Max-Planck-Institut für Plasmaphysik

Overview of the results from the divertor experiments at Wendelstein 7-X and their implications for steady-state operation

Marcin Jakubowski for the W7-X Team

MAX PLANCK GESELLSCHAFT

EUROfusion

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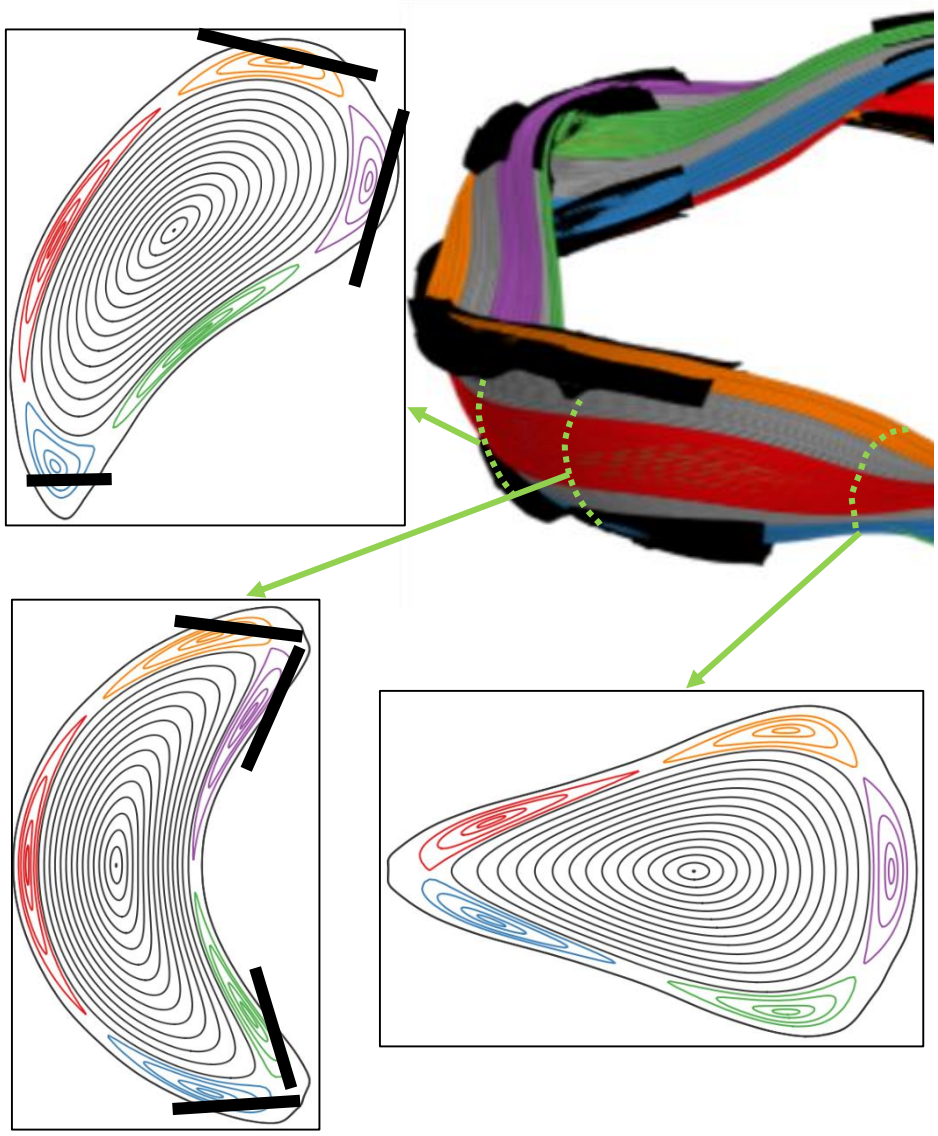
Outline of this presentation

- **Main features of the island divertor**
- **Attached plasmas**
- **Steady-state compatible, complete detachment**
- **Summary**

Island divertor: exhaust for helical plasma

W7-X wants to demonstrate **high power, high performance at steady-state** [1]
10 separate divertor units, adapted to the shape of the flux surfaces

Large magnetic islands (standard: 5/5) form so-called **island divertor**.
Resonant islands require error field correction [2,3]



[1] T.S. Pedersen, this conference
[2] S. A. Bozhenkov *et al.*, Nucl. Fus. **57**,126030 (2017)
[3] S. A. Lazerson *et al.*, Nucl. Fus. **57**, 046026 (2017)

Island divertor: exhaust for helical plasma

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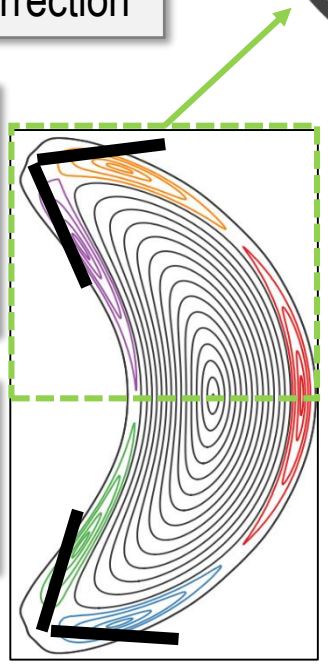
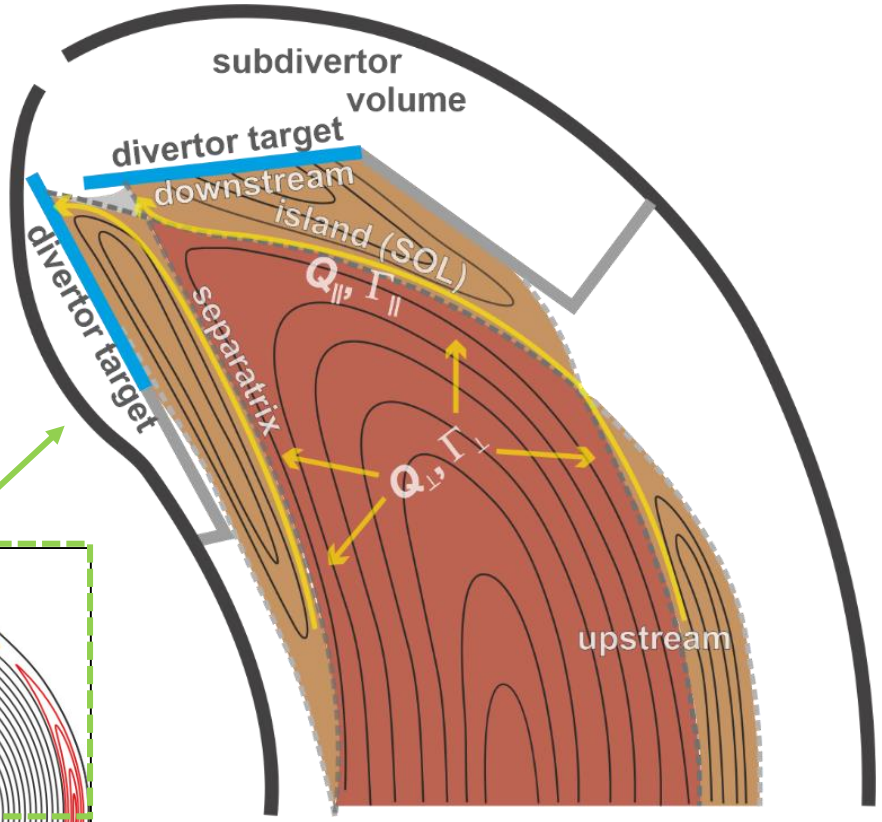
10 separate divertor units, adapted to the shape of the flux surfaces

