedestal density**
  $1\text{-}3\times10^{20}$ m^{-3} ($n_{GW} \approx 2\times10^{20}$)
- **Radial transport coeff. (ITER-like)**
  $D = 0.33$ m^2/s
  $\chi_{e,i} = 0.5$ m^2/s

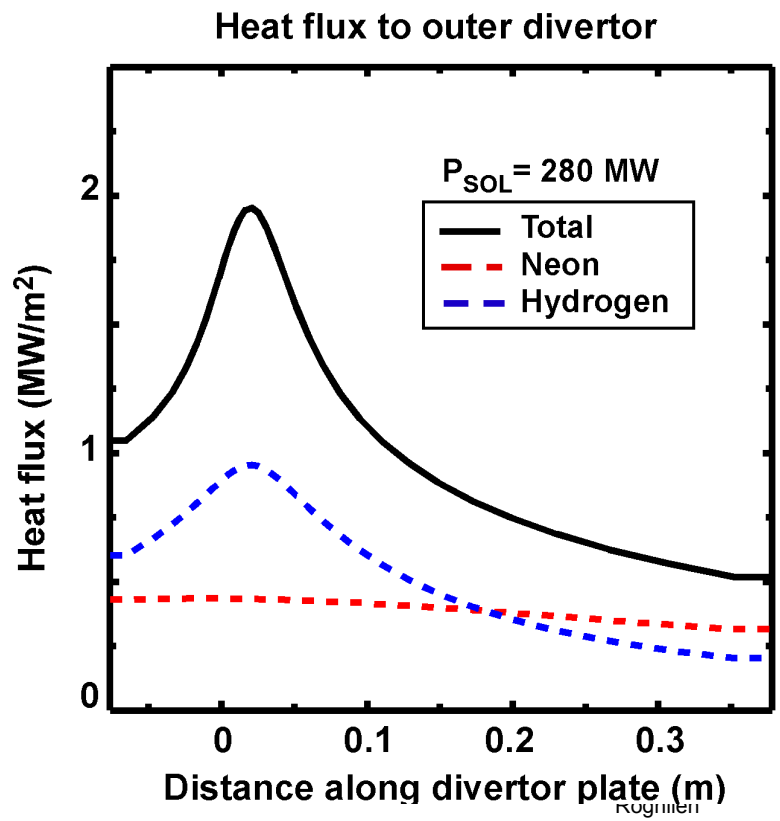
Shifting to the high density, neon impurity cases; a range of acceptable radiating SOL cases



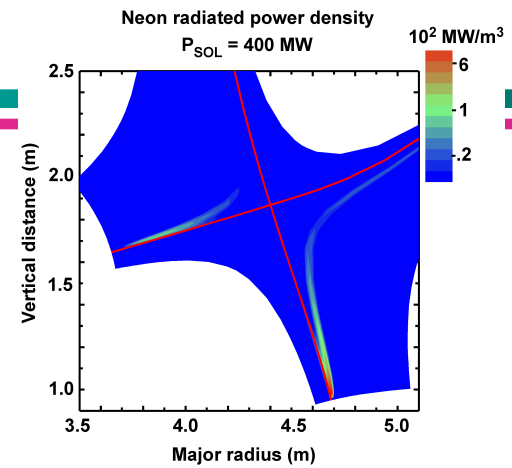
A 280 MW case shows acceptable heat loads

