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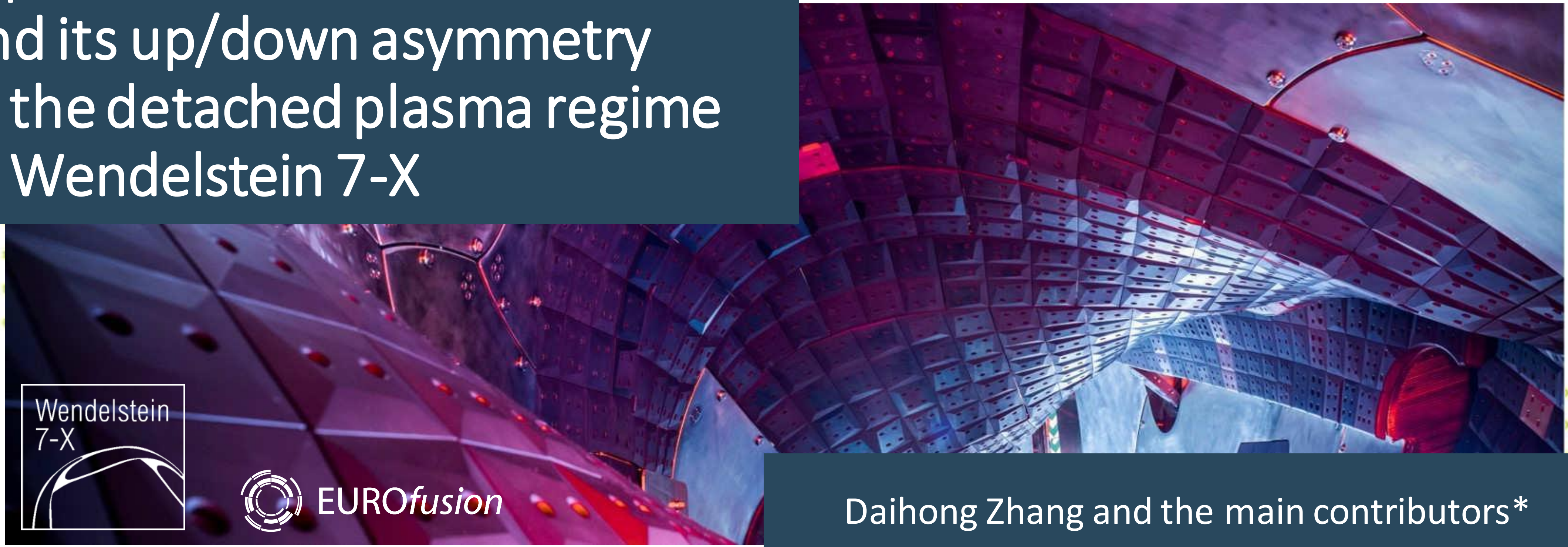
FÜR PLASMAPHYSIK

X-point radiation and its up/down asymmetry in the detached plasma regime in Wendelstein 7-X



Daihong Zhang and the main contributors*

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Preface: Stable X-point radiation in the detached plasma (DP) regime

- Plasma detachment with high impurity radiation is a promising solution for reducing divertor target heat load, preventing material erosion, and thus ensuring the safety operation of fusion devices.
- In the DP scenarios in tokamaks (typically with a single-null divertor configuration), most of the radiation originates from the vicinity of the single X-point (B_p=0) (so-called X-point radiator).

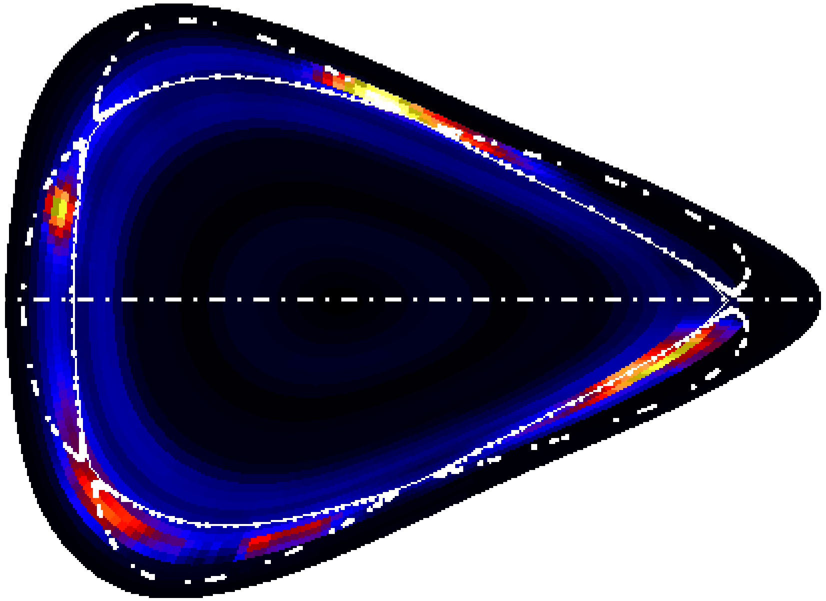
[Bernert, et al. Nuc. Mat. Eng.,2025]
[Stroth, et al., NF,2022]

Preface: stable X-point radiation in the detached plasma (DP) regime

- Plasma detachment with high impurity radiation is a promising solution for reducing divertor target heat load, preventing material erosion, and thus ensuring the safety operation of fusion devices.

This presentation addresses X-point radiation (XPR) in stellarator W7-X

Normal magnetic field direction (B+: counterclockwise from top view of W7-X)



bolometer tomography

[Zhang, et. al, NF, 2019]

Stable, highly-radiative DP phases obtainable:

- w. intrinsic impurities (e.g., C and O)

[Zhang, et. al,2019, PRL]

[Pedersen, et. al, 2019, NF]

[Schmitz, et. al, 2021,NF]

[Jakubowski, et. al, NF, 2021]

- w. seeding

[Effenberg, et. al, NF, 2019]

! controllable [Krychowiak, et. al , NME, 2023]

! Radiation fraction $f_{rad}=P_{rad}/P_{heat}$ governs the DP processing

[Feng, et. al, NF, 2021]

How about the radiation structure?