Large magnetic islands (standard: 5/5) form so-called **island divertor**.
Resonant islands require error field correction

Open field lines guide ions lost from the confined plasma to the divertor target (**scrape-off layer**)
Island divertor features ExB drifts [1]

Neutral compression provided by neutrals **recycling** near the divertor target

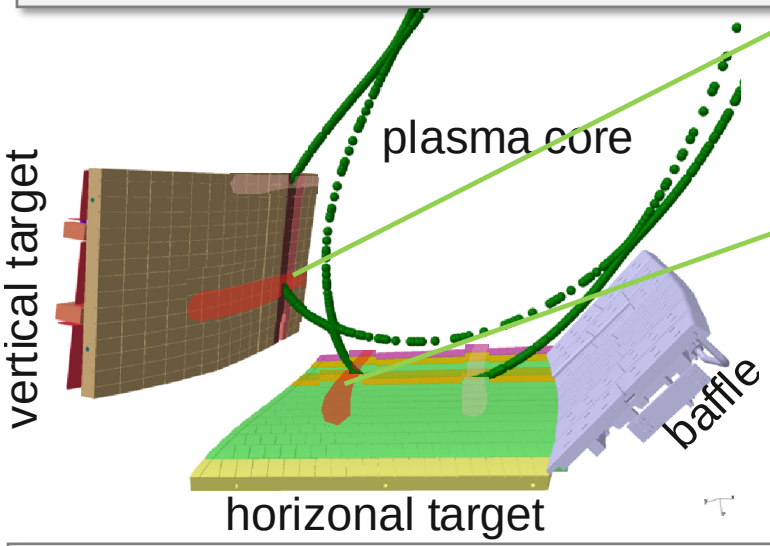


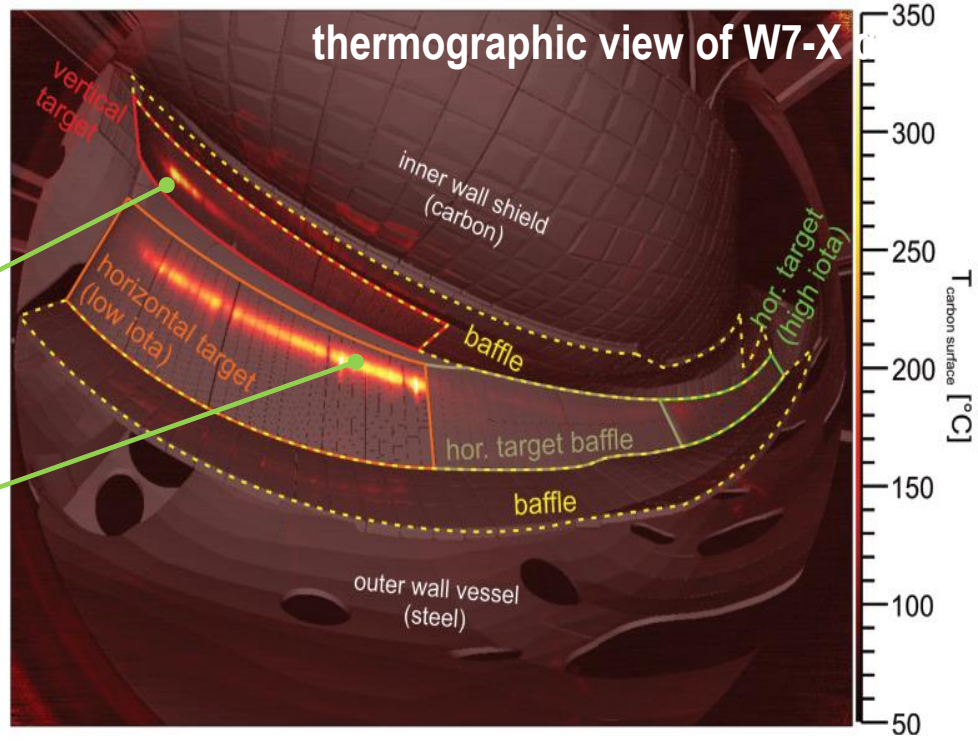


[1] K. C. Hammond *et al.*, PPCF **61**, 125001 (2019)

Three-dimensional strike line of the island divertor

- Island divertor at W7-X in **standard configuration** forms **two strike-lines** on horizontal and vertical target [2,3].
- Strike lines may be affected by toroidal currents [1-3]





