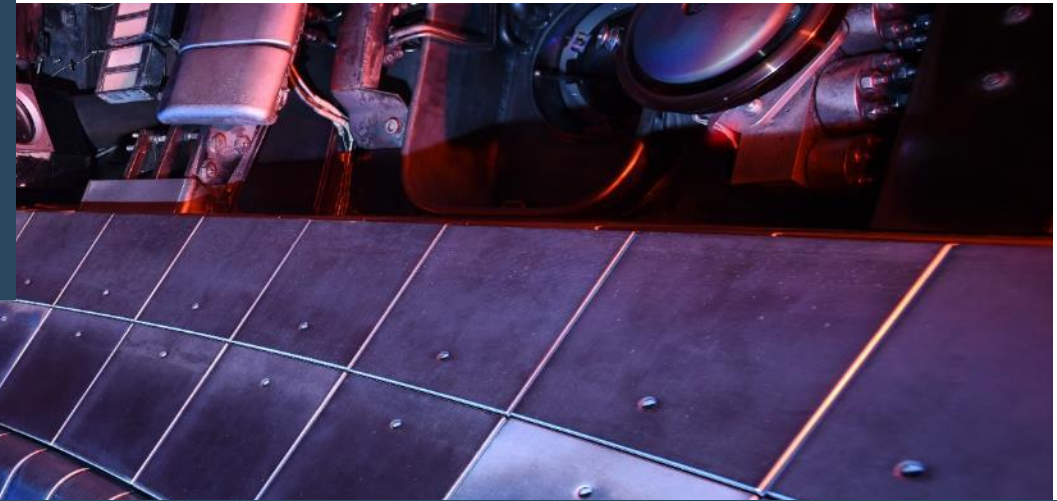




Dependence of turbulent transport on the divertor flux expansion in ASDEX Upgrade



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1. **Motivation: power exhaust and advanced divertor configurations (ADCs)**
2. **The three studied AUG configurations and the GRILLIX simulation setup**
3. **Divertor heat flux profiles: geometry vs. turbulence**
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Based on: J. Pfennig-Bär et al 2026 Nucl. Fusion **66** 036004

Advanced divertor configurations and turbulence



The heat exhaust problem

- $q_{\perp}^{\text{target}} \lesssim 10 \text{ MW/m}^2$ is not automatically reached in a reactor
- Mitigation: core radiation, detachment, X-point radiator — and ADCs

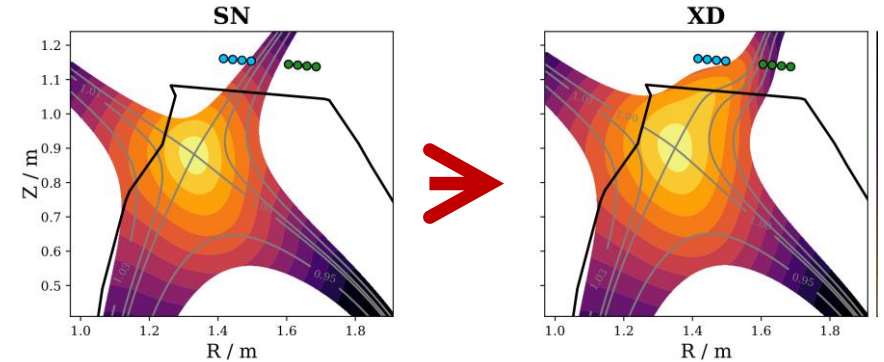
What an advanced divertor configuration does

- shapes the poloidal field near the divertor (in-vessel coils)
- option 1 — Increase distance between target and OMP
- option 2 — SOL splitting by secondary X-points
- option 3 — flux expansion $f_x = |\nabla\Psi|/|\nabla\Psi|_{\text{OMP}}$
- X-Divertor (XD): utilizes f_x , simplest ADC $\rightarrow$ EU-DEMO candidate

Why turbulence has to be simulated

- lower magnetic shear at the X-point $\rightarrow$ weaker filament decorrelation?
- flux expansion stretches filaments radially $\rightarrow$ more radial $E \times B$ advection?
- yet transport codes prescribe anomalous D , χ — these set the result!