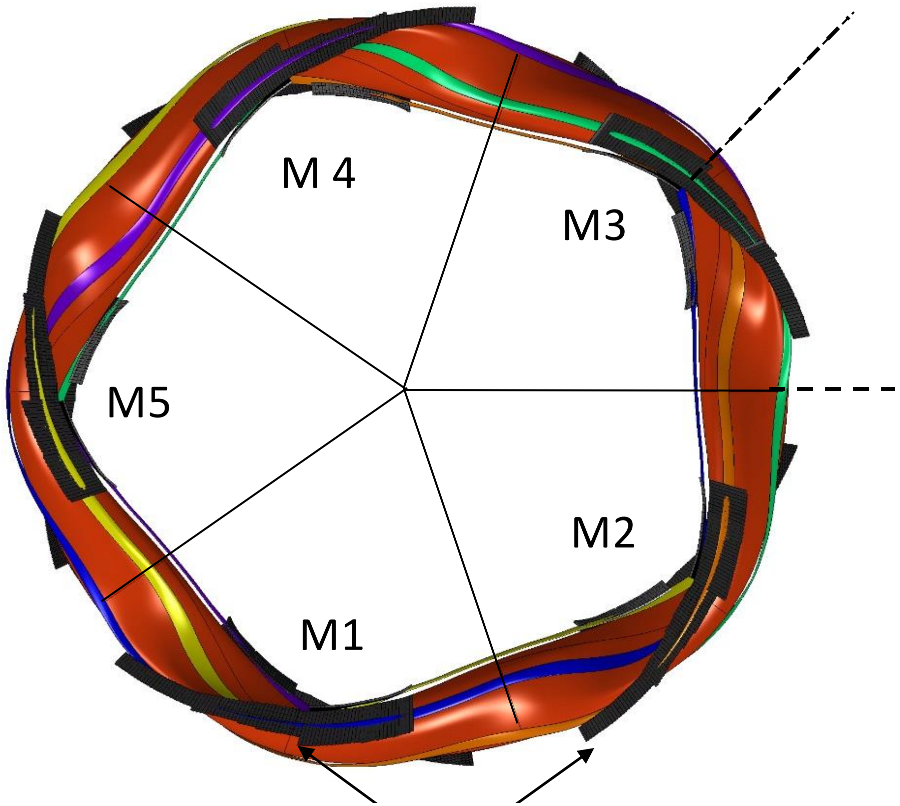
OUTLINE

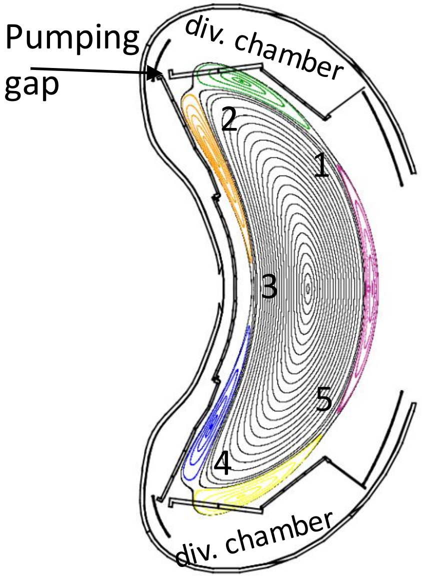
- **Introduction**
- **Experimental results**
  i. multi-X-point radiation with up/down asymmetry in the detached plasma regime
  ii. Magnetic-field direction dependent up/down asymmetry
- **Discussions on a simplified model**

  - pol. E × B drift effects on impurity transport and radiation asymmetry
- **Summary**

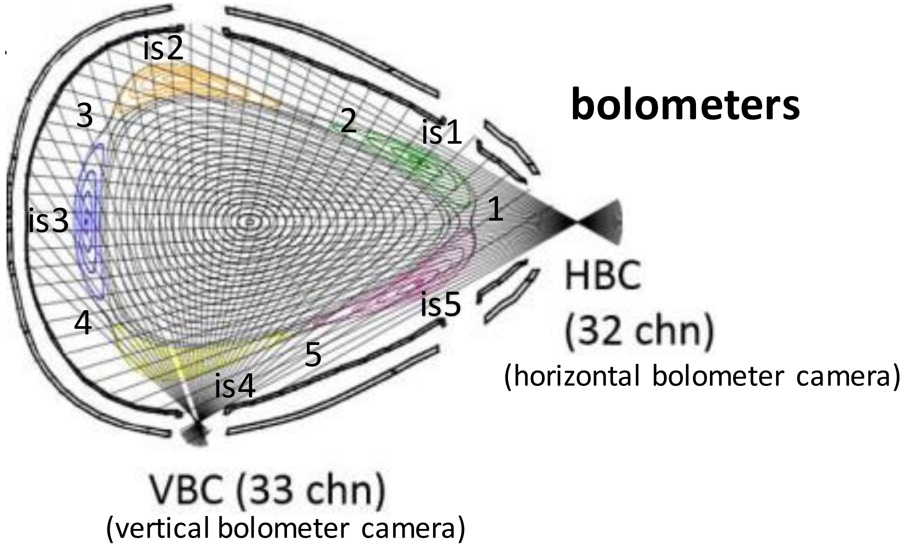
Introduction

Magnetic topology
- 'standard' divertor configuration
- iota = 1 (5/5)
- Magnetic Island dimension r_w ~7 cm