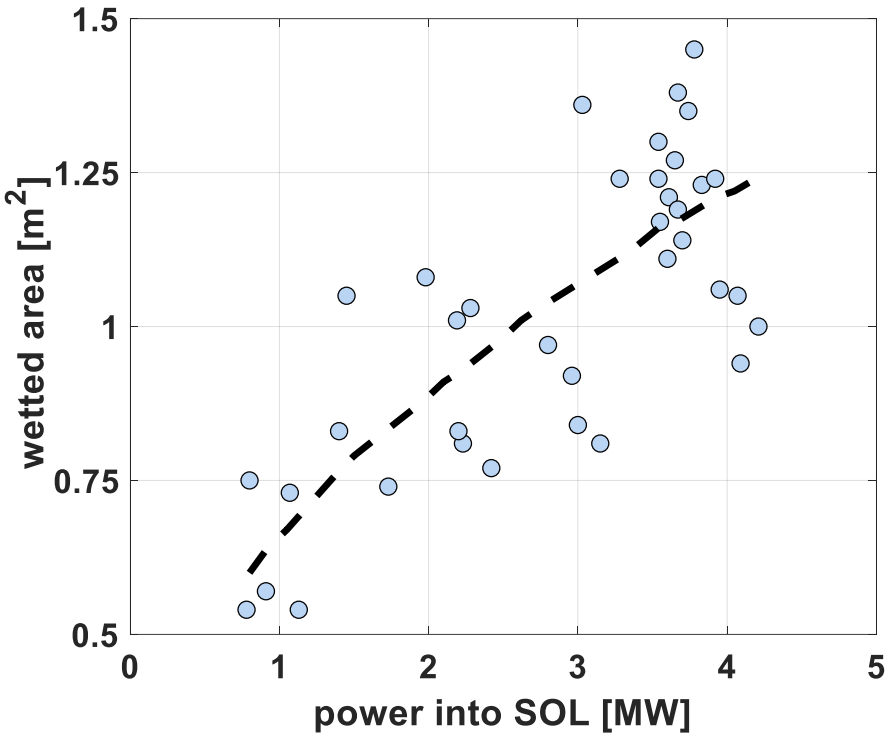
How well island divertor can **spread power** on the **divertor surface**? W7-X will operate with up to **30 minutes of plasma duration** with 10 MW of heating with technical limit of the divertor heat flux at 10 MW/m^2.

[1] A. Dinklage, this conference, [2] Yu Gao et al 2019 Nucl. Fusion 59 106015(2019),
[3] T. S. Pedersen *et al.*, Nuclear Fusion **59**, 096014 (2019)

Island divertor allows efficient heat flux spreading

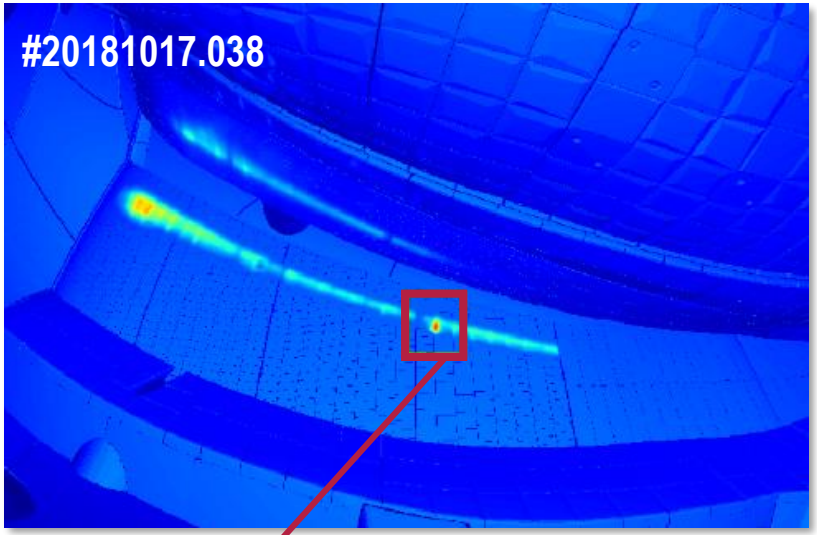
- Wetted area A_{wet} is ratio of heat absorbed by the divertor (in eg. MW) to peak heat flux (in eg. MW/m^2)
- The allowed peak heat flux of the HHF divertor is 10 MW/m^2
  ➔ If P_{SOL} ~ 8 MW so A_{wet} > 0.8 m^2
- **Positive scaling with SOL power observed for attached plasmas**
  $\boldsymbol{A_{wet} \sim P_{SOL}^{0.44}}$

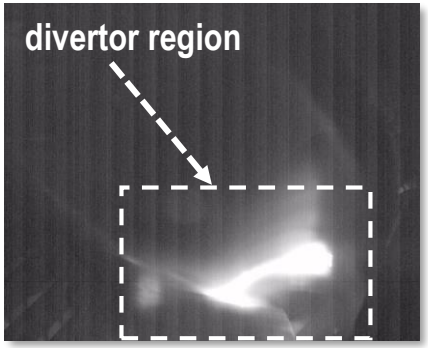
W7-X (standard): < 1.5 m^2 [1]
JET (L-mode): <1.6 m^2 [2]
ASDEX Upgrade (L-mode): < 0.8 m^2 [3]



[1] H. Niemann *et al.*, Nucl. Fusion 60 (2020) 084003
[2] T. Eich, et al., JNM 415 (2011) S856, [3] B. Sieglin, et al., PPCF 58

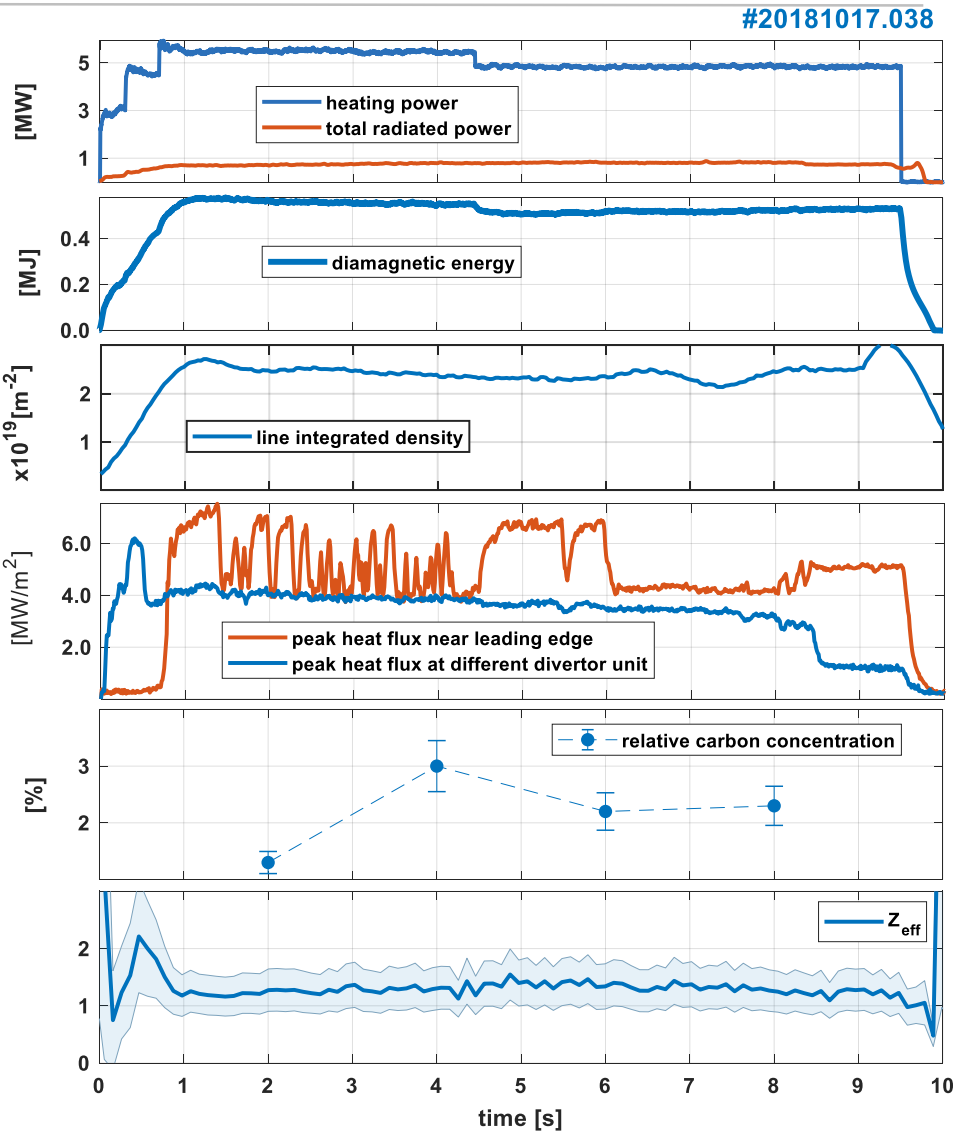
W7-X plasma is resilient to strong influx of impurities





