Assessing simple models for density build up & impurity exhaust in the island divertor of W7-X

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Wendelstein 7-X

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1. ABSTRACT

Stable, detached divertor plasmas were demonstrated in W7-X [1,2,3,4]. These plasma also showed particle exhaust that enables high density steady-state operation and provided good impurity retention [5]. Hence, the initial results from W7-X operation show a potential of the island divertor concept used in W7-X for a reactor.

Measurements show the existence of a high-density divertor regime in W7-X not observed in the predecessor W7-AS [6,7]. Achieved neutral divertor pressures so far have been limited to low values of < 0.1Pa. Given its crucial role as a design parameter of the ITER divertor [8] and its exhaust regime the understanding of the density build-up in the island divertor is crucial to assess the particle exhaust properties and their scaling towards a reactor device, in particular for He-ash.

Simplified models and comparison to modeling is used to assess their applicability to the W7-X data. The model [2] implies a crucial role of the pressure loss factors and the island fieldline pitch Θ.

2. ROLE OF DENSITY

Particle & Power Exhaust

- Radiated power scales with density (unseeded conditions)

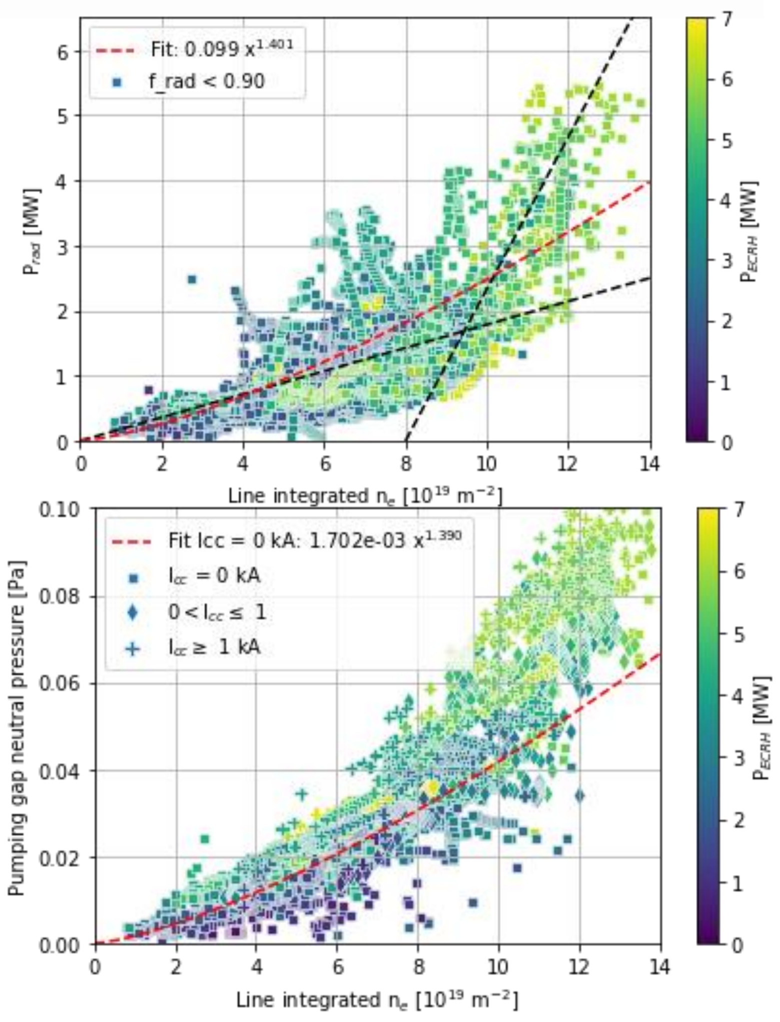
$$P_{rad} \propto 0.1\, n_{e,int}^{1.4}$$

- Neutral pressure scales with density

$$p_{div} \propto 1.7 10^{-3}\, n_{e,int}^{1.4}$$

Impurity Exhaust

- Density threshold for friction force-dominated parallel transport regime [9]
- Decreased ionization mfp
- Increased entrainment & pumping
  → better retention & exhaust



Exhaust parameter scalings with line-integrated density.

