Modeling snowflake divertors in MAST-U tokamak

ID: 771

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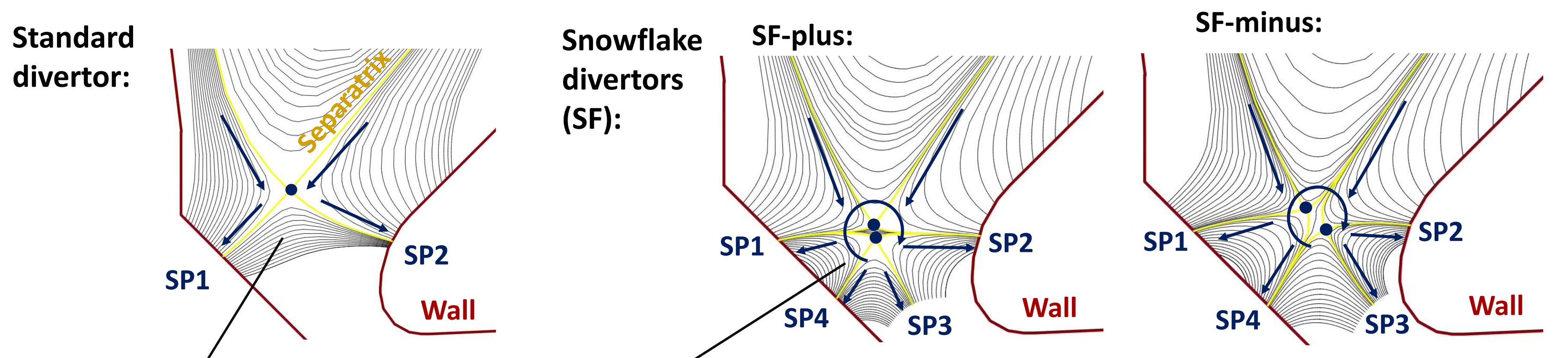
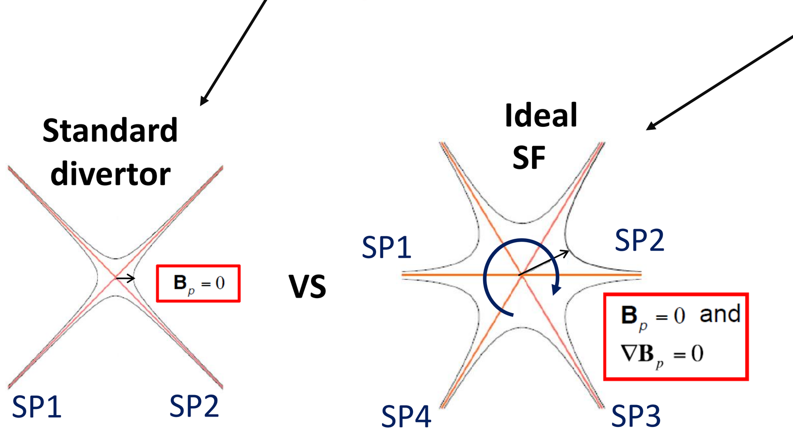
ABSTRACT

- In a snowflake (SF) divertor, two magnetic field nulls are placed close to each other creating four strike points (SPs) cf. two in a standard X-point divertor.
- In preparation to MAST-U experiments, X-point and SF divertors with various locations and separation distances of the nulls were modeled using a 2D multi-fluid code UEDGE with a full plasma transport model featuring charge-state-resolved sputtered carbon impurities.
- The complex interplay of the SF plasma transport ("churning" mode) and magnetic configurations was comprehensively studied.