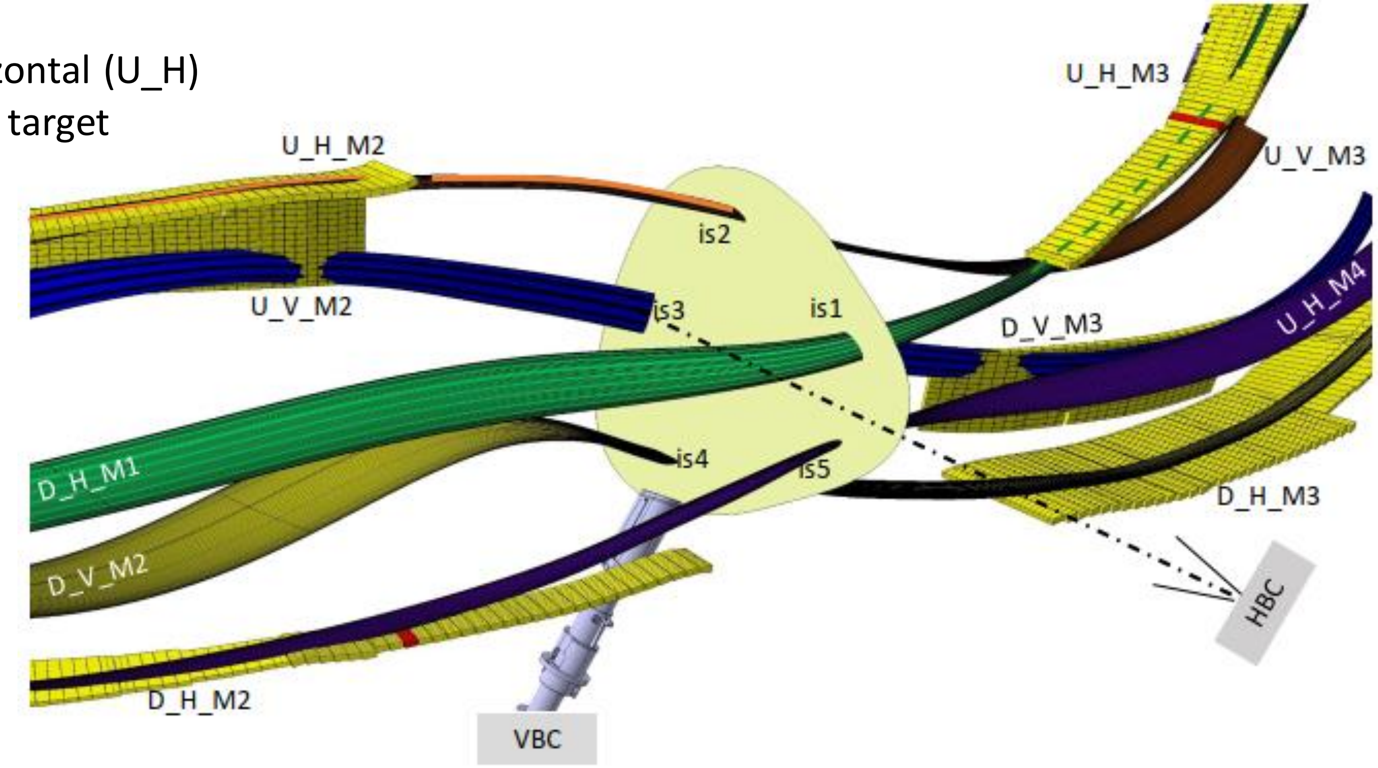


- Five islands intersecting the divertor targets
- 3D magnetic topology and SOL (scrape-off layer)
- Main radiators: **target-released carbon impurity ions**



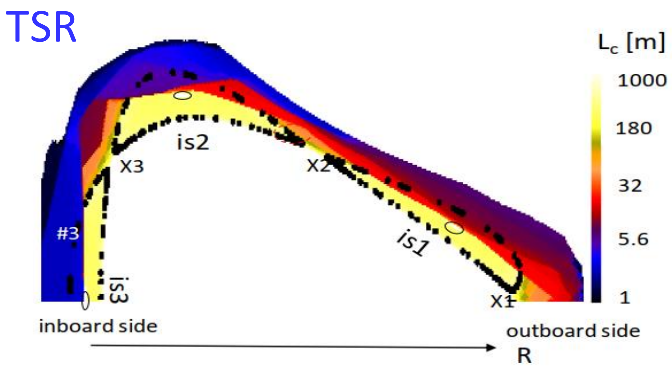
Magnetic connection length

Up horizontal (U_H)
divertor target



down horizontal (D_H)
divertor target in M2

connection length Lc (wall-to-wall)



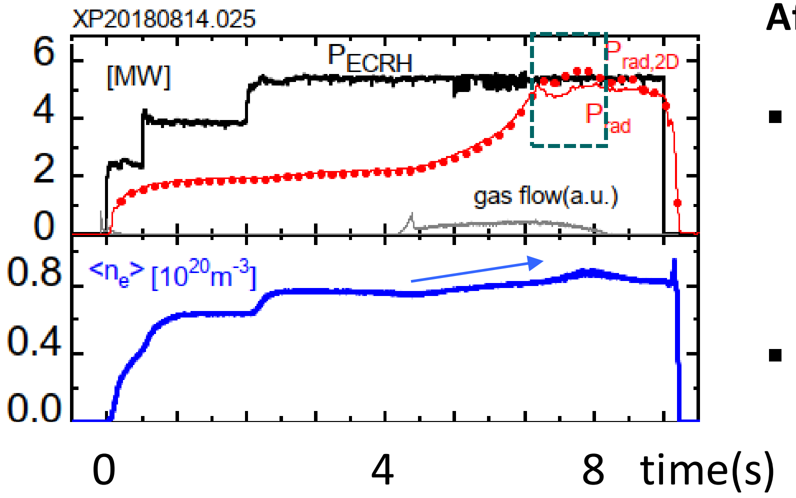
Calculated using EMC3-lite
[Feng, PPCF, 2022]

Triangular cross-section:
- w/o target elements
- Outmost region: target shadow (TSR)
- Shortest Lc ~3 m (e.g. is3 to vertical targets)

Target-released carbon impurities can reach other regions through parallel and cross-field transport (e.g. diffusion & drift)

Experimental results: establishing the radiative plasma detachment

Representative hydrogen discharge: 5.5MW ECRH



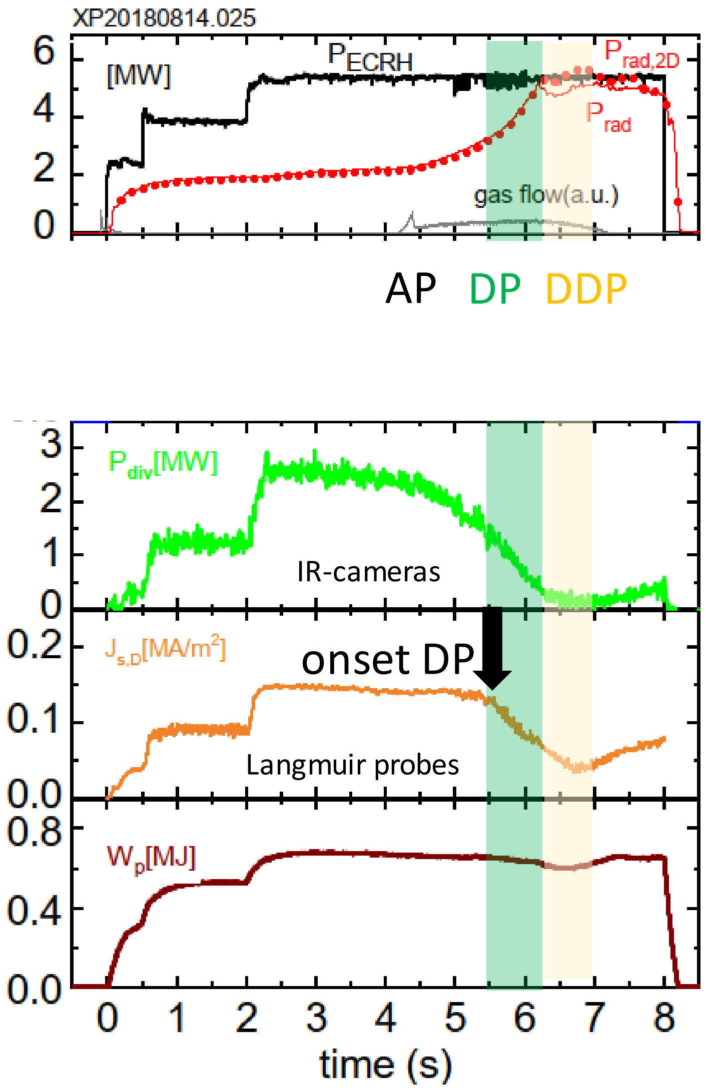
After hydrogen-gas refueling (t>4s; up to 8s)