3. DENSITY SCALING

Spectroscopic density measurement in density ramp experiments

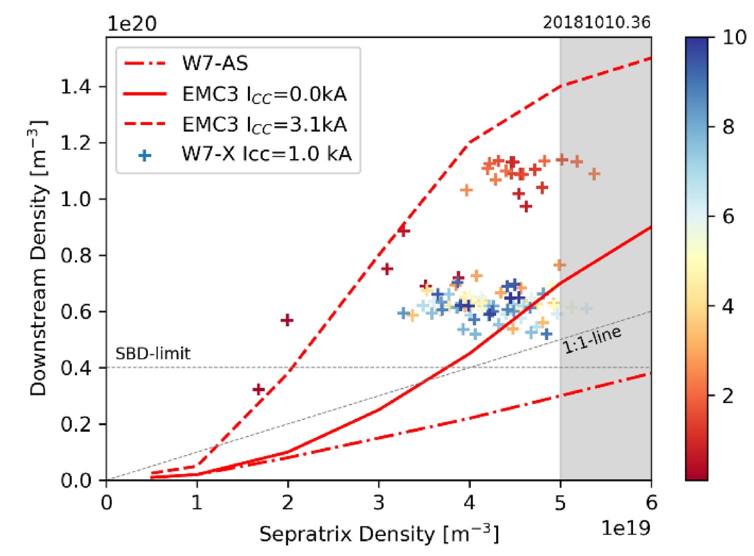
- Density ramp experiments using a feedback controlled gas puff system.
- Density measurement via Stark broadening of Balmer n=6-2 transition.
- Valid down to 2.5x 10^{19} m^{-3}.

Main observations

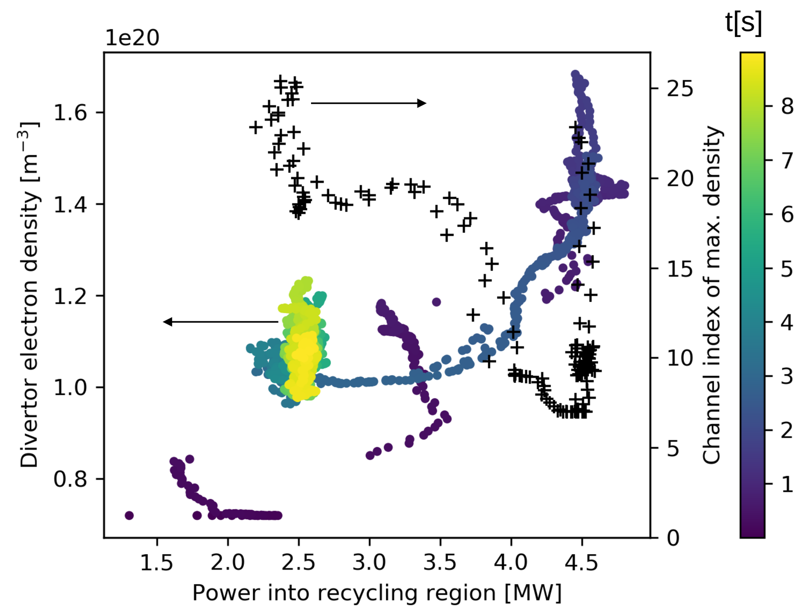
- High divertor densities measured by spectroscopy (10^{20} m^{-3}) with $n_{div} > n_{up}$

$$n_{div} \approx 3 n_{up}$$

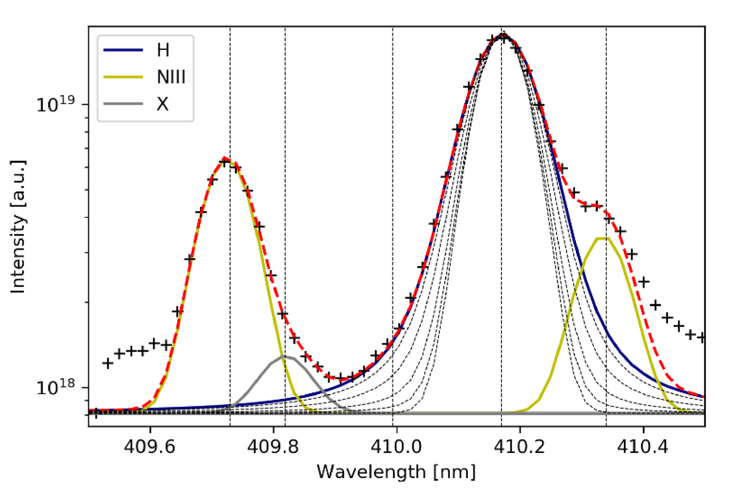
- High neutral retention with decreased compression during detachment
- Divertor density roll-over consistent with power starvation