BACKGROUND

- The performance of a snowflake divertor is an interplay of the magnetic field geometry and fast plasma mixing:





Potential advantages of snowflake configurations:

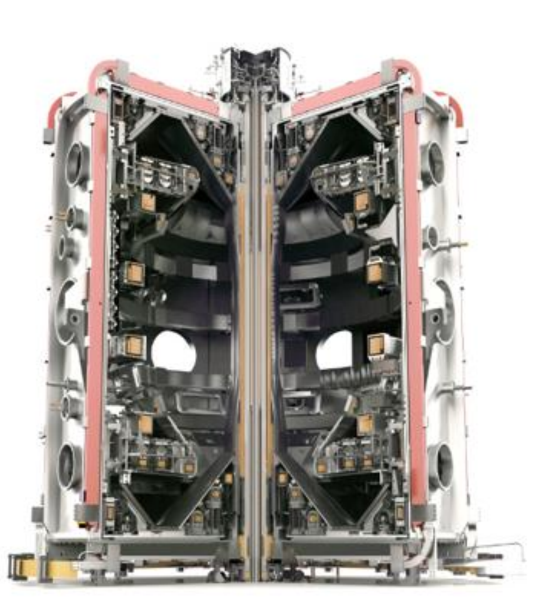
High flux expansion → large region of small B_p → "churning" mode instability

Increased connection length → higher radiative energy loss and lower peak heat fluxes to the divertor plates.

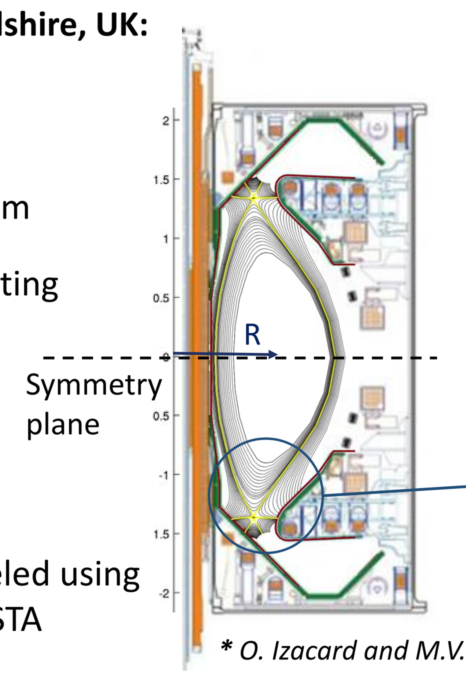
Plasma rotation in the two-null region ("churning mode") → heat/particle fluxes are directed to all divertor legs.

- Snowflake divertor experiments are planed on the upgraded MAST-U tokamak:

Spherical tokamak in Culham Center for Fusion Energy, Oxfordshire, UK:



- Research focus on divertor processes
- Major radius R = 0.7 m
- Up to 5 MW NBI heating
- First wall material: graphite
- Plasma current 2MA
- Magnetic field modeled using equilibrium solver FIESTA



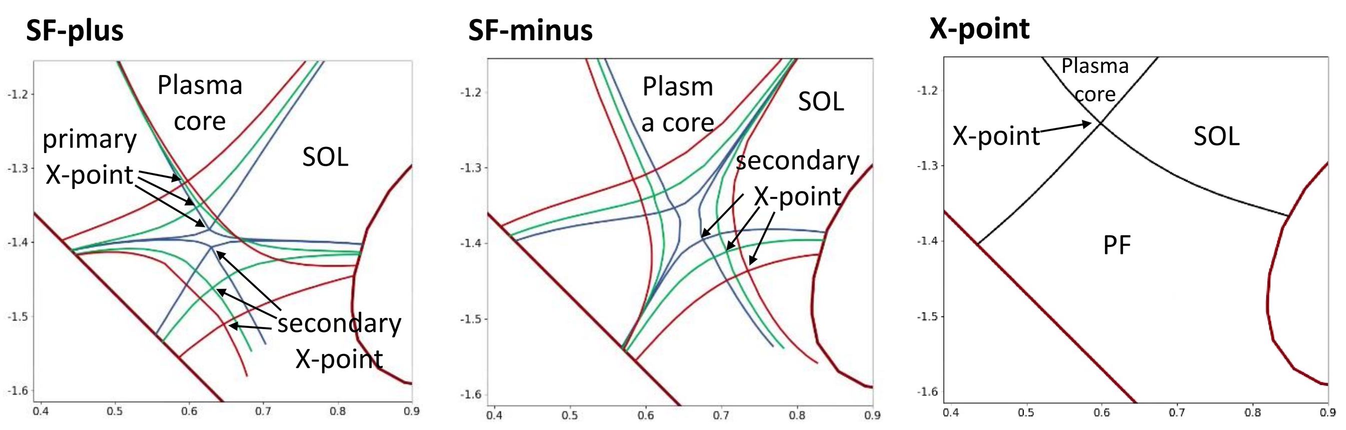
Gingred* code was substantially enhanced to create high-resolution field-aligned SF computational grids

