Direct 2D measurements of parallel counter-streaming flows in the W7-X scrape-off layer for attached and detached plasmas

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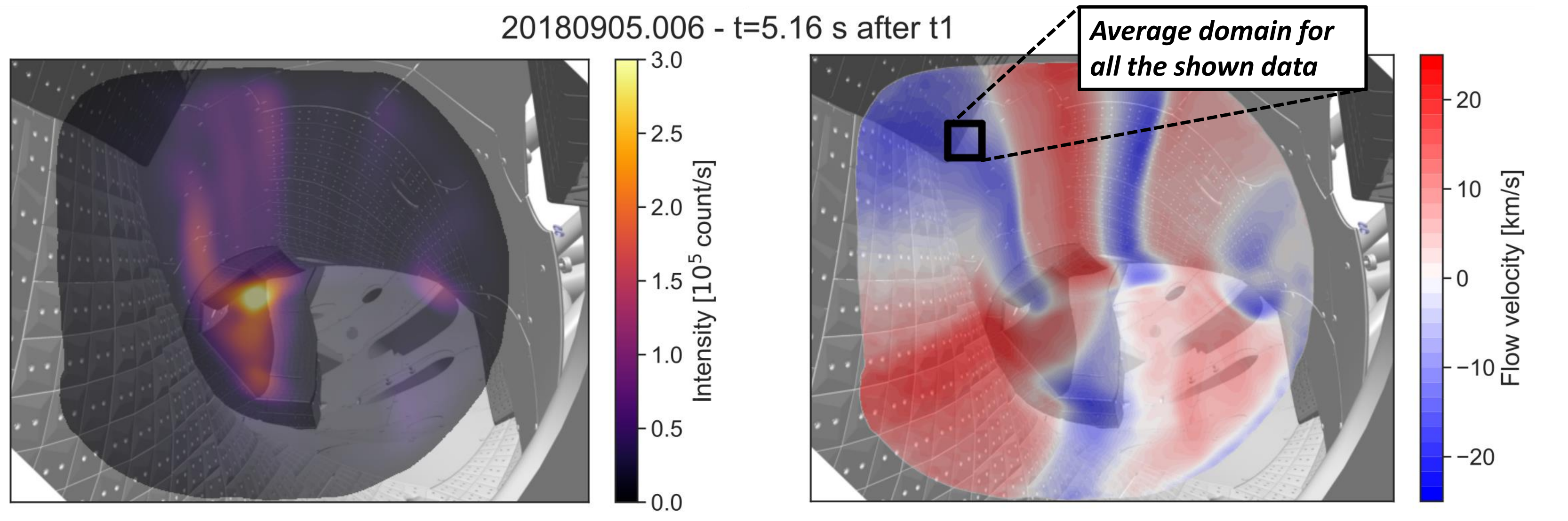
1. MOTIVATION

- Scrape-off layer (SOL) of W7-X: island divertor → unique divertor configuration
- Interplay of parallel and perpendicular transport + distribution of sources in the SOL
  → determination of the effectiveness of the divertor configuration
- Parallel particle flow dynamics give information about the predominant flow directions of main plasma ions and impurities, and is a direct representation of convective heat transport
  → investigations of parallel particle flows can help in understanding the SOL physics
- Comparison with attached and detached plasma scenarios helpful for a thorough analysis