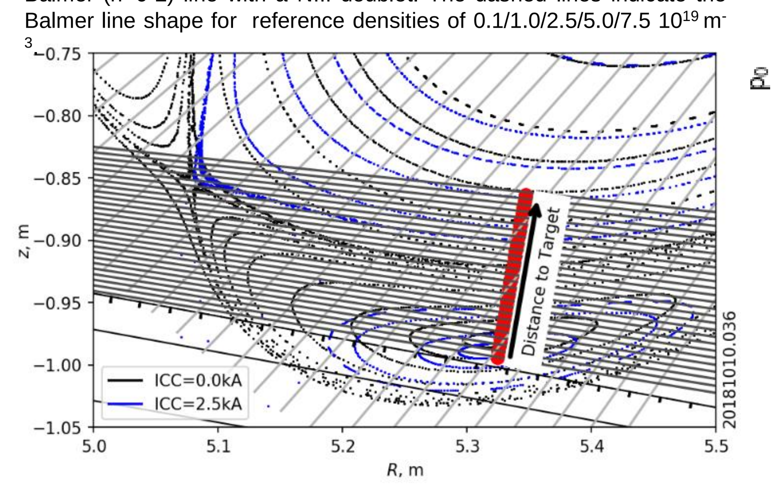
Divertor density evolution. Red curves are modelling predictions for W7-X and W7-AS from EMC3.



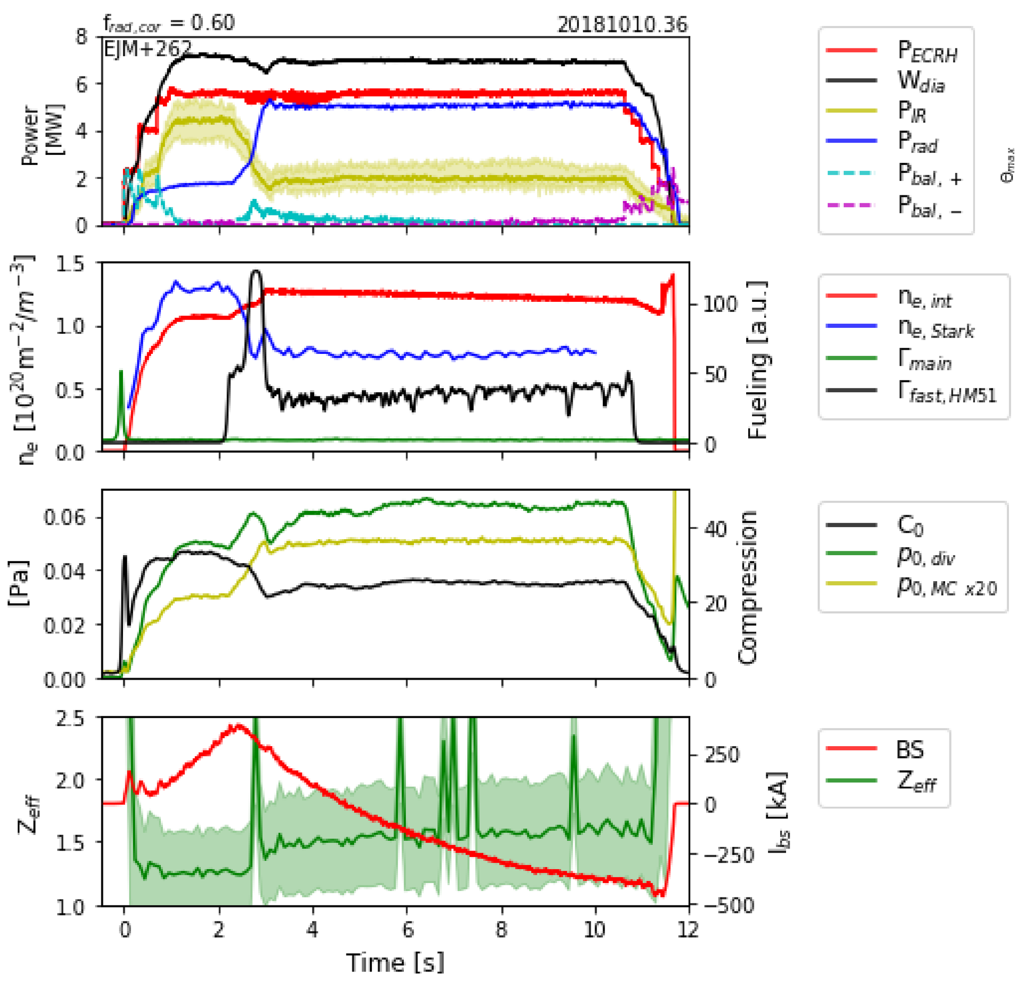
The maximum divertor density scales with power into the divertor ($P_H - P_{rad}$). The black crosses show the LOS index of the measured maximum density.