** O. Izacard and M.V. Umansky, arXiv:1705.05717 (2017)*

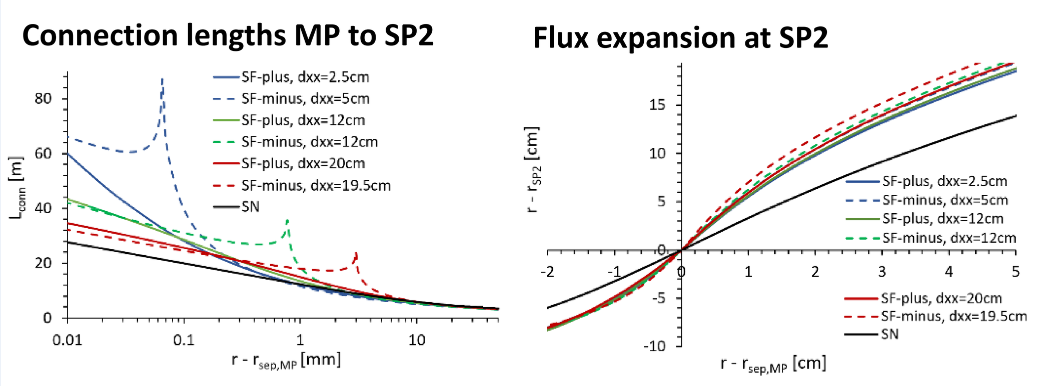
COMPUTATIONAL MODEL IN UEDGE

X-POINT AND SF CONFIGURATIONS IN MAST-U TOKAMAK

SF-plus and SF-minus configurations with various null separation were modelled:



- Pimary strike points SP1 and SP2 in all configurations were placed at close locations.



- Connection lengths in all configurations except the SF-minus with large d_{xx} are only different within first 1 mm from the separatrix; compare to λ_q ~ 5 mm.
- Magnetic in the vicinity of SP2 is close in all SF configurations and is considerably larger than in the X-point divertor.

TRANSPORT MODEL IN UEDGE

- Multi-fluid model
- Multi-component transport for D, D^+, C, C^+, C^{2+}, C^{3+}, C^{4+}, C^{5+} , C^{6+}
- Heat transfer for electrons and heavy particles

Boundary conditions

- Symmetric conditions at the midplane (only bottom modeled)
- NBI heating 2.5 MW (1.25 MW for a bottom half of a tokamak).
- 98% ion recycling at the walls and divertor.
- 98% neutral albedo coefficient at side walls.
- 100% albedo at divertor targets.
- Davis-Haasz sputtering model for C sputtering

Fast plasma mixing in the two-null region of SF divertors was modelled by adding two Gaussian profiles* centered at the PF nulls to transport coefficients ($D_\perp$ and $\chi_\perp$)**:

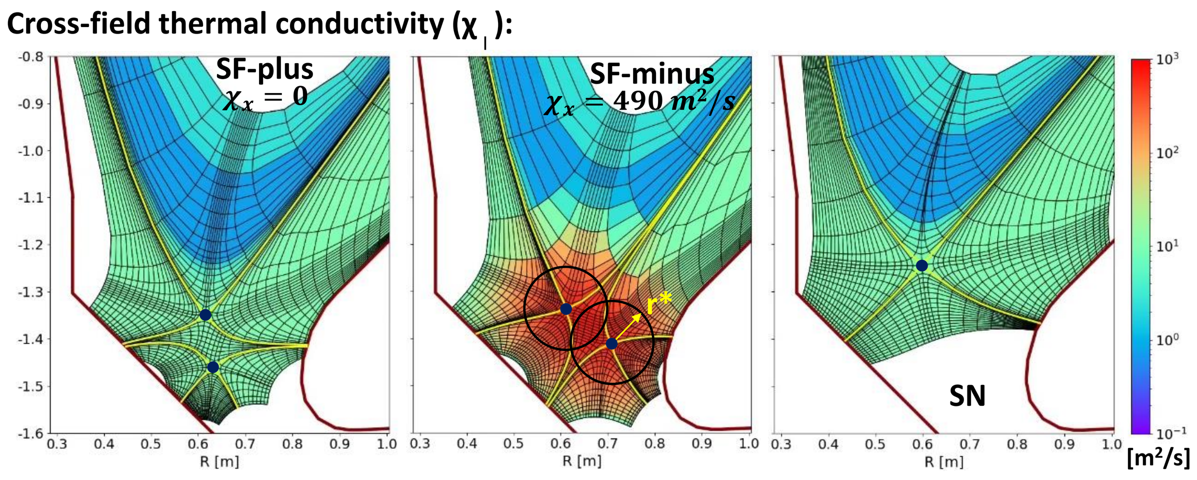
$$D_{\perp,mix} = D_\perp + D_{add},$$

$$D_{add} = D_x\left[exp\left(-\left(\frac{r-r_1}{r^*}\right)^2-\left(\frac{z-z_1}{r^*}\right)^2\right)+exp\left(-\left(\frac{r-r_2}{r^*}\right)^2-\left(\frac{z-z_2}{r^*}\right)^2\right)\right]$$

D_x, χ_x were varied in a range 0 to 490 m²/s $r^* = 0.81\,a\,(\beta_p\,a/R)^{1/3} \approx 10cm$

$\chi_{\perp,mix}$ was treated similarly

Cross-field thermal conductivity ($\chi_\perp$):



**D. Moulton et al, Proc. 44th EPS Conf. (Belfast, UK, 2017)*   ***T.D. Rognlien, 56th APS-DPP Meeting (New Orleans, LA, 2014)*

ACKNOWLEDGEMENTS

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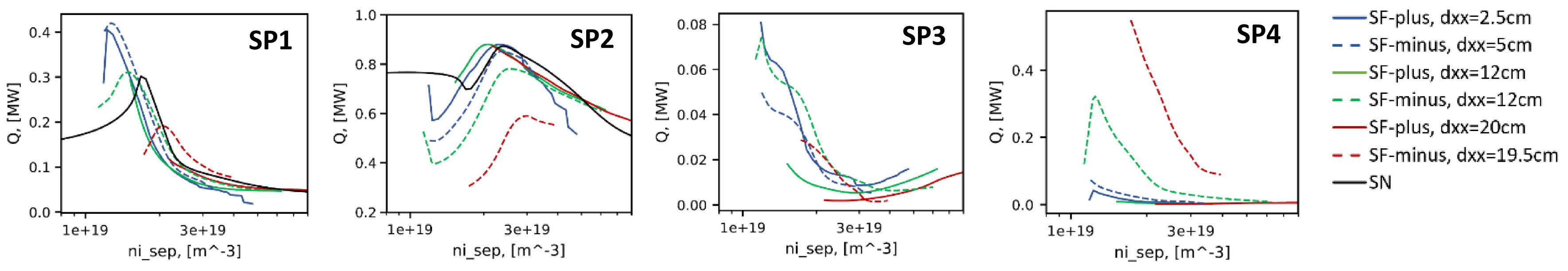
RESULTS

EFFECT OF THE MAGNETIC FIELD GEOMETRY

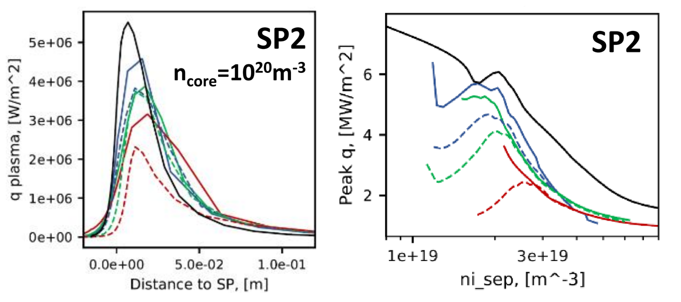
In this section, modeling results for X-point and SF divertors with no SF mixing (Dx=0) are presented to analyze solely the effect of magnetic field geometry on the divertor operation.