- P_{rad} increasing;
  Prad_2D (tomography beads)
  Prad (HBC measurements based)
  - deviation between them indicating **phase transition of pol. asymmetry in radiation patterns**

- Plasma density increasing

Experimental results: establishing the radiative plasma detachment

Representative discharge: 5.5MW ECRH; density ramp



After hydrogen-gas refueling (t>4s)

- Prad increasing;
  - radiation zone shifting

AP = attached plasma
DP = detached plasma
DDP = deep detached plasma

- Diverter target heat load decreasing

Onset of DP definition:

- Particle flux on divertor target start to decrease

- Plasma stored energy:
  - **quasi-stationary**;
  - slight decrease in the later DP phase (called deep DP)

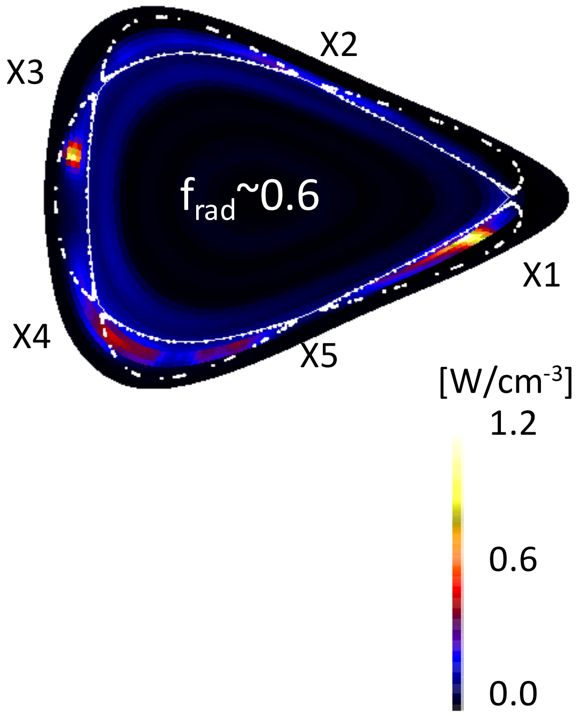
Other parameter variation:

(AP→ DDP)

- T_e(LCFS): ~100eV → <50eV
- $T_{e,tar}$: ~15eV → ~3.5eV
- $f_{rad,core}$: ~0.2 → ~0.6

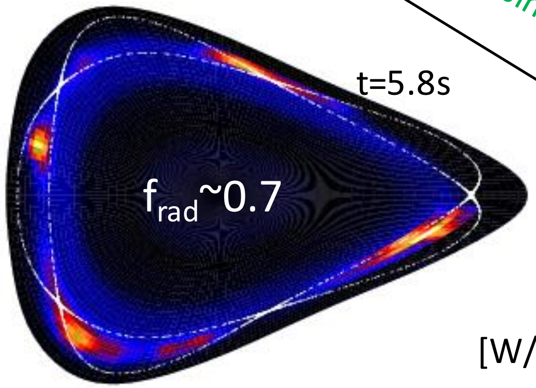
Establishment of multi-X-point radiation (multi-XPR) structure

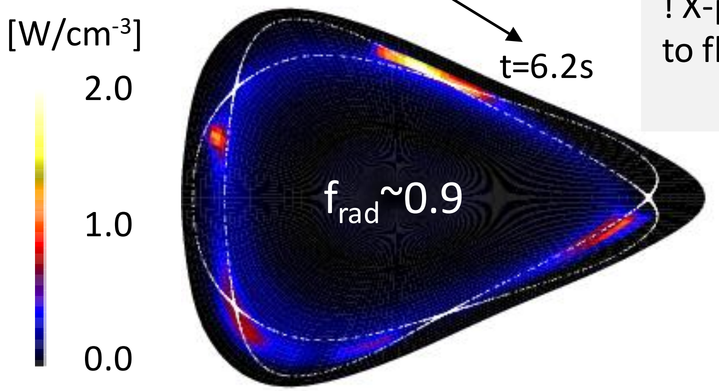
Bolometer tomography

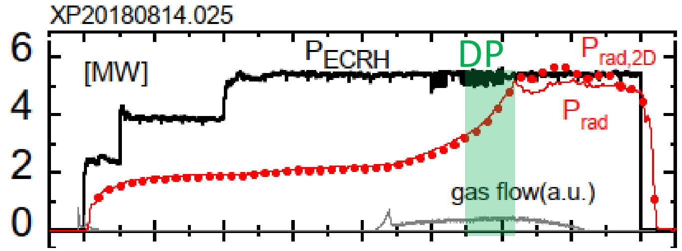


Onset DP
t=5.5s

f_{rad} increasing (DP)







2D radiation profile feature:

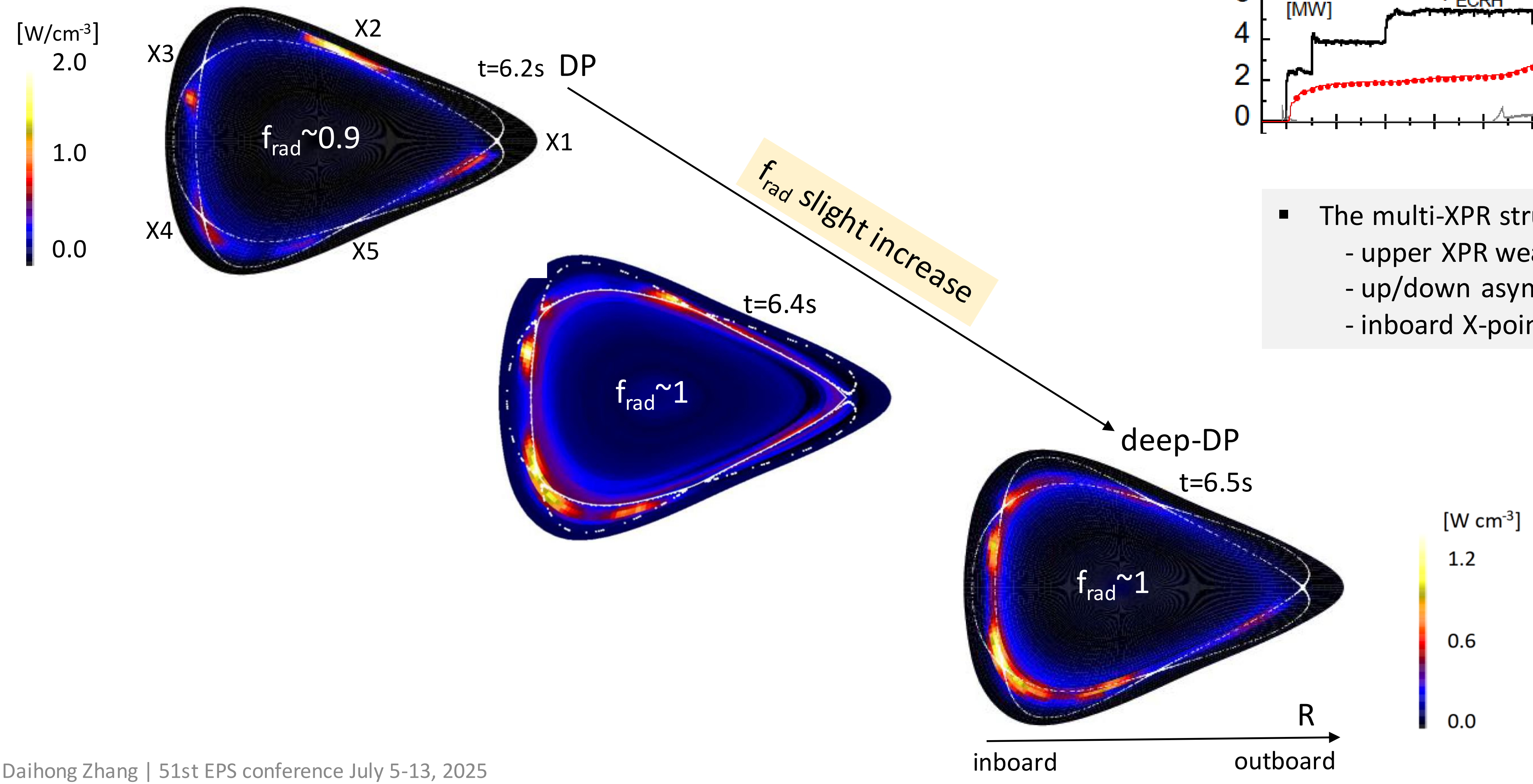
- SOL localized
- high dynamics
- up/down asymmetry of emissivity