Balmer (n=6-2) line with a NIII doublet. The dashed lines indicate the Balmer line shape for reference densities of 0.1/1.0/2.5/5.0/7.5 10^{19} m^{-3}



Line-of-sight viewing geometry of divertor spectroscopy system. The magnetic equilibrium of the standard configuration is shown for two different control coil currents (black, blue).



Discharge parameters of 20181010.36. A detachment experiment with constant heating power using a feed-back density ramp to detach the targets.

4. SIMPLIFIED MODELS

Stellarator specific aspects

- Long connection length (L_c=1km) & low island field line pitch (Θ = 10^{-3}-10^{-2})
- Importance of cross-field transport:

$$\Theta\frac{d}{dx}\left(-\kappa_e T^{\frac{5}{2}}\Theta\frac{dT}{dx}\right)+\frac{d}{dx}\left(-\chi n_e\frac{dT}{dx}\right)=S_{loss}$$

$$\Theta\frac{d}{dx}\left(m n_e v_\parallel^2+p\right)=S_{mom}$$

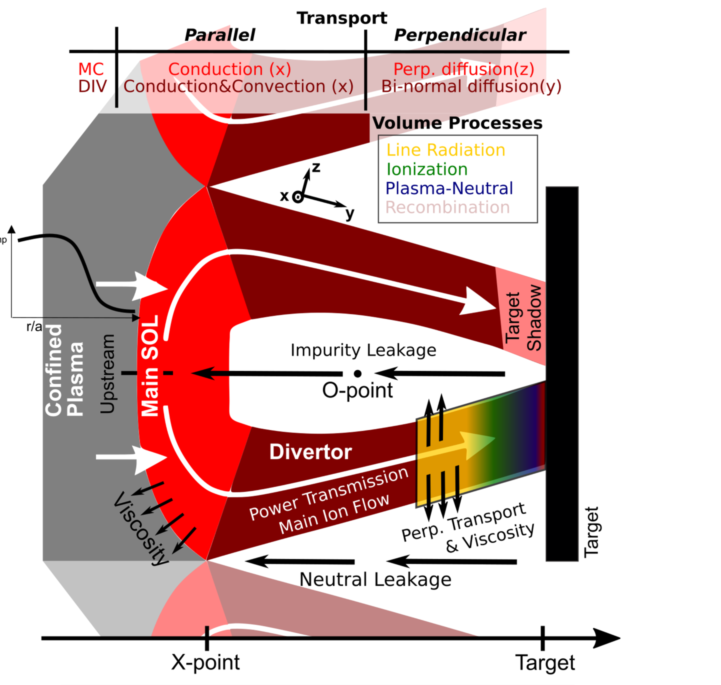
↓

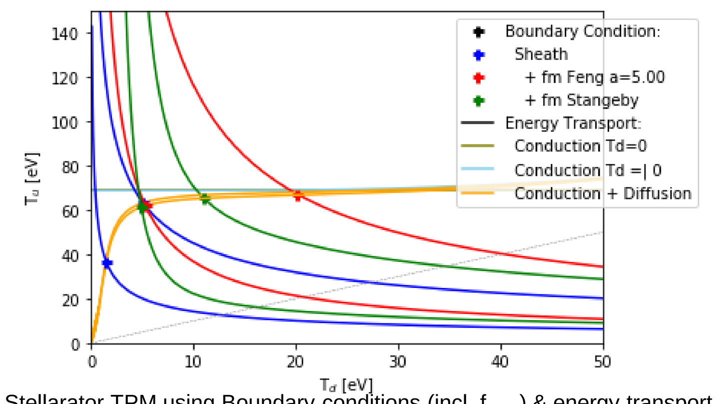
$$T_u^{7/2}=T_d^{7/2}+\frac{7}{2}\frac{q_\parallel L_c}{\kappa_e}-7\frac{\chi(n_{e,u}+n_{e,d})}{\kappa_e\Theta^2}(T_u-T_d)$$