2. MAIN TOOL: COHERENCE IMAGING SPECTROSCOPY

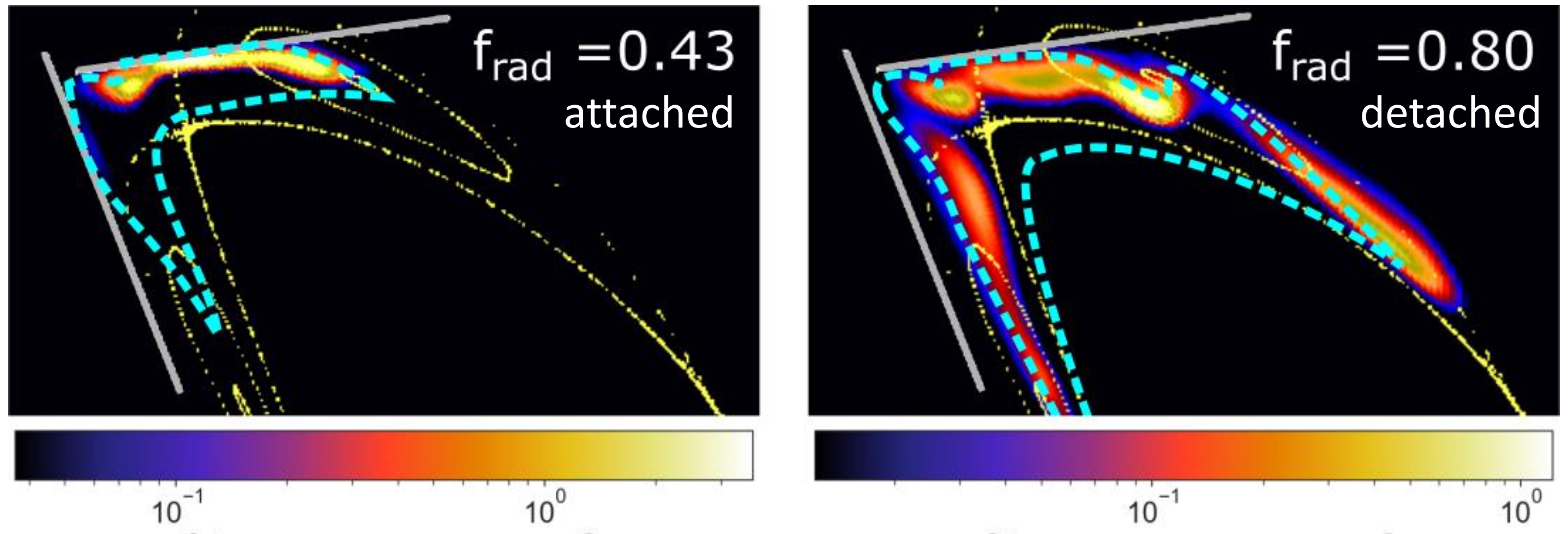
- At W7-X: possible to monitor impurity behaviour with the Coherence Imaging Spectroscopy (CIS) diagnostic
- Main characteristics of the W7-X CIS measurements:
  - 2D images of line emission intensity and flow velocity of a selected particle charged state
  - Passive measurements of C^{2+} impurity in hydrogen plasmas throughout the entire last operational campaign (OP1.2b, year 2018)
    → line-integrated measurements restricted to the SOL by the temperature dependence of the C^{2+} emission, which peak for $T_e \approx$ 10-20 eV