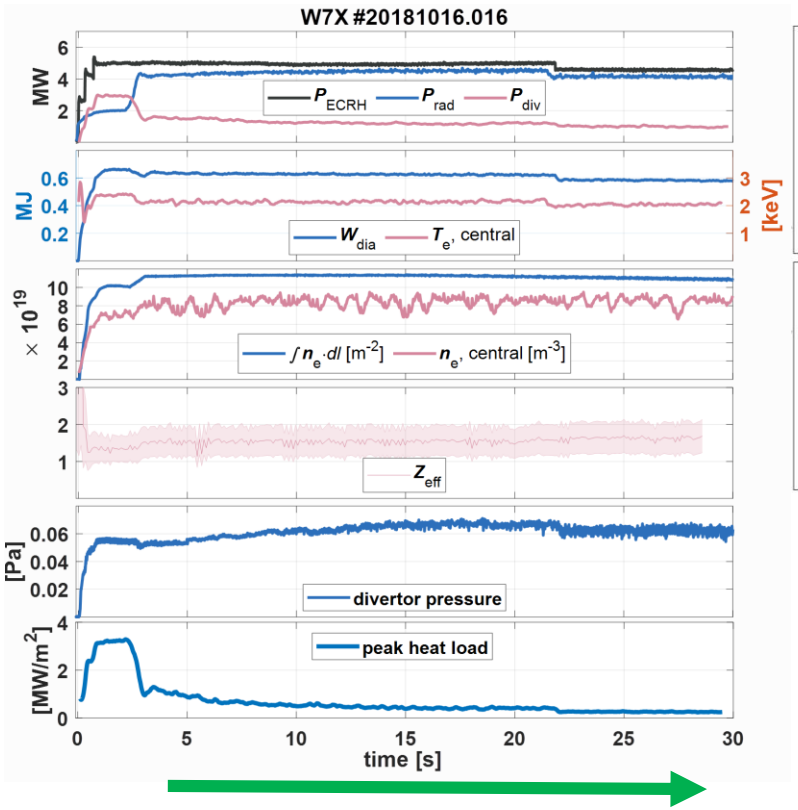
[M.W. Jakubowski, et al., PSI 2020]

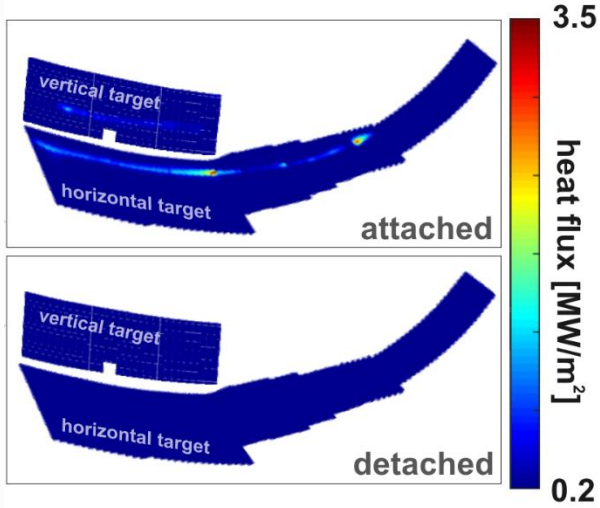
[S.Brezinsek, this conference]



Stable detachment regime

- Radiated power fraction of 80-90%
- Drop in diamagnetic energy $\lesssim$10 %
- Constant $Z_{eff} \approx 1.5$
- Sufficient sub-divertor pressure
- Virtually no convective loads to the target.