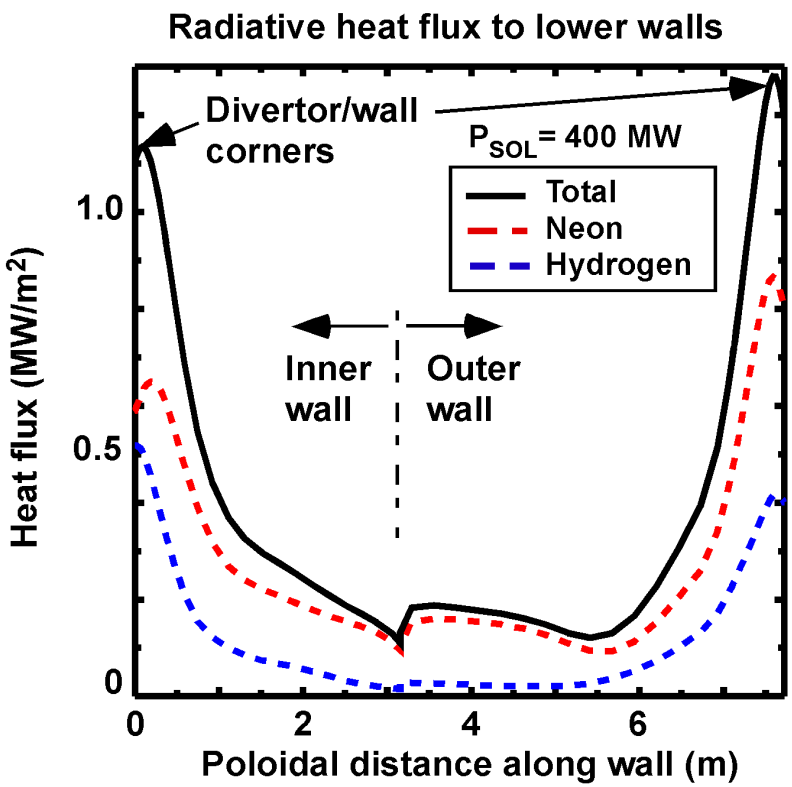


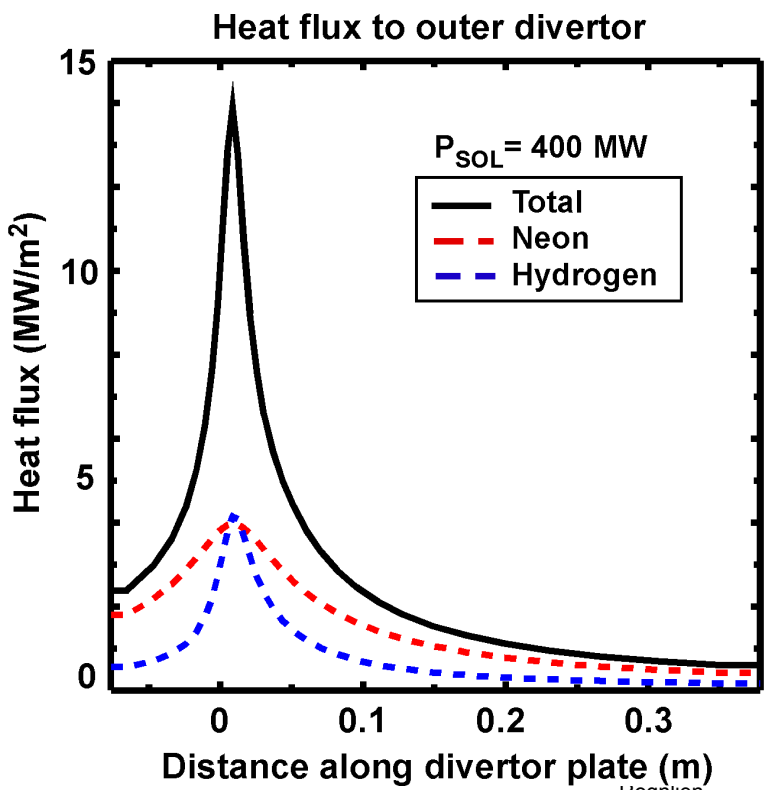




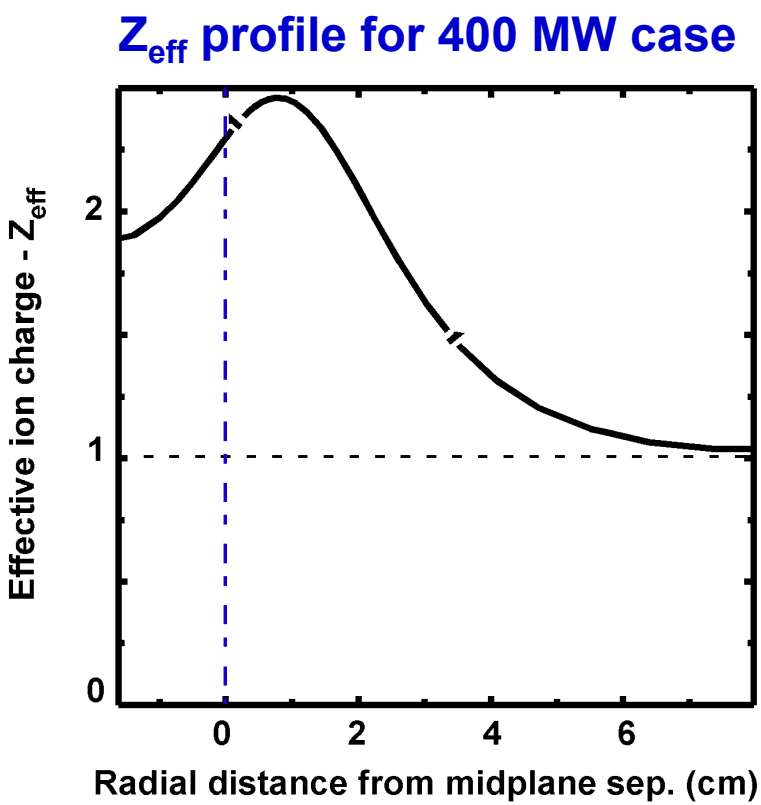
Corresponding 400 MW case is modestly over 10 MW/m^2 limit