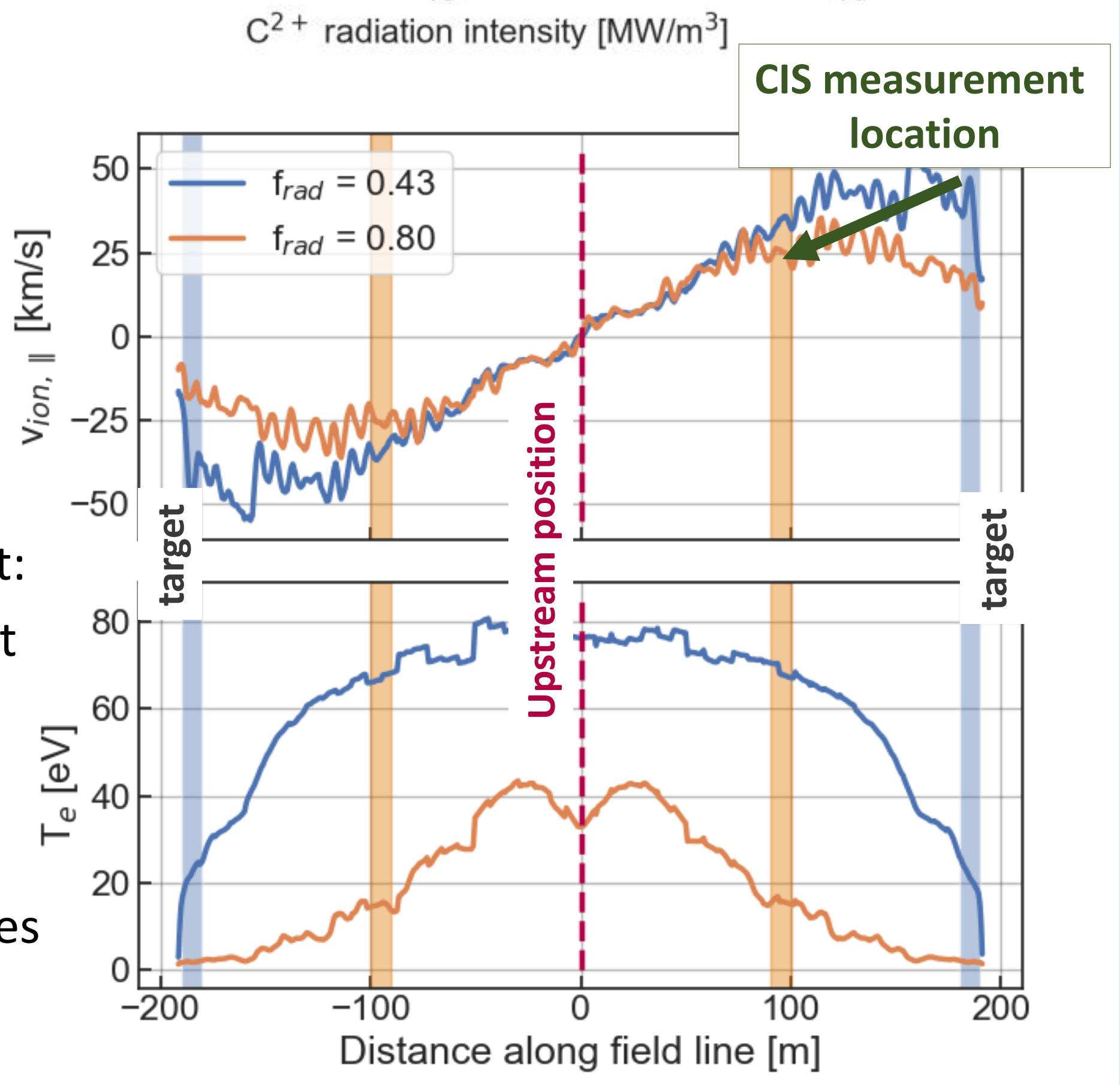


Example of CIS measurement (C^{2+} impurity, attached scenario)

4. C^{2+} IMPURITY AND MAIN ION COUPLING

- Temperature range for observation: 10-20 eV → same as for ionisation of hydrogen
- EMC3-EIRENE simulation: identification of locations of hydrogen ionisation (dashed cyan lines) and of C^{2+} impurity radiation (colourmap)





→ C^{2+} radiation is always between H ionisation and divertor targets (in radial direction)

→ Friction force scenario for C^{2+}, i.e. impurity is a good proxy for main ions

- Movement of radiation due to change in plasma parameters (e.g. T_e)
- Along open magnetic field line in detachment:
  - Shallow T_e profile between radiation front (orange highlight) and target
  - Flattening of $v_\parallel$ in the same region

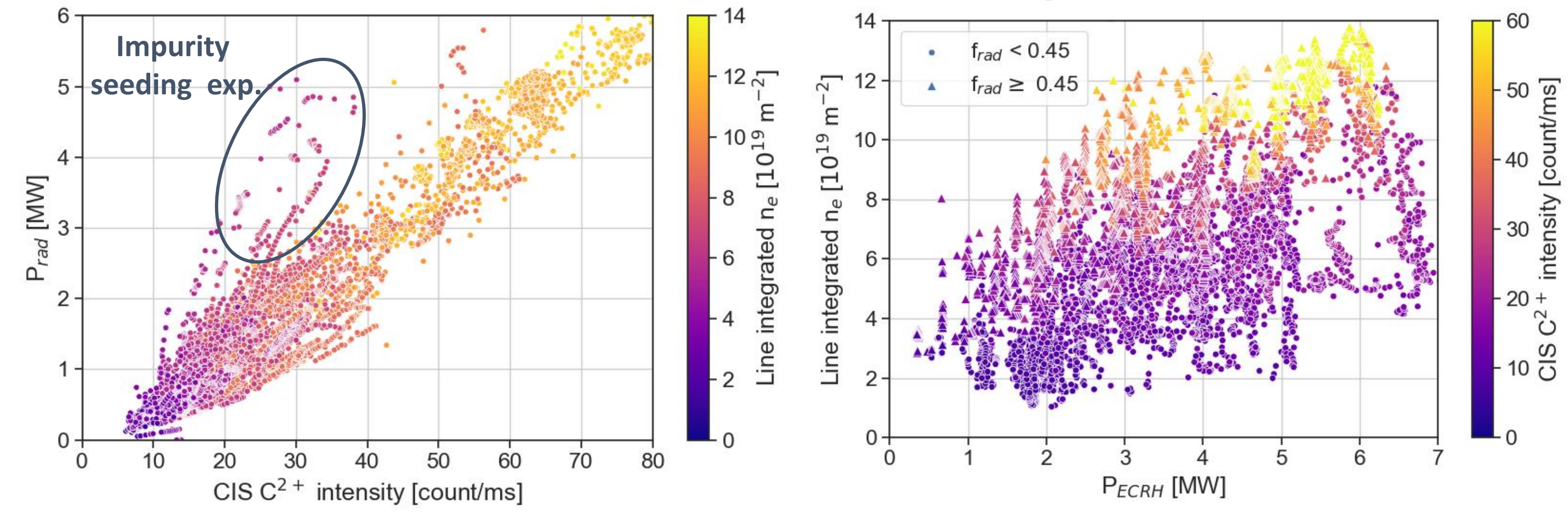
→ Movement of radiation changes CIS measurement location but the flat $v_\parallel$ ensures that the CIS results are still representative for what happens in the divertor area