detachment

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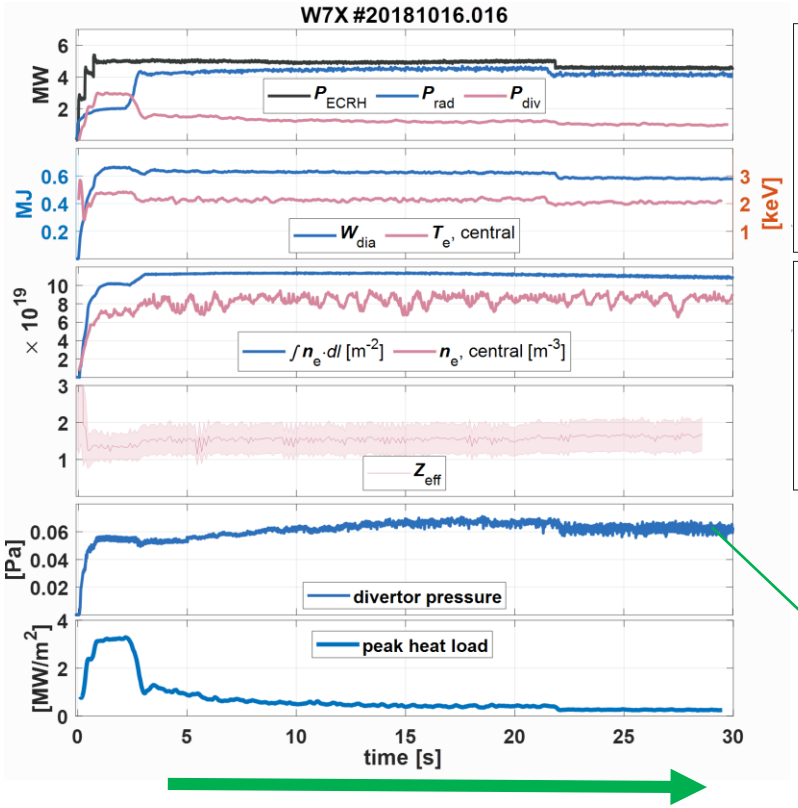
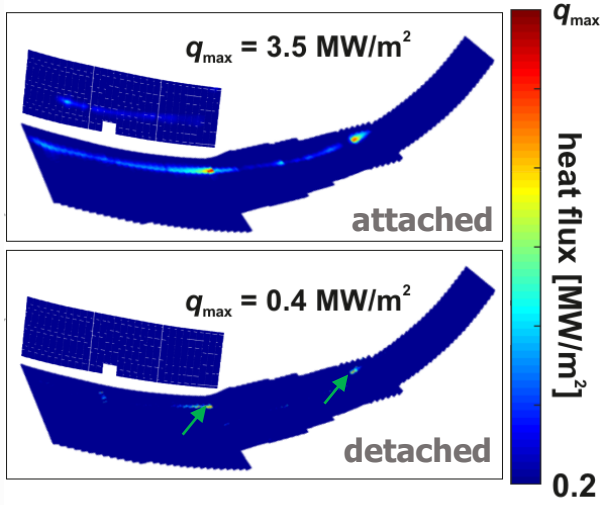
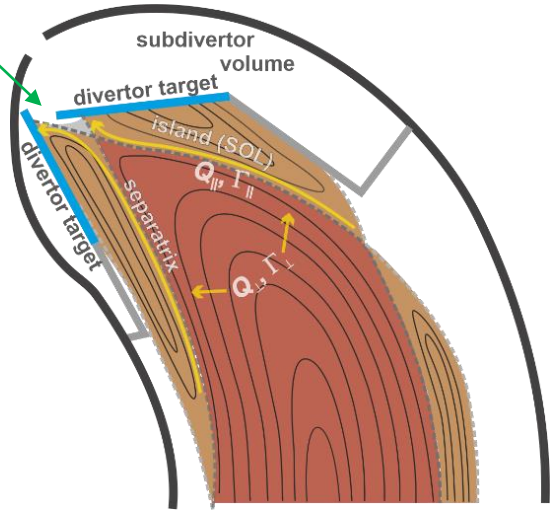