$\Rightarrow$ global, full- f , self-consistent turbulence simulations are needed to disentangle the geometric from the turbulent contribution



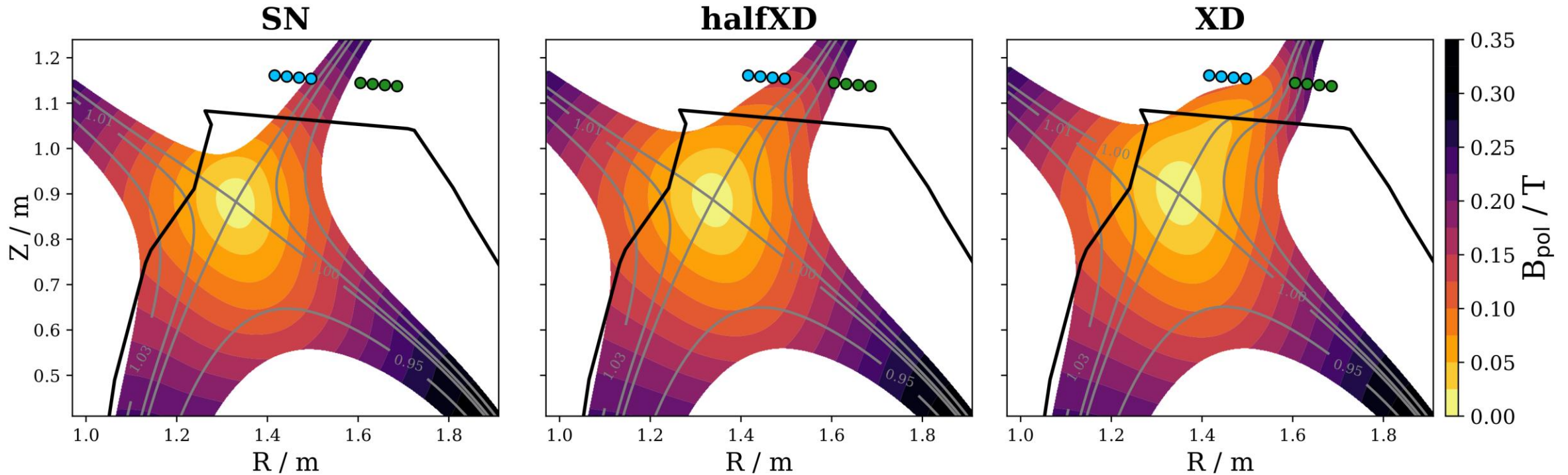
single null $\rightarrow$ X-Divertor: the poloidal field well widens and f_x grows by more than $\times 3$ at the strike line

Geometric merit: the same parallel power is deposited over a larger wetted area

Turbulent merit?

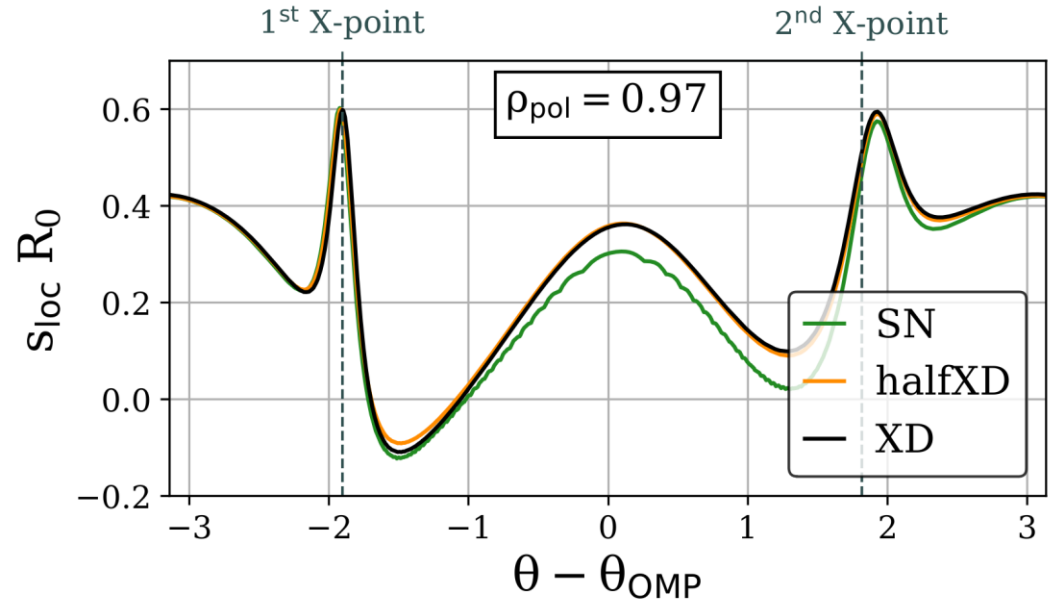
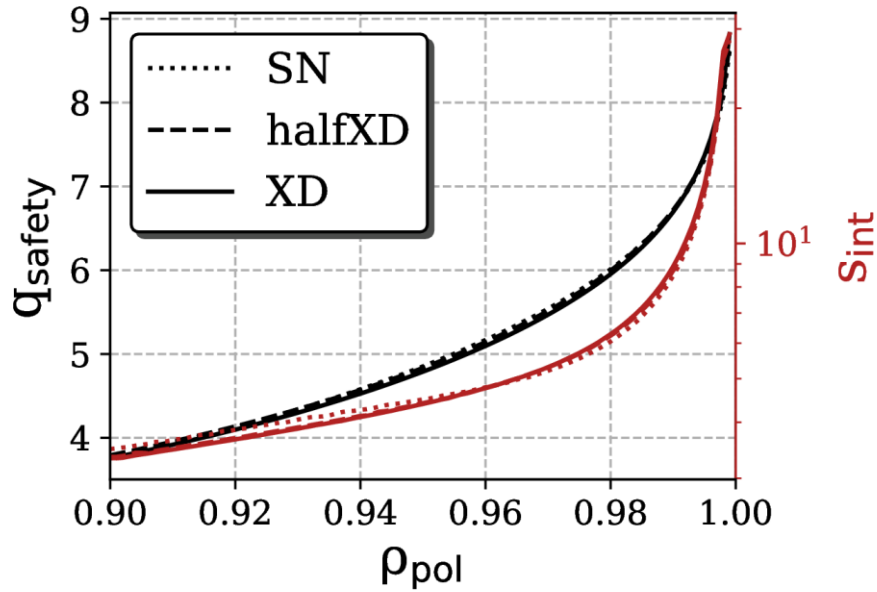
Does the modified divertor geometry also enhance the cross-field $E \times B$ transport — and by how much?