$$p_u=2p_d(1+f_m)$$

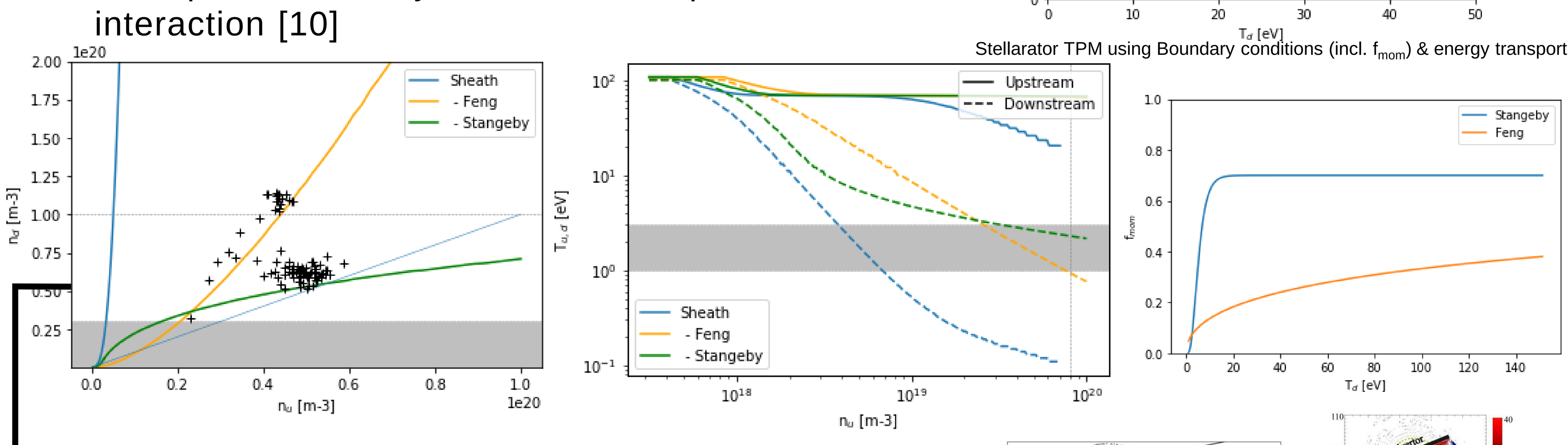
- Different pressure losses:

  Transport: viscosity rather than plasma-neutral interaction [10]



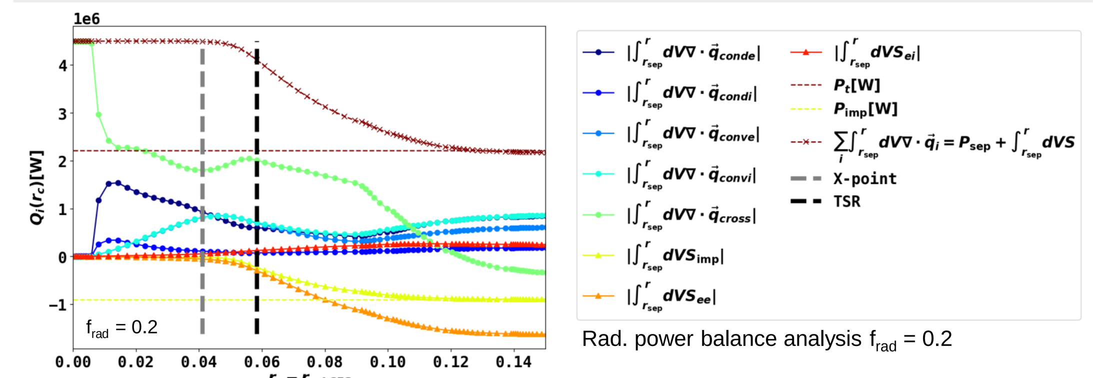


Stellarator TPM using Boundary conditions (incl. f_{mom}) & energy transport



Ext. Stellarator TPM scalings with 'fitted' parameters using different momentum loss parameterizatons