6. CONCLUSIONS

- C^{2+} impurity radiation and flow velocity measured by CIS show clear dependencies on plasma parameters, in particular P_{rad} and n_e
- C^{2+} flow velocities respond to density increase in both attached and detached plasmas, but in opposite ways
- C^{2+} flow velocities tendencies can be explained with 1D fluid model, characterized by the major role of ionisation in the SOL: any change in the source term causes a change in velocity
- Main assumption: constant cross-field transport with plasma parameters change → limits of validity to be assessed with future modelling
- With help of EMC3-EIRENE: use of CIS velocity measurements to quantify the convective contribution to the heat transport

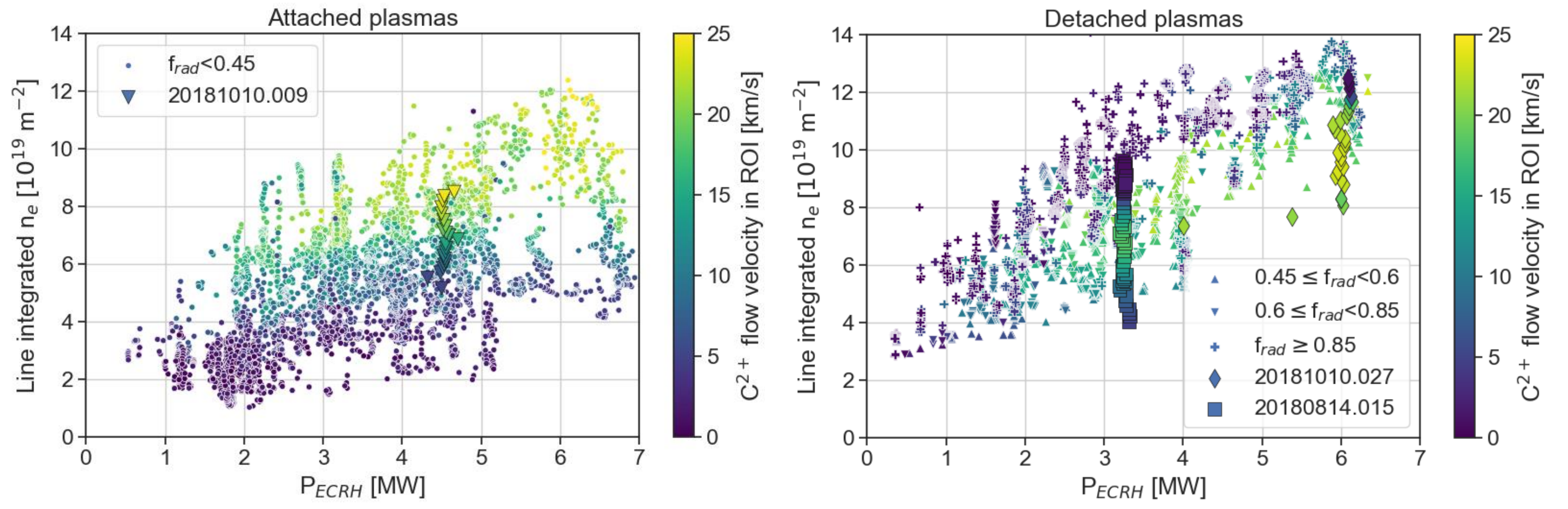
3. CIS OBSERVATIONS

- Data: full OP1.2b (year 2018) after boronization in one magnetic configuration (standard)
- C^{2+} radiation: well coupled with radiated power $P_{rad} \propto n_e n_{imp}$