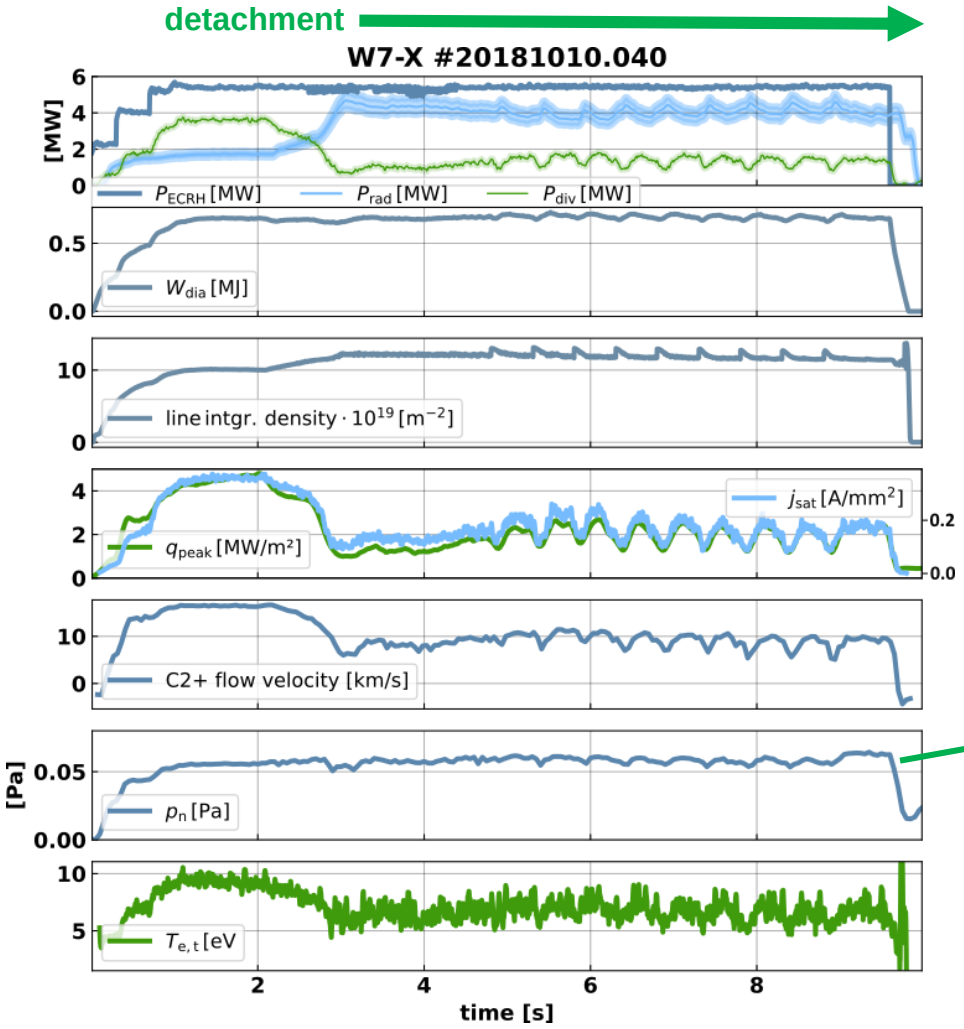
detachment

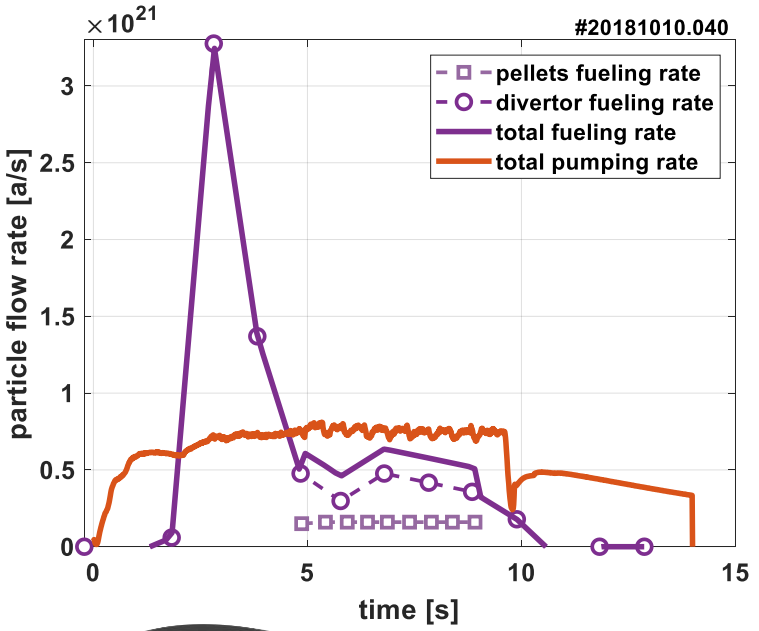


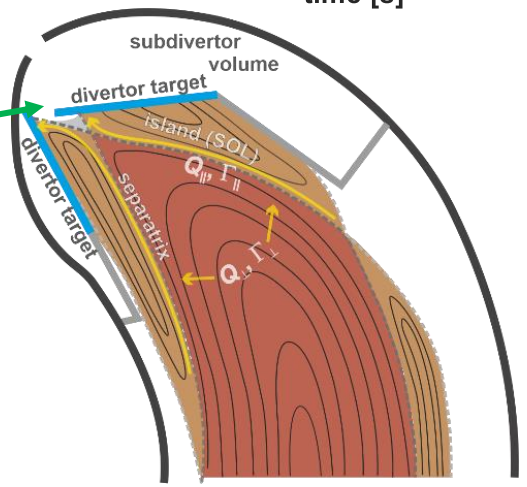


[O. Schmitz, et al., Nucl. Fusion 61 (2021) 016026]