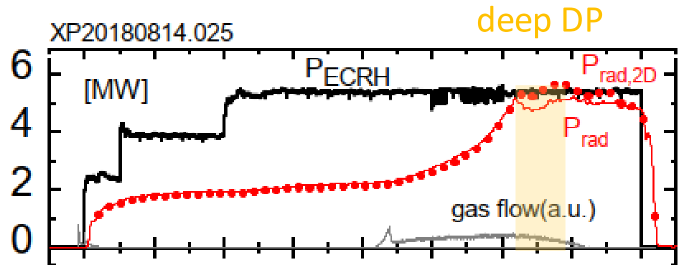
-radial + poloidal shift to certain X-points →
forming a **multi-XPR structure**

! X-point radiation condensation is due to flux surface expansion
[Feng, NF, 2024]

Dynamics of the multi-XPR structure
- transition to deep detached plasma (deep DP) phase

Bolometer tomography





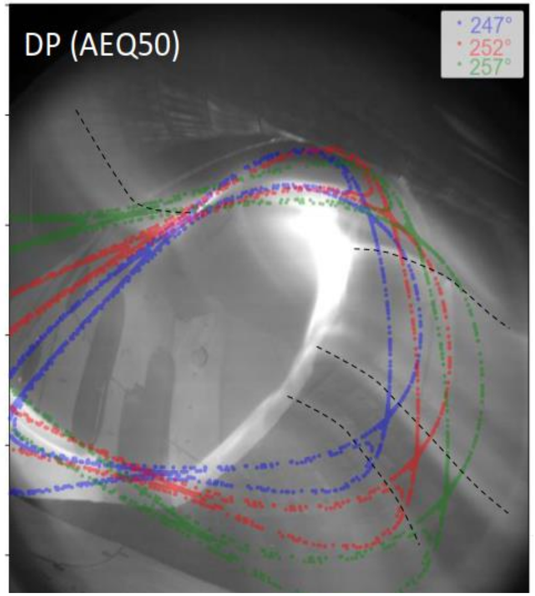
- The multi-XPR structure variations
  - upper XPR weakening
  - up/down asymmetry reducing
  - inboard X-points brightening

Visible video cameras: Confirmation of the bolometer results

[G. Cseh, et al.,
this conference, 3P203]

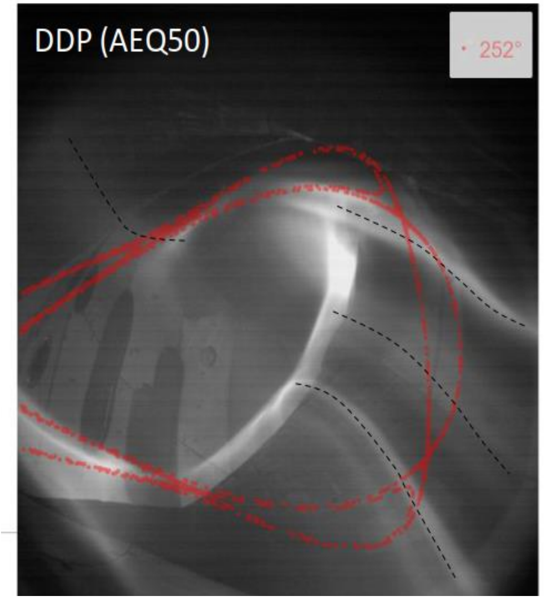
- *Sensitive to line emission from Hα, CII, CIII*
- Toroidal extent of FoV ~55°
- Overlaid Poincaré plots:
  ϕ=247°, 252°, 257°

DP (6.2s)



outer board inboard

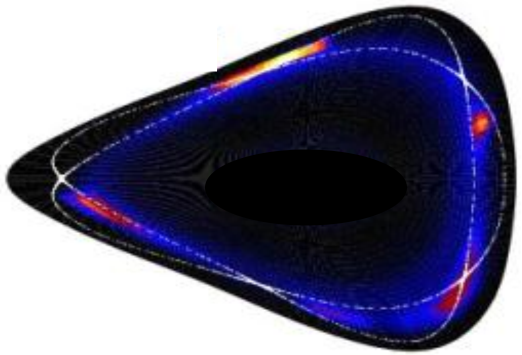
Deep DP (6.5s)



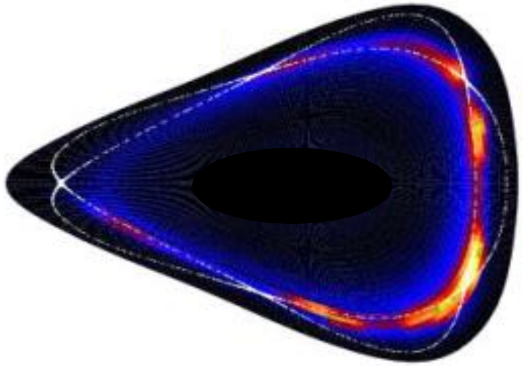
outer board inboard

DP phase:

- Upper XPR brightest



bolometer results
(horizontally flipped)