Plasma heat to all divertor targets (SP1 – SP4) in X-point and SF divertors:



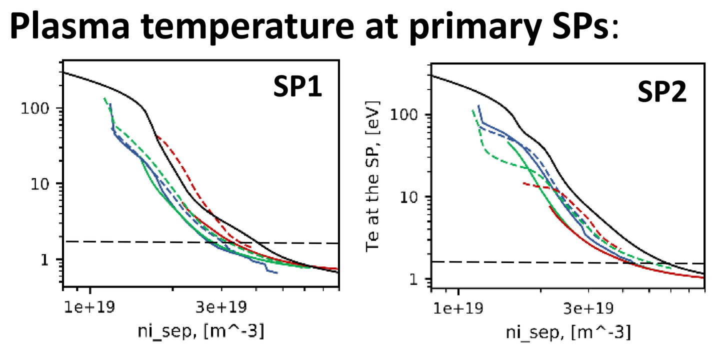
- Each primary SP (SP1 and SP2) receives nearly same amount of heat in the X-point divertor, all SF-plus divertors and SF-minus divertor with small d_{xx}. Secondary SPs receive a small fraction of power
- In SF-minus divertors with larger d_{xx}, substantial fraction of the SOL power is directed towards SP4. Correspondingly, heat flux to SP2 is smaller.

Heat flux profile and peak value:



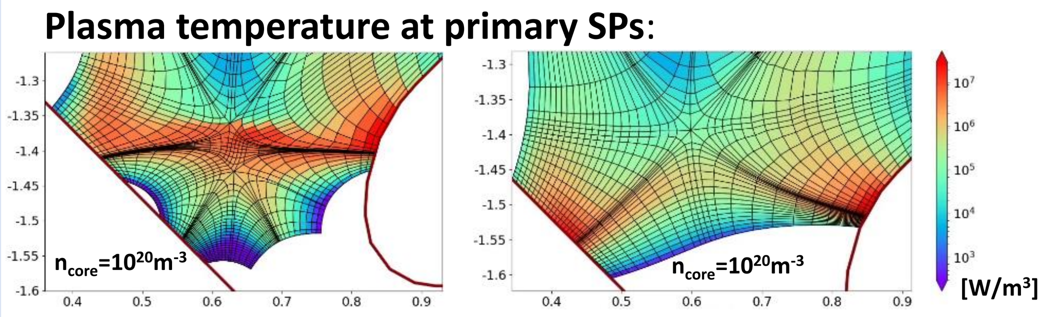
- Peak heat fluxes at SPs are noticeably reduced in the SFs compared to the X-point divertor.
- Heat flux profiles are substantially broadened and flattened out in the SFs due to higher magnetic flux expansion.

Plasma temperature at primary SPs:



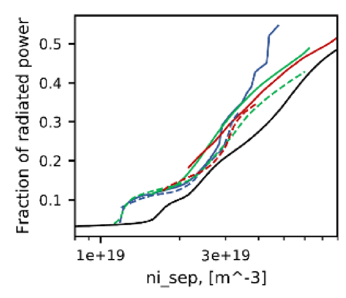
- Electron temperature at primary SPs is lower in SF divertors.
- A radiation front forms at SP1. It spreads towards the null region with the separatrix density increase.
- In the SFs, radiation volume is broader

Plasma temperature at primary SPs:



Total radiation:

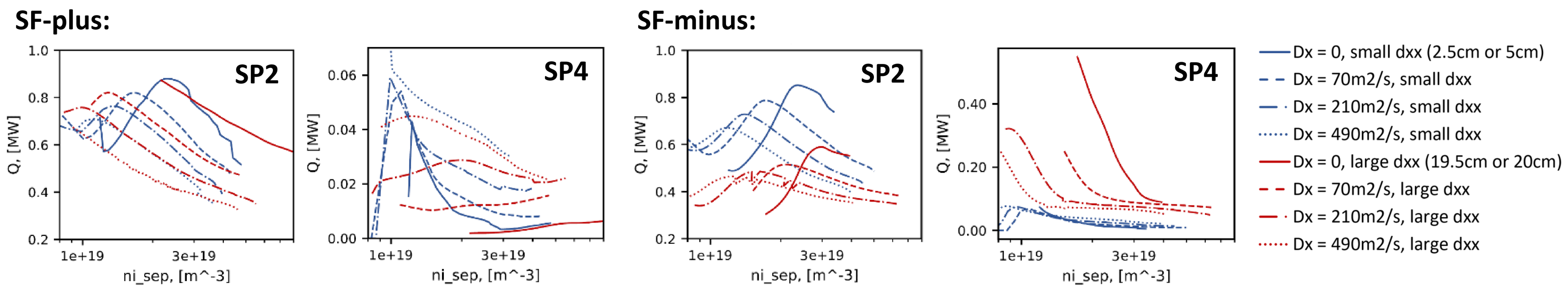
- In the SFs, total radiated energy is higher.



EFFECT OF FAST PLASMA MIXING ON THE PERFORMANCE OF SF DIVERTORS

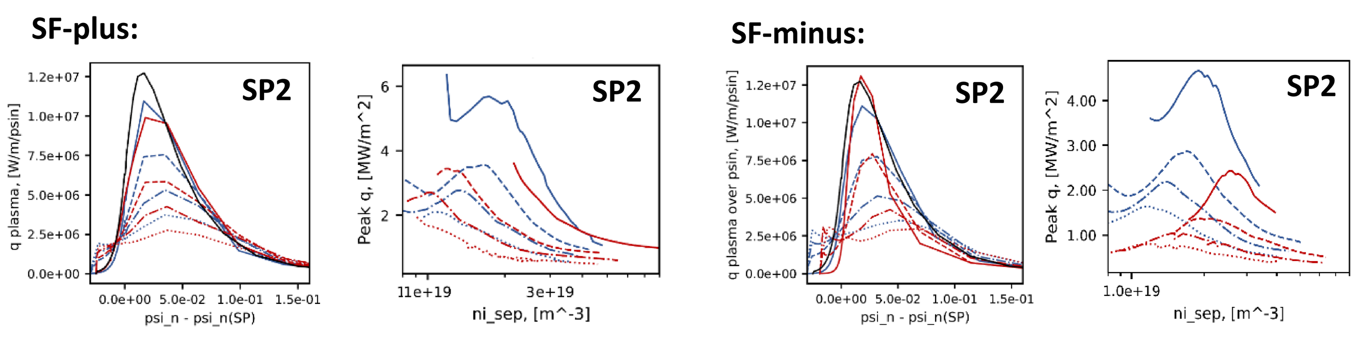
In this section, fast plasma mixing intensity (parameter D_x in Eq. (1)) is varied from 0 (no plasma mixing) to 490 m²/s. SF-plus and SF-minus divertors with smallest and largest d_{xx} are modelled.

Plasma heat to all divertor targets (SP1 – SP4) in SF divertors with and without mixing modeled:



- Power load to primary SPs substantially reduces with the SF mixing in all SF divertors.
- In all SF-plus divertors and in the SF-minus divertor with smallest d_{xx}, the heat reduction at SP2 is partially driven by the power redistribution towards secondary SPs.