Neutral pressure sufficient for steady-state density control at W7-X

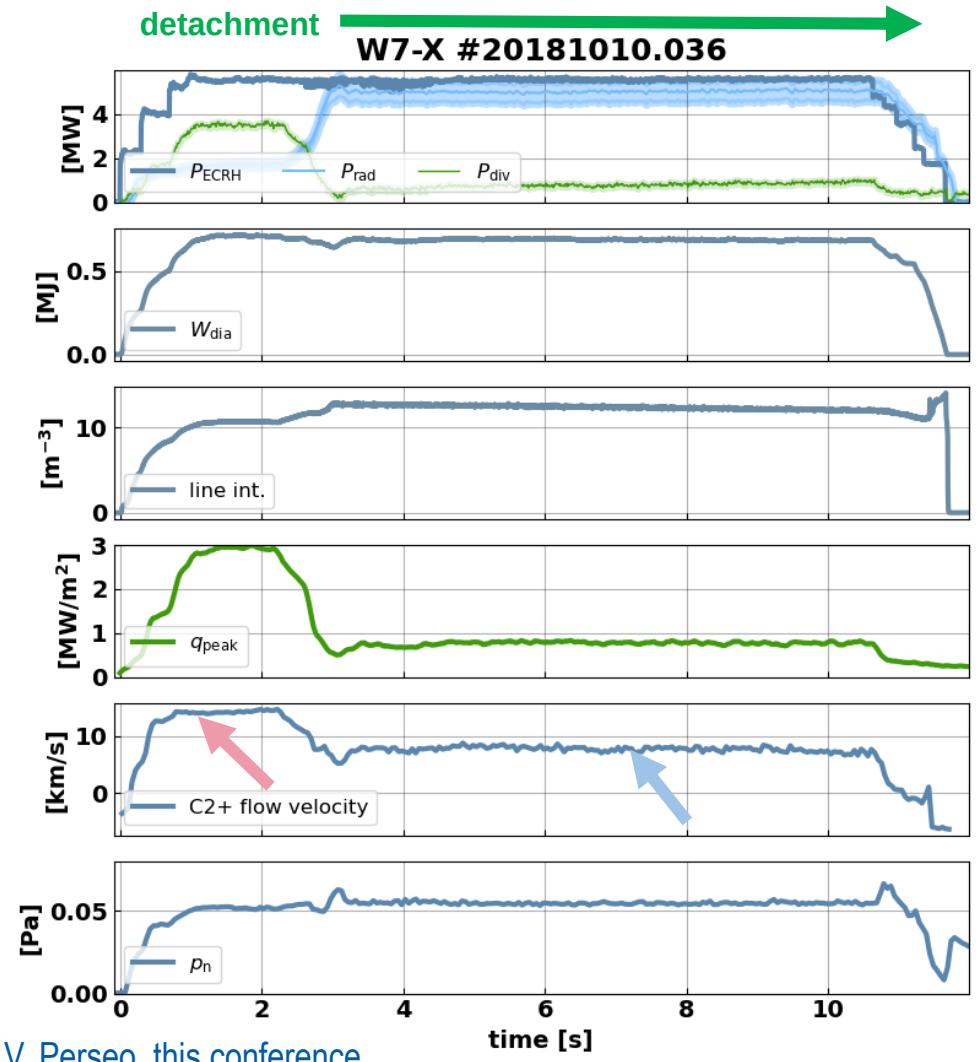


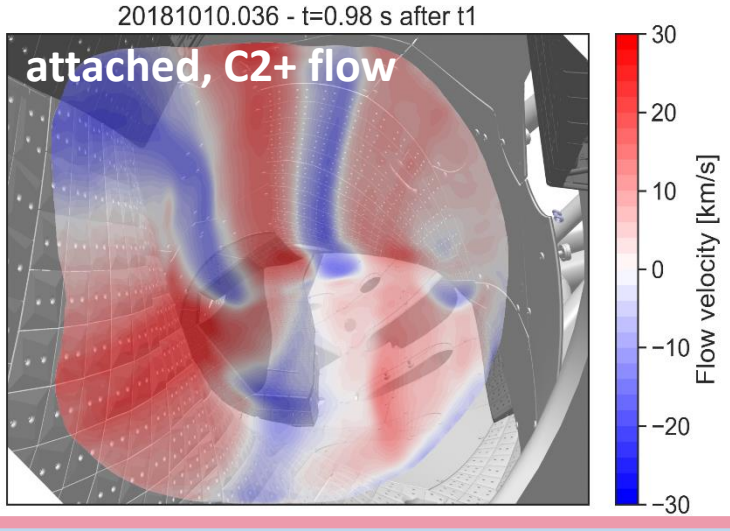


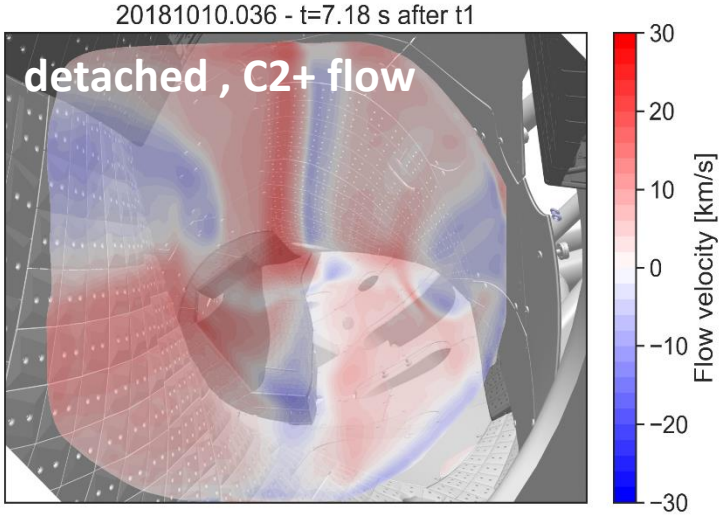


See also [G. Schlisio *et al.*, Nuclear Fusion **61**, 036031 (2021)]