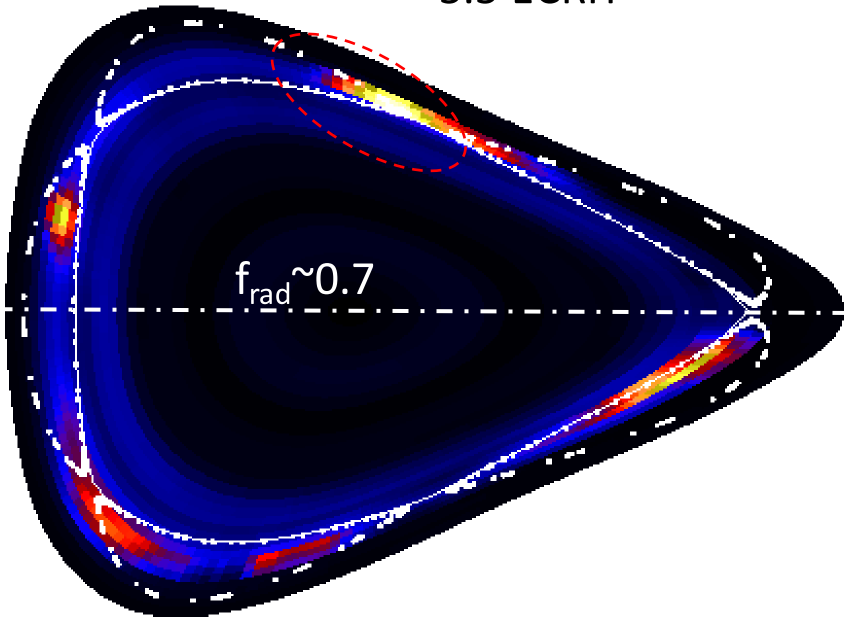
deep DP phase:

- Upper XPR weakens
- Inboard XPR brightens

Magnetic field reversal effect on pol. asymmetry of carbon radiation in density ramp experiments at W7-X (2018 & 2025)

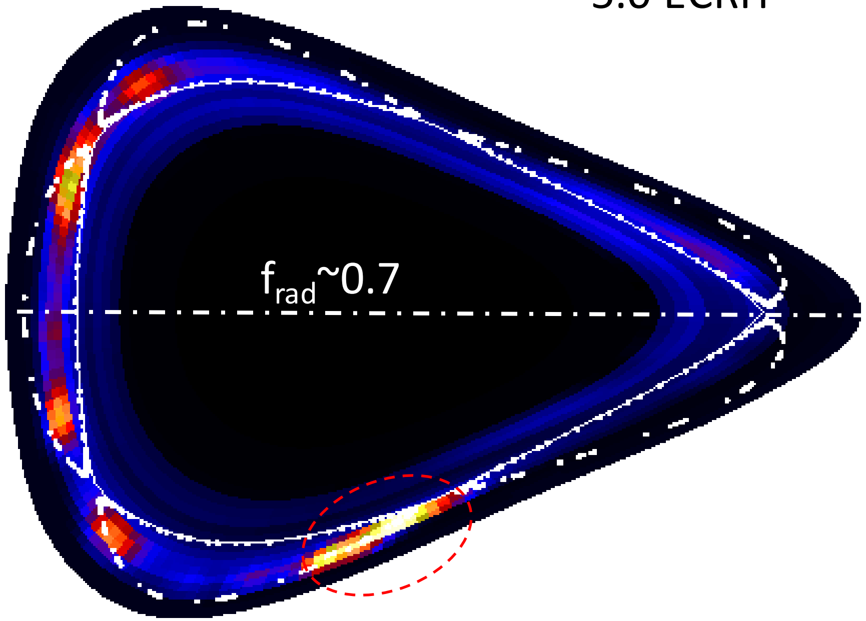
Normal magnetic field direction (B+)
OP1.2b (2018; XP20180814.025)

5.5 ECRH



Reversed magnetic field direction (B-)
OP2.3 (2025; XP20250313.040)

5.0 ECRH



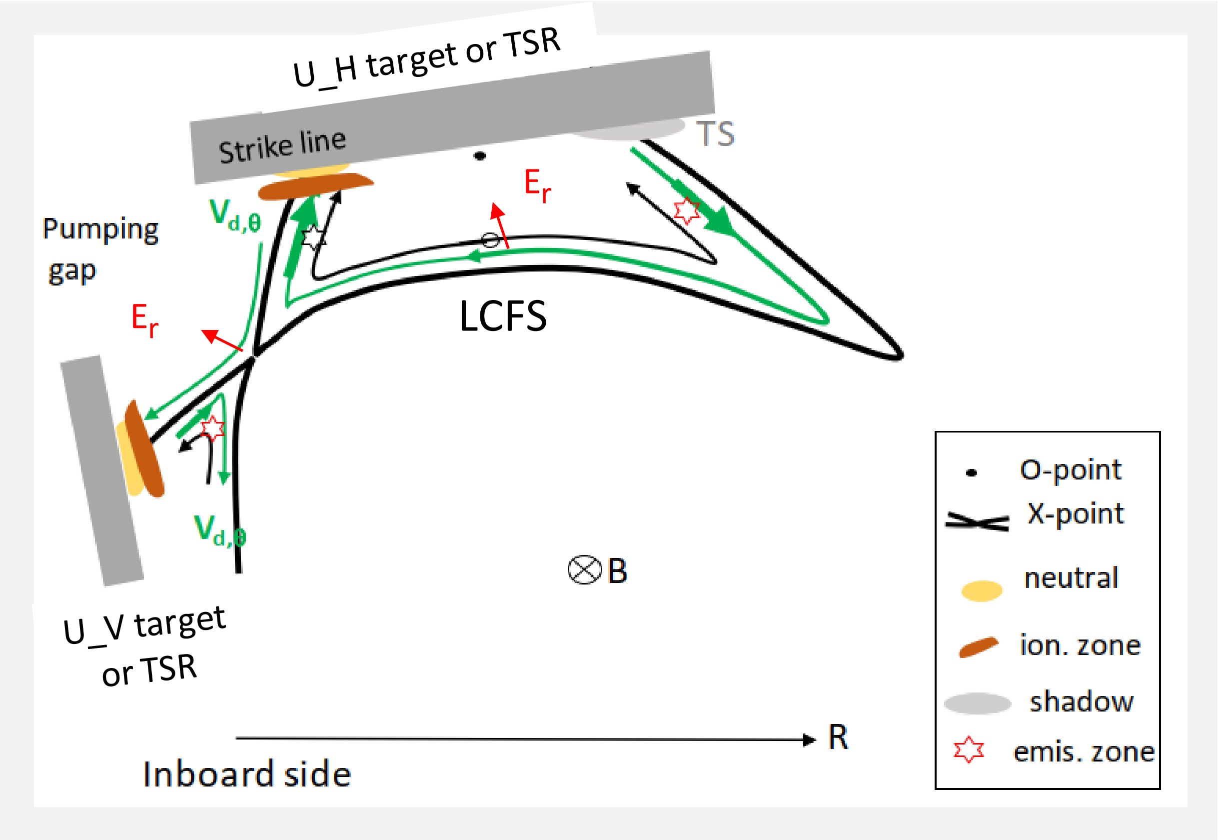
- **The asymmetry in the multi-XPR structure is magnetic-field-direction dependent**