→ Carbon main radiator in W7-X (apart from impurity seeding experiments), clear dependence on electron density n_e, no direct dependence on input power P_{ECRH}

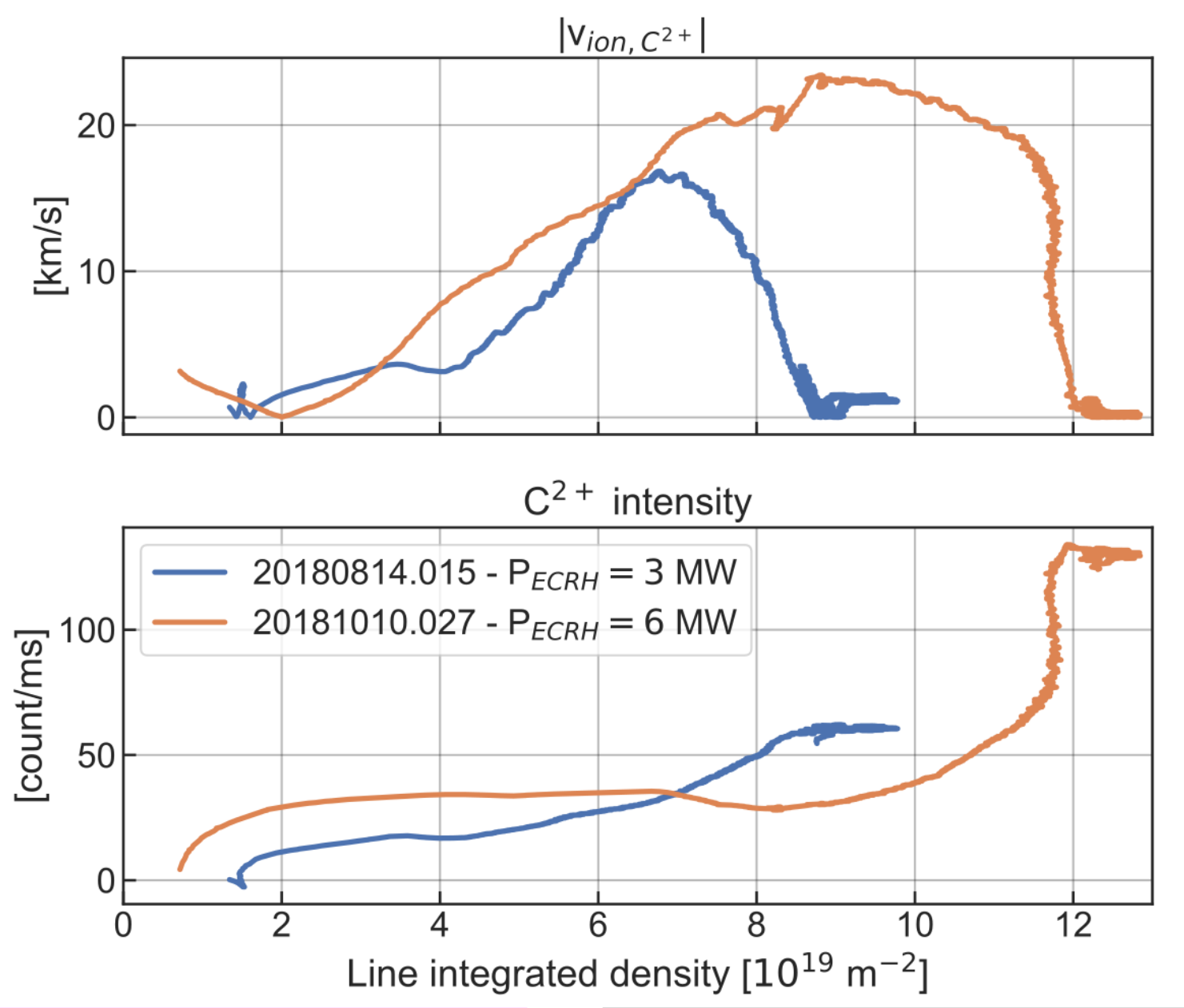
- C^{2+} velocity: clear difference in behaviour in attached and detached plasmas