5. VALIDITY & EXTENSIONS



Rad. power balance analysis f_{rad} = 0.2

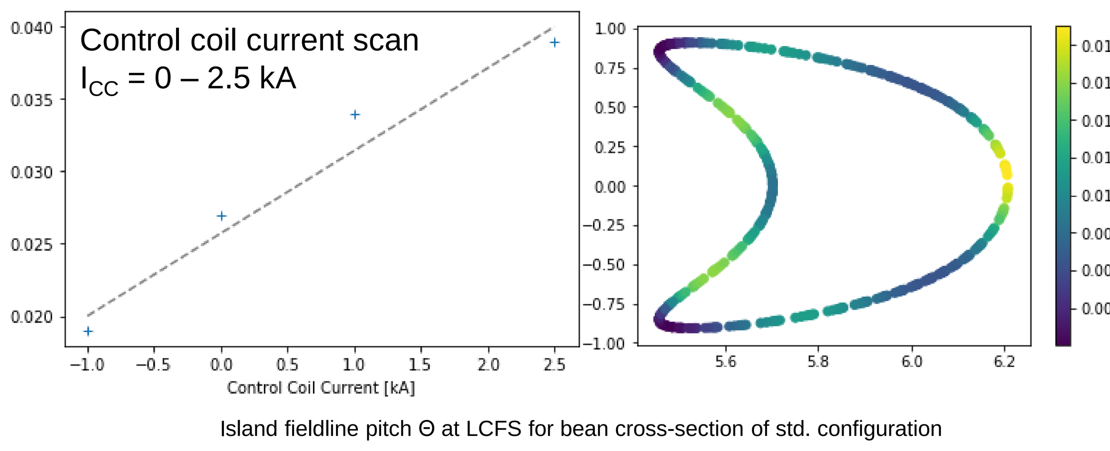
Comparison with EMC3-Modeling shows that fundamental assumptions are violated:

- Radial perp. transport dominant
  → tor. asymmetries not important
- Convection competes/dominates conduction
  → couples particle balance into the model
- Multiple passes through divertor plasma
  → Profiles are non-monotonous (3D)
- Complex parallel profile structures, but 'well behaved' between different fieldlines

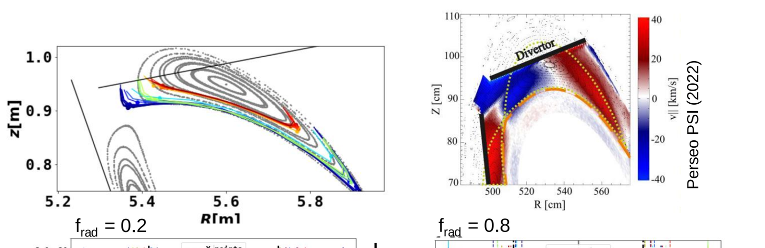
Simillar simplified models from tokamaks are difficult to apply: Radiation [11,12], Flows [13]