Plasma flows en-route to detachment

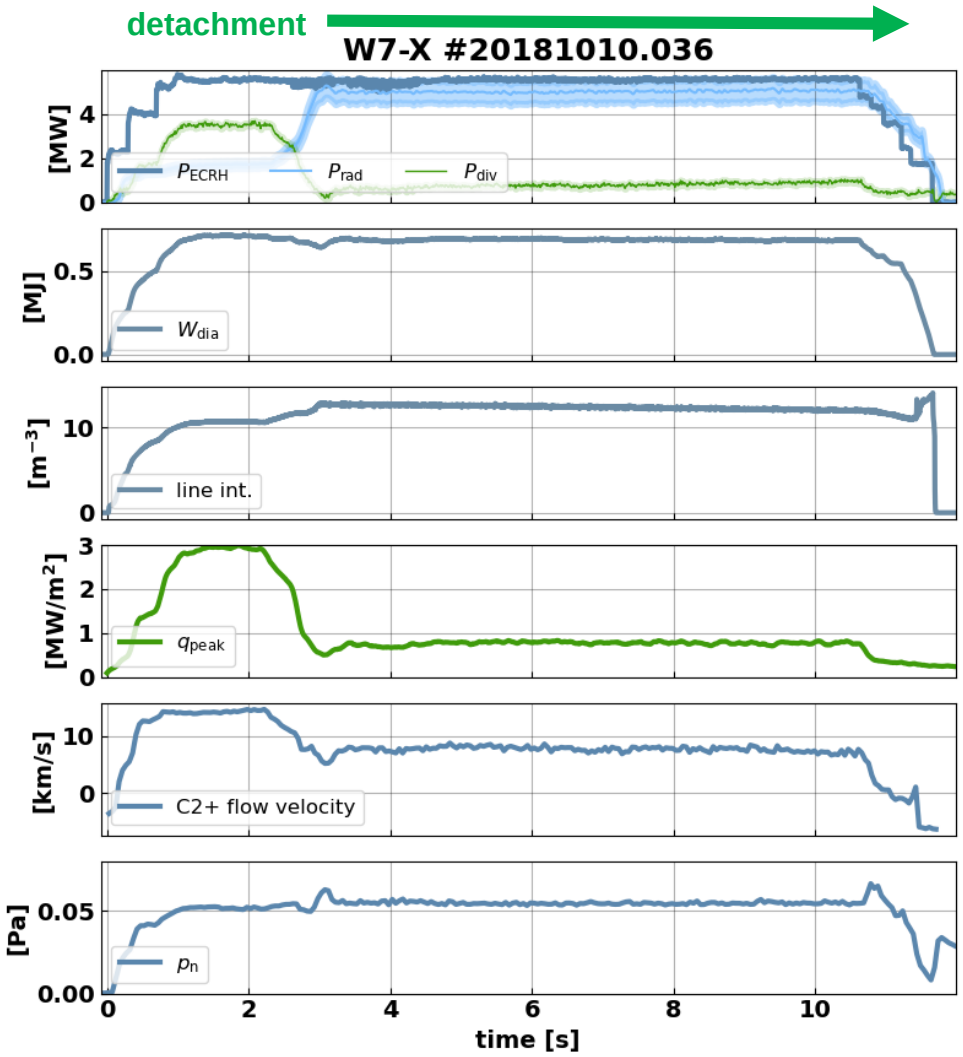


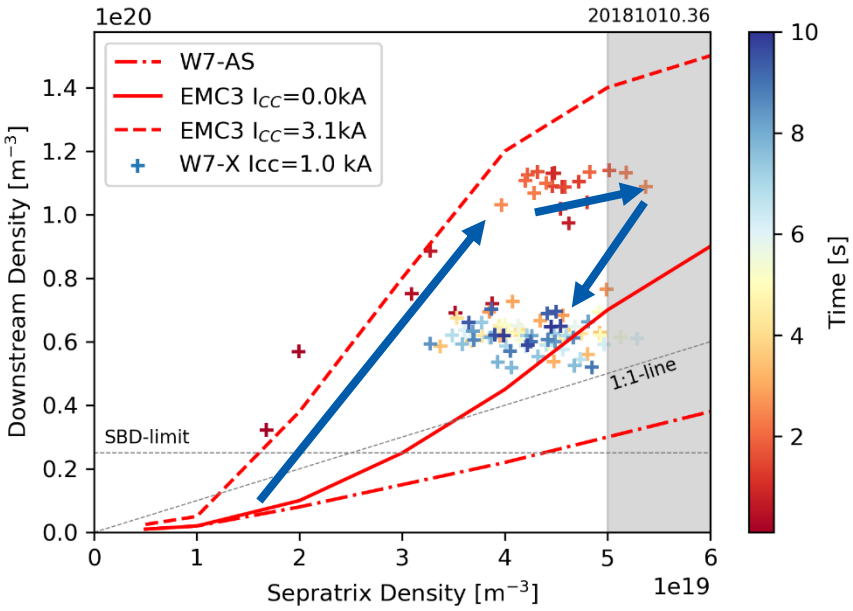


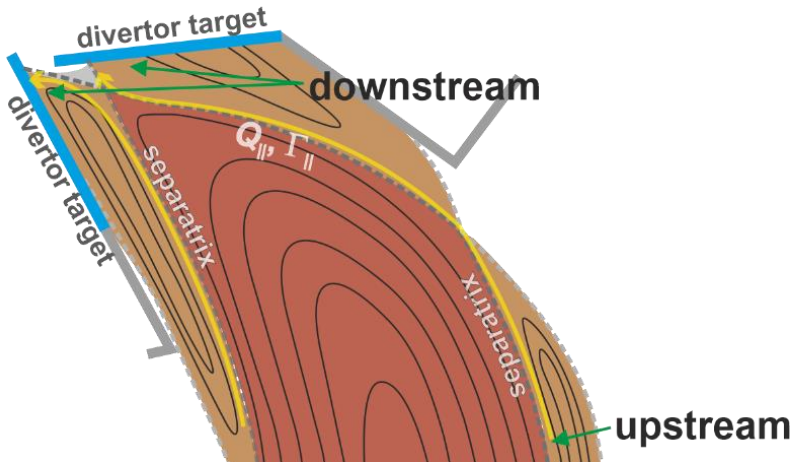


V. Perseo, this conference,
[V. Perseo, et al., Nuclear Fusion **59**, 124003 (2019)]

Higher recycling on transition to detachment





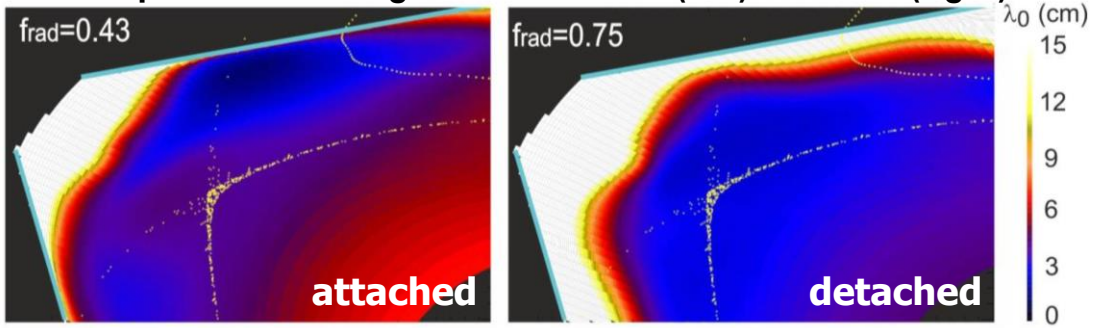


F. Reimold, this conference

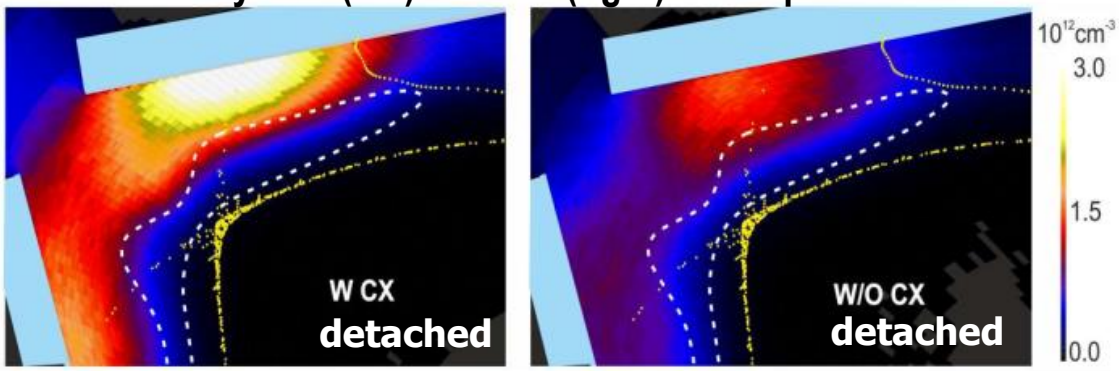
Distribution of neutrals defines neutral influx $\Gamma_{in,\,H^0}$ into pumping domain

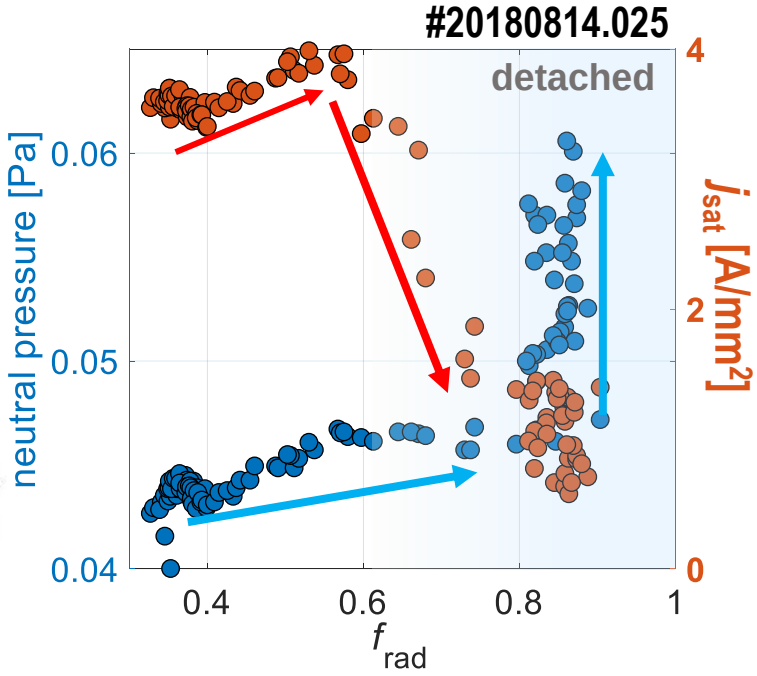
EMC3-Eirene, Y. Feng, NF (submitted)

neutral penetration length at frad = 0.43 (left) and 0.75 (right)



neutral density with (left) and w/o (right) CXRS processes





$$\lambda_0 = v_{ith}/n\sqrt{<\sigma v>_{CX}<\sigma v>_i}$$

Two effects increase neutral pressure:

1. Longer penetration length mainly due to lower plasma temperature (5 eV) in the islands
2. CXRS processes between fast ions coming from upstream and slow neutrals downstream.

Summary

- **Wendelstein 7-X** demonstrated that **island divertor** is an attractive exhaust concept.
- In attached state
  - We can efficiently spread heat with **wetted area of up to 1.5 m^2** Moreover it **increases with P_{SOL}**.
  - **Overloading divertor** leading edge showed that **plasma core is robust against impurity** accumulation.
- **En-route to detachment** we observed **higher recycling regime**. This has been enabled by **good separation of counter-streaming flows** in the island divertor.
- **Stable (≤ 26 s), complete detachment** in many scenarios was achieved