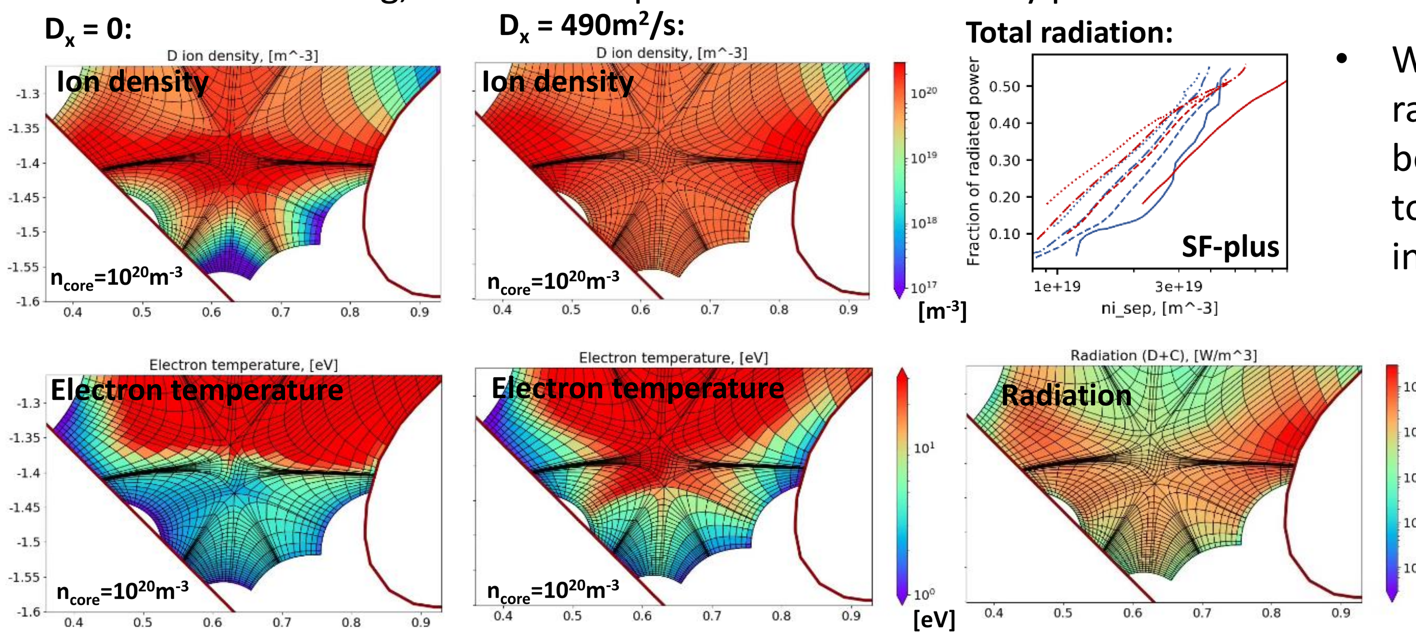
Heat flux profile and peak value:



- With the mixing increase, heat flux profiles at SP2 broaden and flatten. Peak heat flux at SP2 reduces.

2D profiles:

- With the SF mixing, electron temperature and ion density profiles become more uniform.



- With the SF mixing, radiation volume becomes broader, and total radiated power increases.
- Accordingly, total heat to the divertor targets reduces.

- In general, the fast plasma mixing does not have a substantial effect on the plasma detachment at primary SPs, but it strongly affects heat distribution between the divertor legs and heat flux profiles.

CONCLUSIONS

- In preparation to MAST-U experiments, numerical simulations of X-point and SF divertors were performed using a 2D multi-fluid code UEDGE with charge-state-resolved carbon impurities.
- For the first time, the complex interplay of the plasma transport and magnetic configurations with various relative locations and separations of the SF nulls was comprehensively studied.
- In all SF configurations, the heat flux profile is broadened and flattened at primary SPs as a result of higher magnetic flux expansion at the divertor targets. Accordingly, peak heat flux is reduced.
- Primary SPs in the SF configurations approach the plasma detachment conditions (the 1 eV threshold) earlier (at lower separatrix densities).
- Fast plasma mixing in SF divertors reduces total heat to primary SPs by a factor of two, broadens heat flux profiles and reduces peak heat fluxes to primary SPs by more than 3 times (on top of the SF geometry effect).