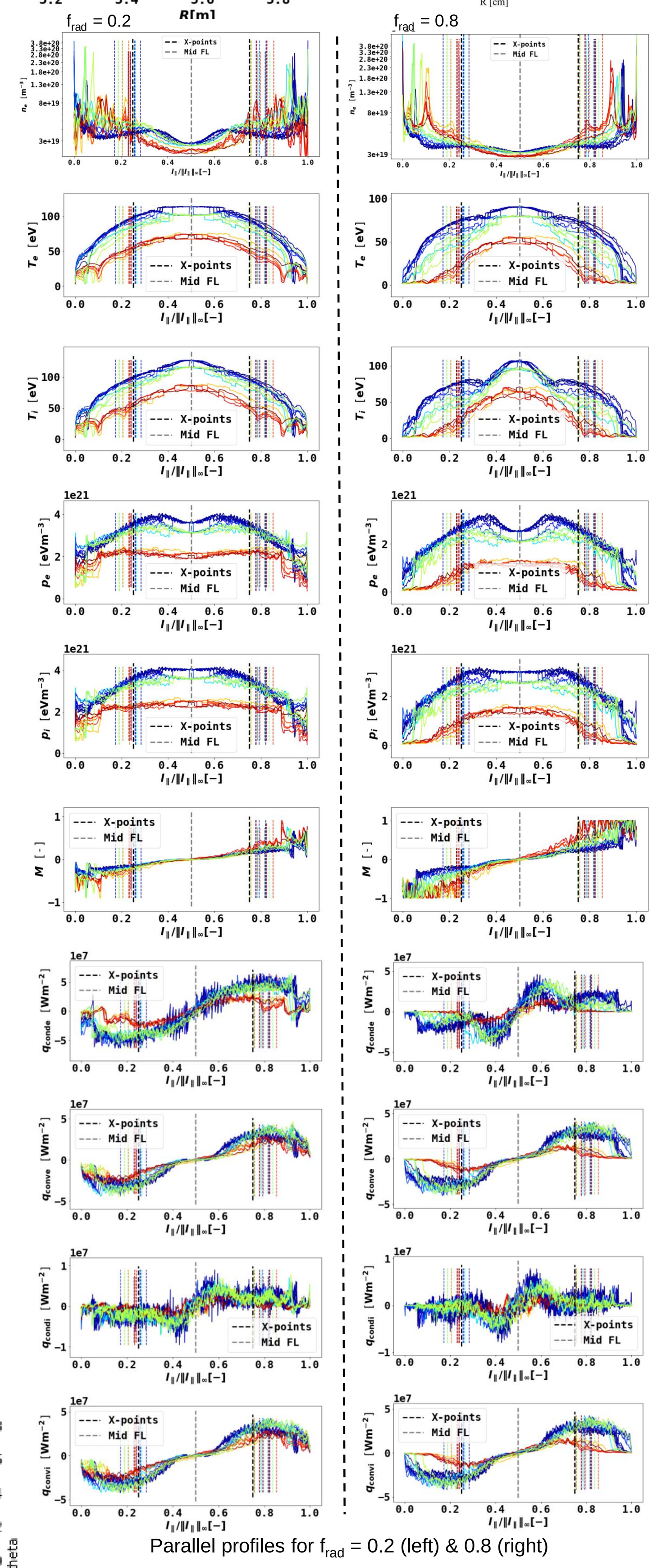
Island geometry is inherently important:

- Island pitch Θ sets par./perp. transport balance
- Island aspect ratio separates main chamber & divertor SOL properties (pol. vs. rad. res. field)
- How to describe 3D divertor geometry effect on neutrals?

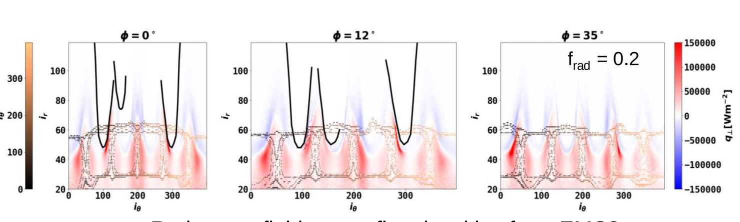


Island fieldline pitch Θ at LCFS for bean cross-section of std. configuration





Parallel profiles for f_{rad} = 0.2 (left) & 0.8 (right)



Rad. cross-field power flux densities from EMC3

CONCLUSION

- 'High-recycling' regime with $n_{div} > n_{up}$ observed in W7-X, but with linear density scaling ($n_{div} \propto n_{up}$) observed. (Line-integrated) Density is a strong driver of the exhaust parameters (P_{rad}, $p_{0,div}$)
- Roll-over driven by power-starvation detachment. No significant (atomic) recombination
- Tokamak simplified models not straightforward to apply due to 3D-topology (source localization) and importance of cross-field transport (bi-normal). Heat conduction not clearly dominant.
- Island geometry inherently connected to transport properties
  → use for investigations and control

[1] M. Jakubowski, NF 61 (2021) [2] O. Schmitz, NF 61 (2020) [3] D. Zhang, PRL 123 (2019) [4] F. Effenberg, NF 59 (2019) [5] V. Winters, PSI 2020 [6] Y. Feng, NF 46 (2006) [7] Y. Feng, Plasma PPCF 53 (2011) [8] A. Kukushkin, Fus. Eng. and Design 86 (2011) [9] V. Winters, NF (submitted) [10] Y. Feng NF 61 (2021), [11] R. Goldston NF 59 (2017), [12] J.F. Agerup, Master Thesis NTU, [13] V. Perseo, this conference

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