  - field reversal leads to displacement of the brightest XPR from the upper to the lower SOL

  ! This reversal of asymmetry suggests that drift (most likely the ExB drift) plays a role. [Stangeby et al 1996, NF]

Discussions: A simplified model considering the poloidal ExB drift effect on impurity flow in the island SOL

Upper SOL



- Parallel impurity transport:
  classical convection driven by
  - thermal force ($\propto \nabla_{//}T_e$; $\nabla_{//}T_i$) +
  - **frictions due to collisions with main ions**

! At W7-X, downstream frictions (<0) dominant

[Feng, NF, 2006]
[Perseo, NF,2019]

$$V_{z,f} = -\Theta V_{Z\parallel} \approx -\Theta V_{i\parallel}$$

$(internal\ field\ line\ pitch\ \Theta \sim 0.001)$

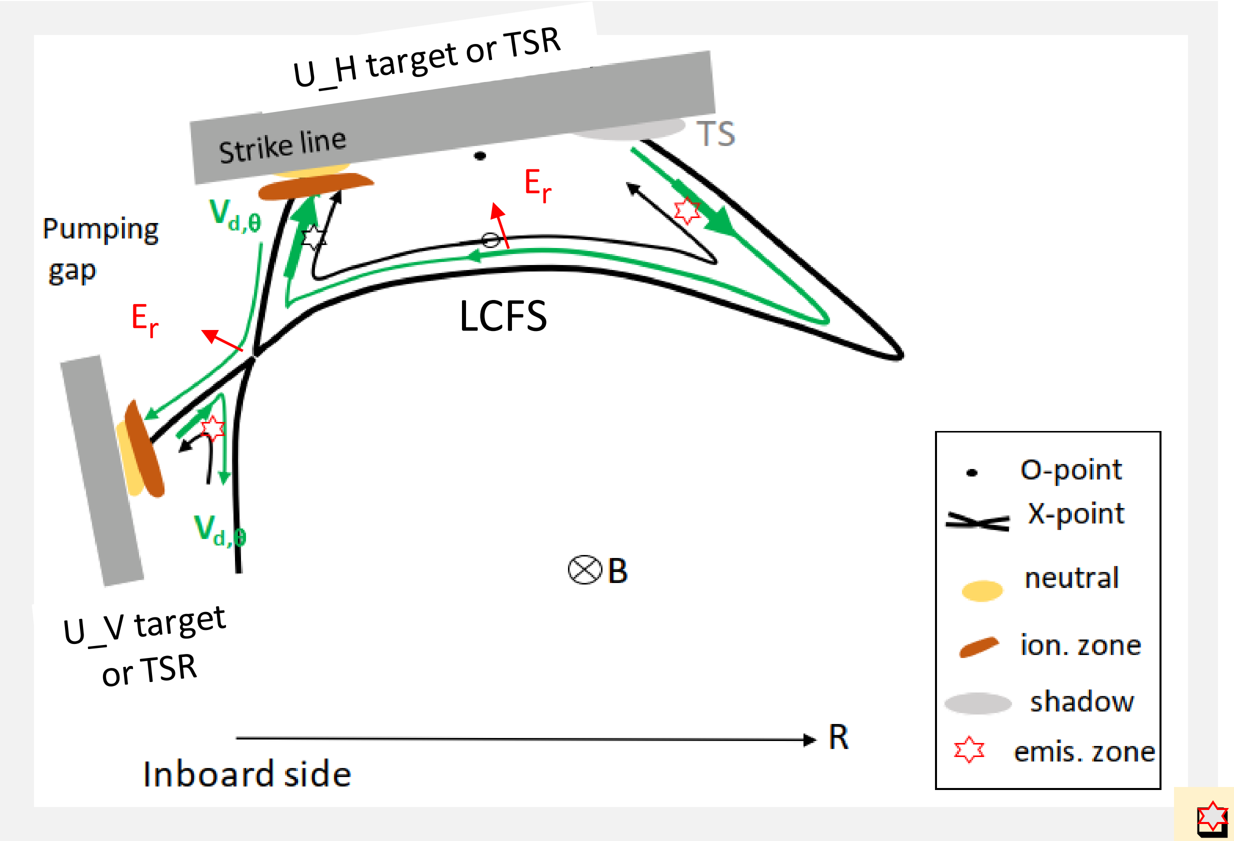
- Poloidal E×B drift, $V_{d,\theta} \propto E_r/B$
  $\mathbf{E_r \equiv -d\phi/dr \propto -dT_e/dr}$

[Kriete, NF,2023]
[Hammod, PPCF, 2021]
[Stangeby, 1996]

- Equally impact on both main ion and impurity ions

Discussions: A simplified model considering the poloidal ExB drift effect on impurity flow in the island SOL

Upper SOL



[Feng, NF, 2006]

1D particle continuity equation in **source free region**:

$$\frac{d}{dx}\left((V_{z,f} + \boldsymbol{V_d})n_z - D\frac{dn_z}{dx}\right) = 0$$

frictions — Pol. E×B drift $V_{d,\theta} \propto E_r/B$ — diffusion

$$\boxed{n_z(x) = n_{zd}\exp\left(\int_{\lambda_0}^{x} \frac{Vz,f + V_d}{D}\,dx\right)}$$

η_{zd}: source asymmetry (downstream TSR)