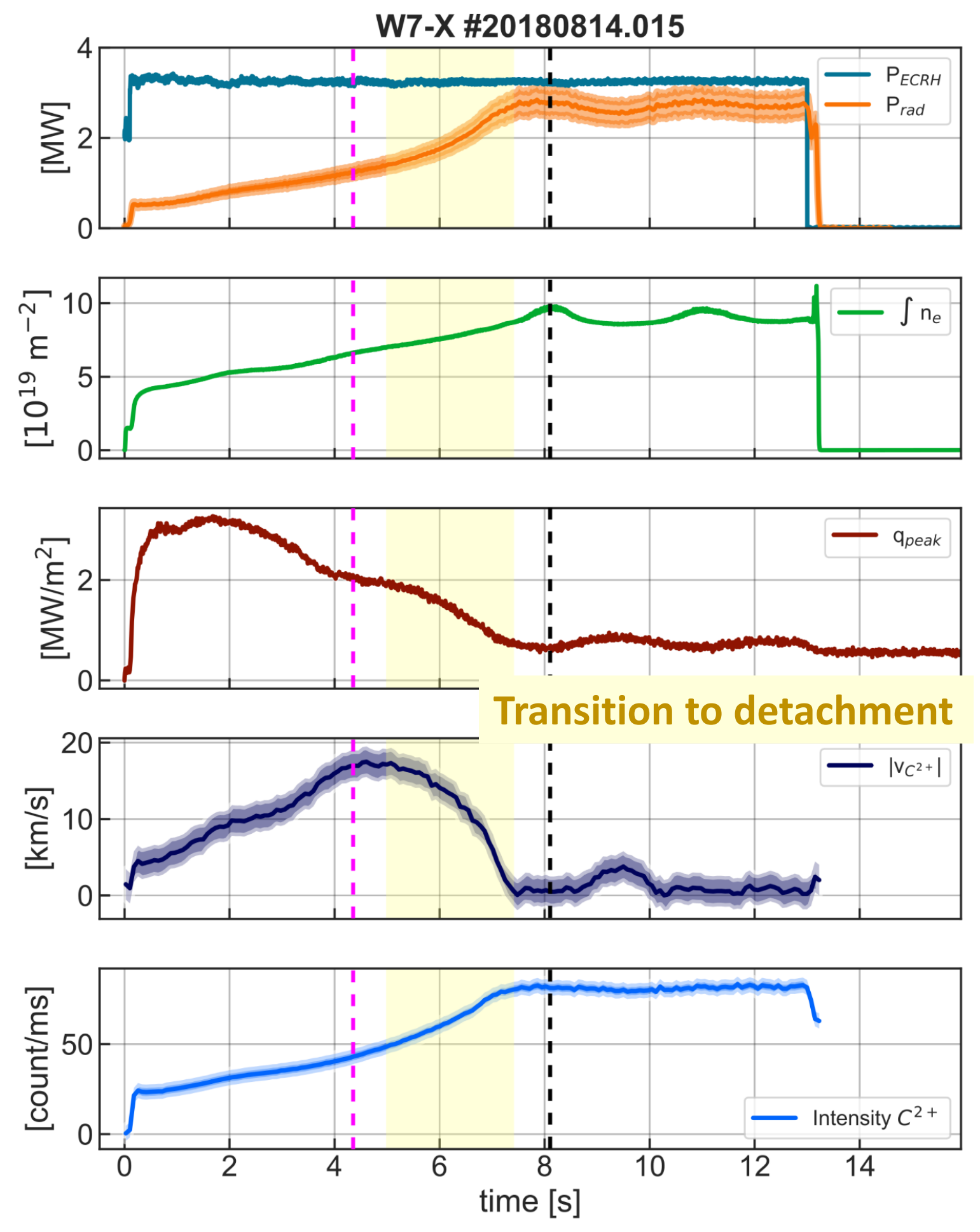


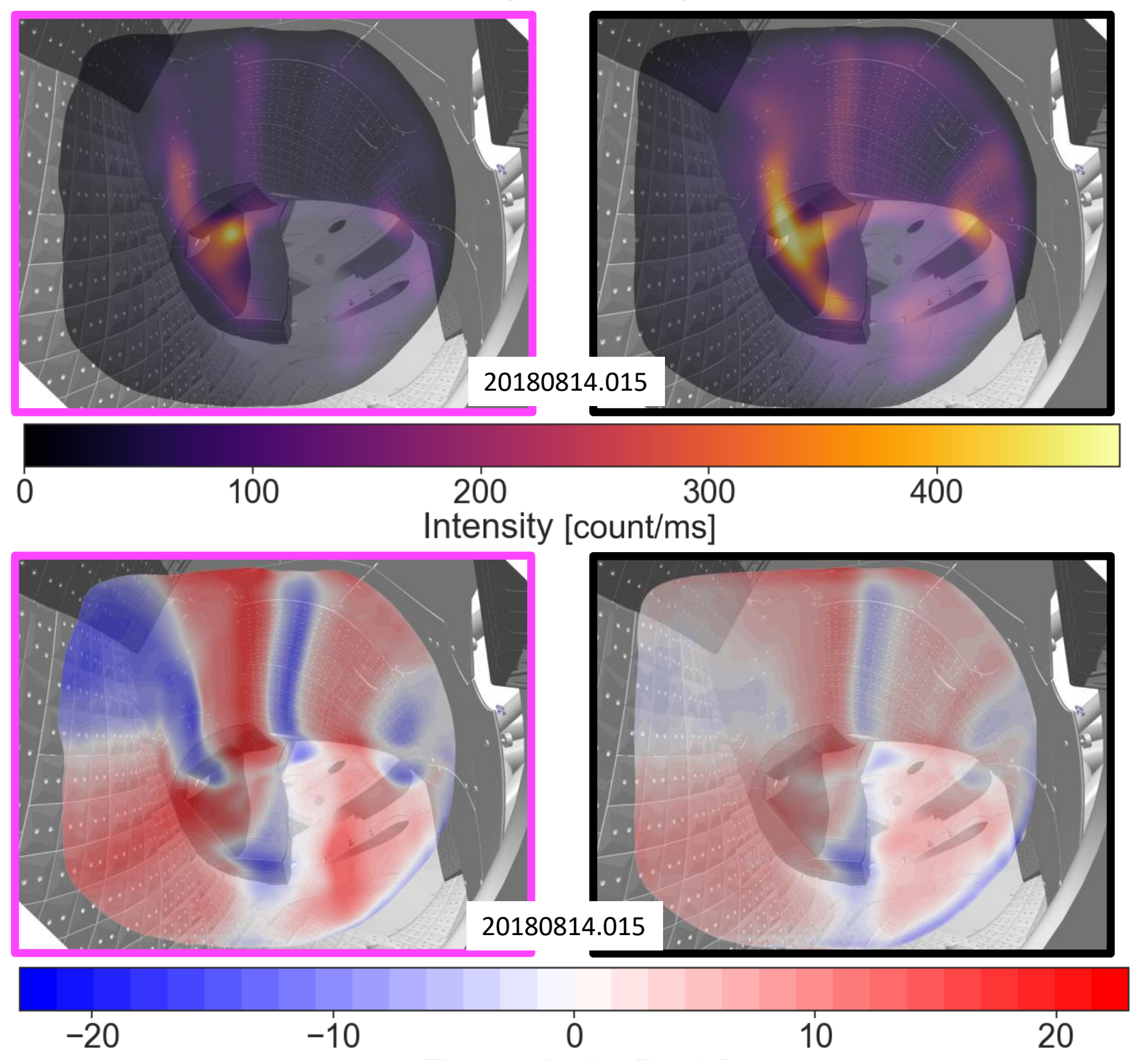
→ Attachment: C^{2+} velocity increases with increasing n_e while staying insensitive to P_{ECRH}

→ Detachment: C^{2+} velocity decreases with increasing n_e, drop $\propto P_{rad}$

- Roll-over of velocity and increase in radiation intensity: well correlated to detachment
- n_e for detachment transition depending on input power → visible with CIS as well







5. PHYSICS INTERPRETATION OF VELOCITY BEHAVIOUR – 1D MODEL

- Thanks to C^{2+} impurity and main ion coupling in the region probed by CIS→ explanation of CIS measurements with respect to main ions $v_\parallel$ (simple 1D fluid model)
- Continuity equation in steady state along magnetic field lines (x-direction) & $n = n_i = n_e$:

$$\frac{d(nv_\parallel)}{dx} = \bigcirc\!\!\!\!\!S_i \quad \text{ionisation source}$$

- Main assumption: constant cross-field transport
- S_i regulated by SOL global power balance

$$P_{in} = \underset{\text{deposited on targets}}{P_t} + \underset{\text{interactions with neutrals (including ionisation)}}{P_{\varepsilon_i}} + \underset{\text{radiated}}{P_{rad}}$$

- $P_{\varepsilon_i} = \varepsilon_i n\, v_\parallel$ with ε_i energy cost for interactions
- In detachment: P_t negligible