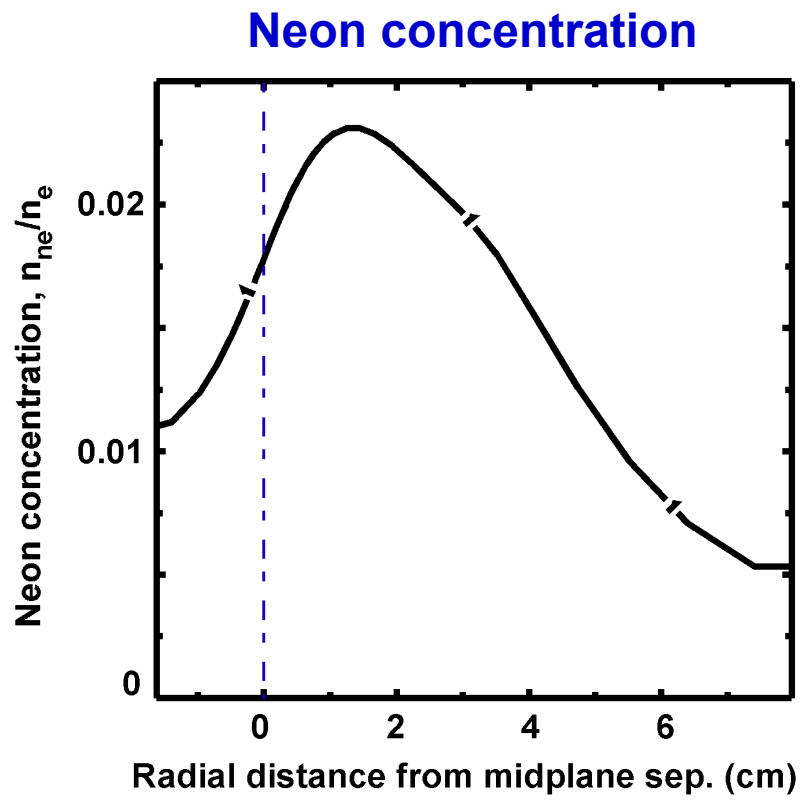


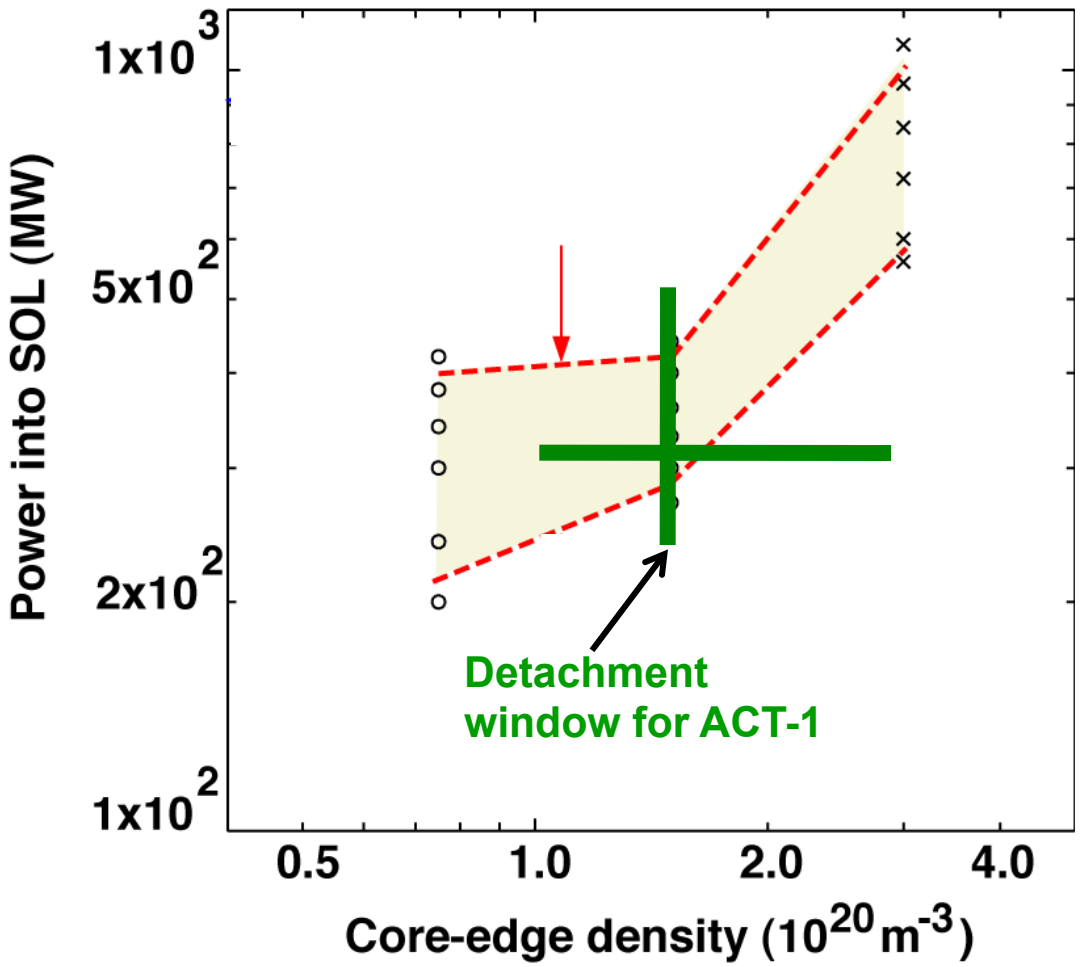




Neon impurity for sufficient SOL power loss results in significant core concentration





Core impurity concentrations are substantially larger for double-null cases than previous single-null (ARIES-RS) cases; edge flows are different

New results for double-null ACT-1 are shifted to higher density