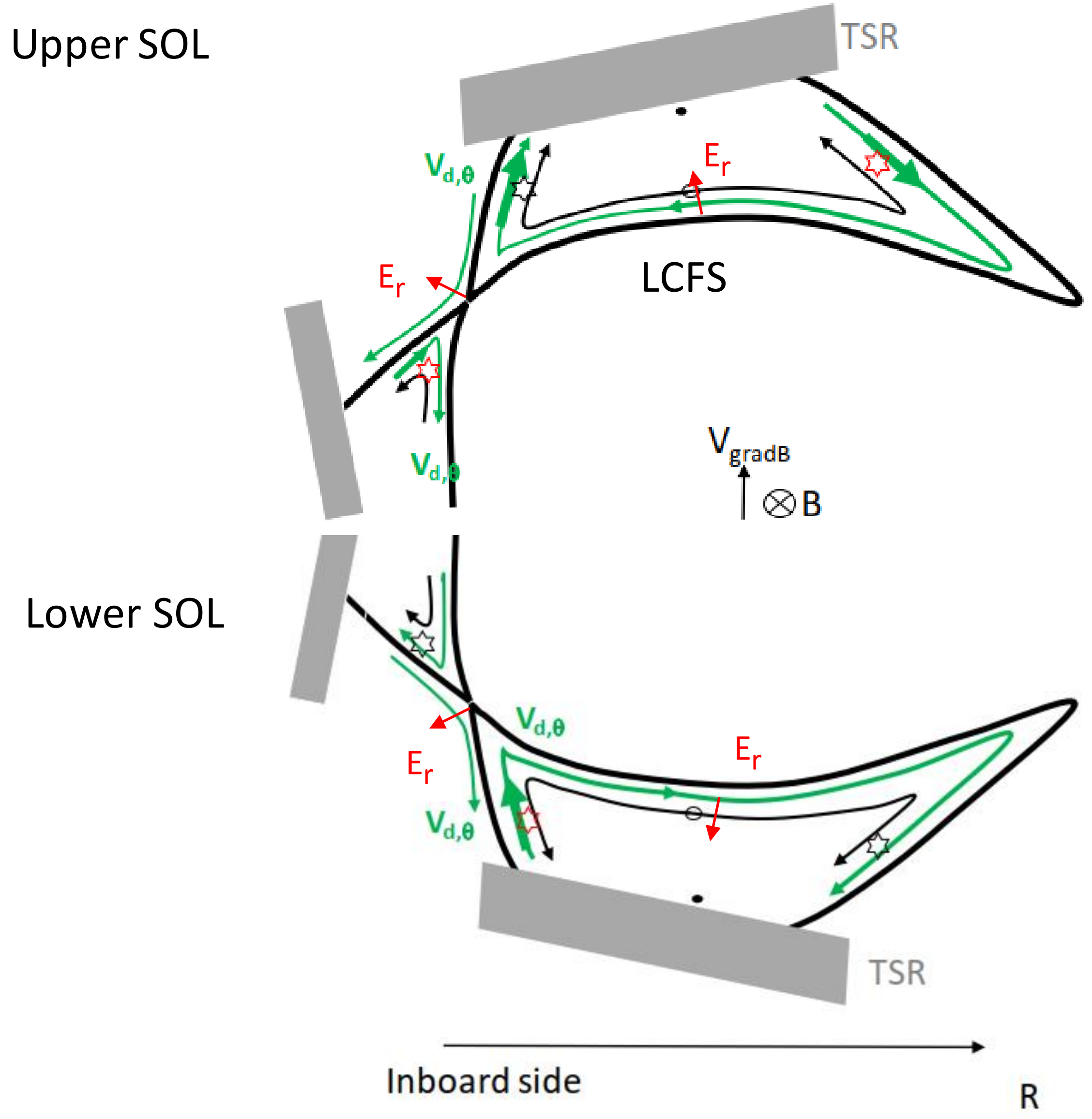
λ_0: neutral penetration length (~1cm - several cm)

x: distance from the TSR

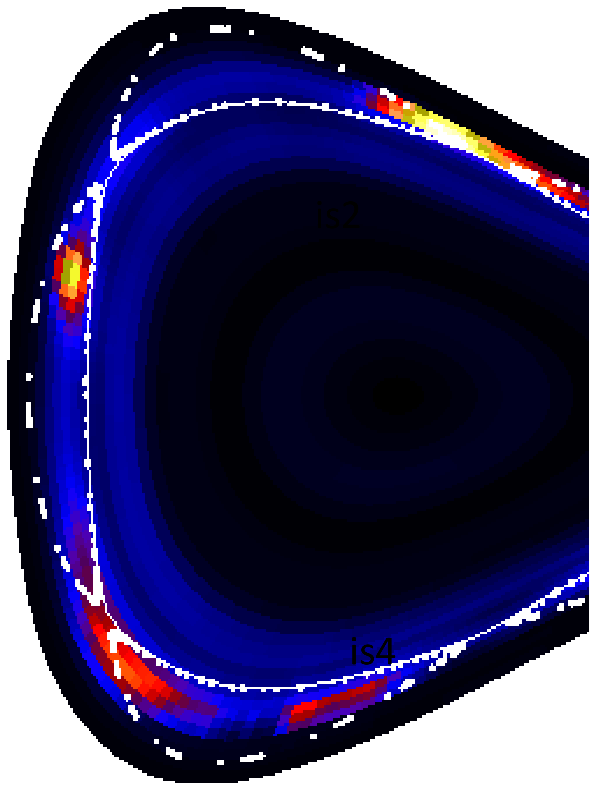
- Upstream drift: $V_d = +V_{d,\theta}$ (>0, toward the LCFS) → increasing n_z → higher radiation
- Down stream drift: $V_d = -V_{d,\theta}$ (<0, toward the target or TSR) → reducing n_z → lower radiation

- *Source asymmetry influences additionally.*

Discussions: How does the poloidal ExB drift affect the up/down symmetry of impurities in the SOL ?



Bolometer tomography



- This simplified model predicts up/down asymmetry in impurity distribution despite the up/down symmetric magnetic topology.
- The up/down asymmetry in impurity radiation is then qualitatively explained.

Summary

In W7-X hydrogen plasmas generated by ECRH,

❑ plasma detachment induced by intrinsic carbon impurity radiation are routinely obtained with ‘standard’ magnetic configuration. It features,

- **in the detached plasma (DP) phase (f_{rad} =0.6-0.9),**

  - a multi-X-point radiation (**multi-XPR**) structure with **up/down asymmetry** despite the up/down symmetric magnetic topology in the FoV of diagnostics (bolometers & video cameras)

  - the **brightest XPR appears near the upper X-point** for the normal magnetic field direction; while displacing to the lower X-point in reversed field experiments, implying that the drift effect plays a role.

- **in the deep DP phase (f_{rad} ~1),**

  - the degree of up/down asymmetry significantly reduces, nearly all SOL power is homogenously dissipated via impurity radiation.

❑ A simplified model is introduced for the DP phase:

- considering the influence of the **poloidal E×B drift** (V_d) on the impurity flow in the SOL
- Qualitatively explained the mechanisms driving the up/down asymmetry in impurity distribution
  - ✓ **downstream drift toward the target or TSR decreasing the impurity content,**
  - ✓ **upstream drift toward the LCFS increasing the impurity content.**
- The poloidal drift potentially leads to an up/down asymmetry of impurity density in the SOL, causing an up/down asymmetric impurity radiation. *The dynamics of the up/down asymmetry in the multi-XPR structure is related to the magnitude V_d/D (normalized to the impurity diffusivity), with additional effects owing to the radial inward shift of the emission zone as well as source asymmetry.*

[Zhang, D. et. al., 2025, submitted to NF]

Thanks for your attention!