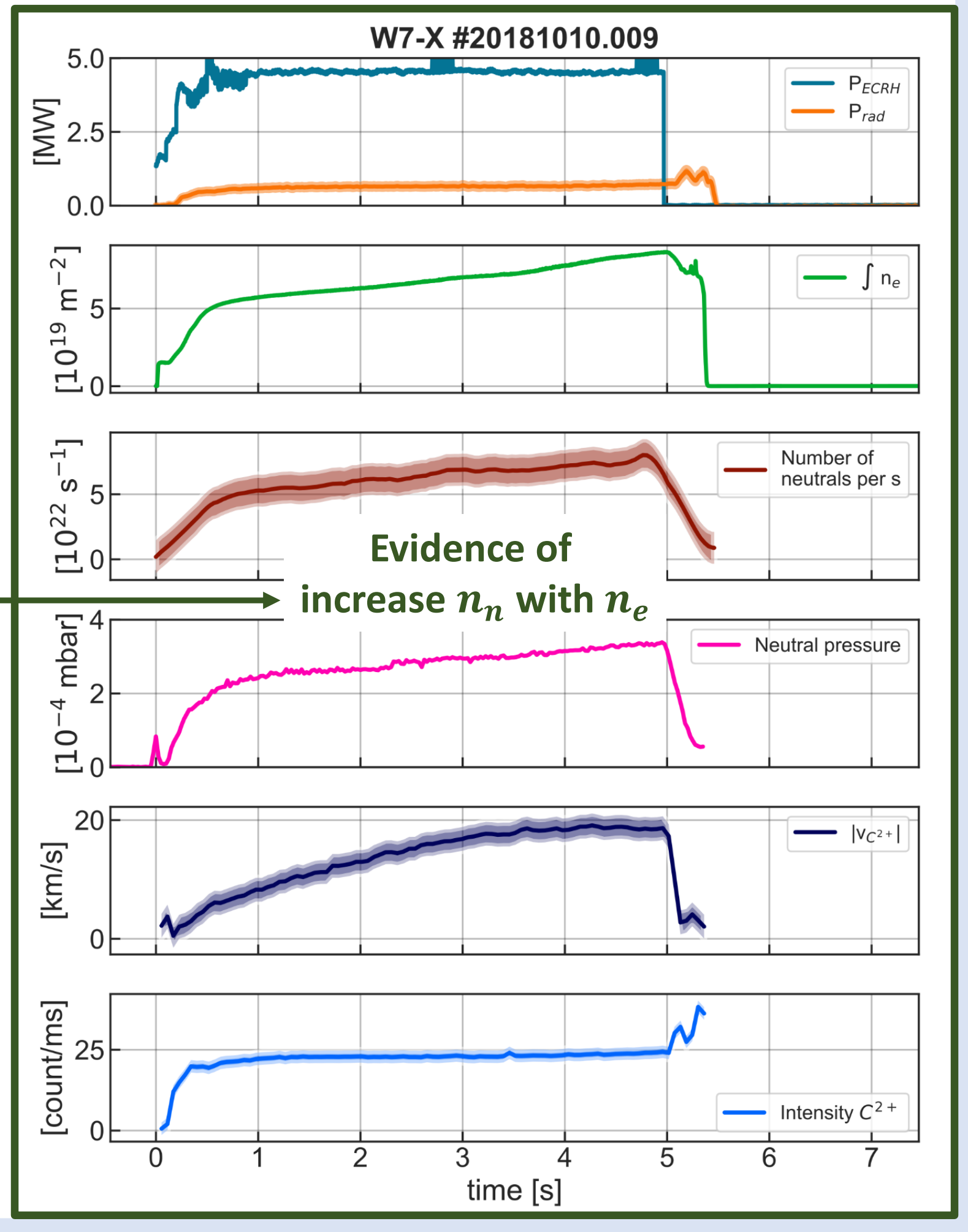
$$v_\parallel \cong \frac{1}{n}\frac{P_{in}-P_{rad}}{\varepsilon_i}$$

→ With increasing P_{rad}, decreasing $v_\parallel$

- In attachment: no easy way to interpret the power balance, for density dependence → S_i definition

$$S_i = n\, n_n\overline{\sigma v_e} \sim Cn^2\overline{\sigma v_e}$$

→ $\frac{d(nv_\parallel)}{dx} \sim Cn^2\overline{\sigma v_e}$ → with increasing n, increasing $v_\parallel$



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