Three configurations in the new AUG upper divertor



- Magnetic equilibrium from AUG #35840 (H-mode!), $t = 2.5$ s: $B_{\text{tor}} = 2.5$ T, $I_p = 800$ kA, favourable ∇B -drift. Only the in-vessel coil currents are scanned (pyequil / Grad-Shafranov solver equil)
- Colour: $|B_{\text{pol}}|$; grey: ρ_{pol} contours; blue / green dots: inner / outer in-vessel coil windings; black: divertor and first wall
- The poloidal field well around the X-point widens with the coil current and the flux surfaces become more tangent to the B_{pol} contours $\rightarrow$ longer parallel connection length to the target

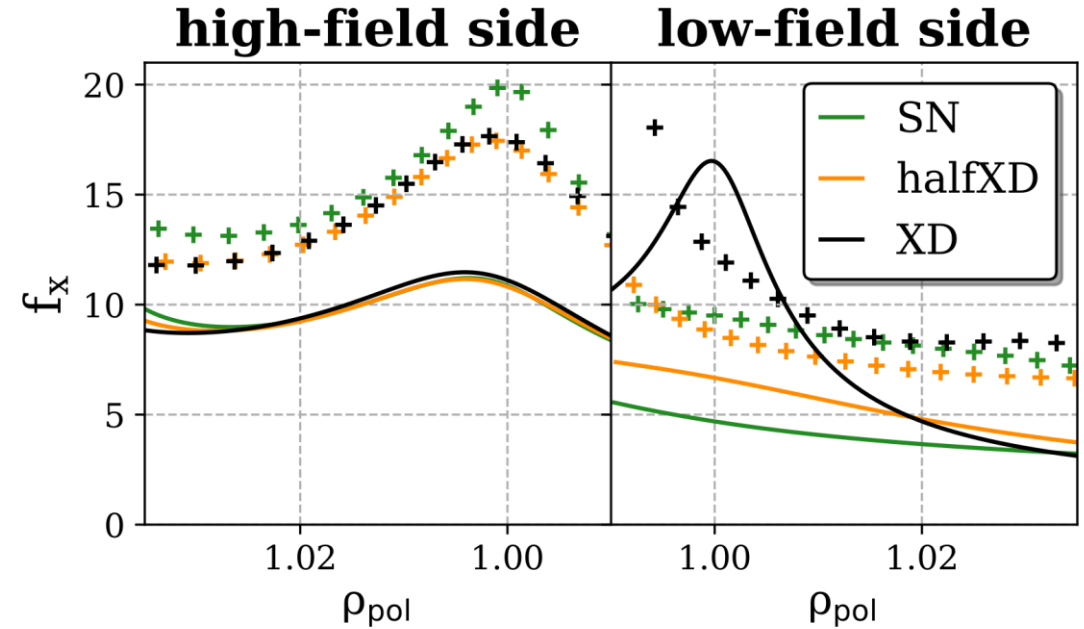
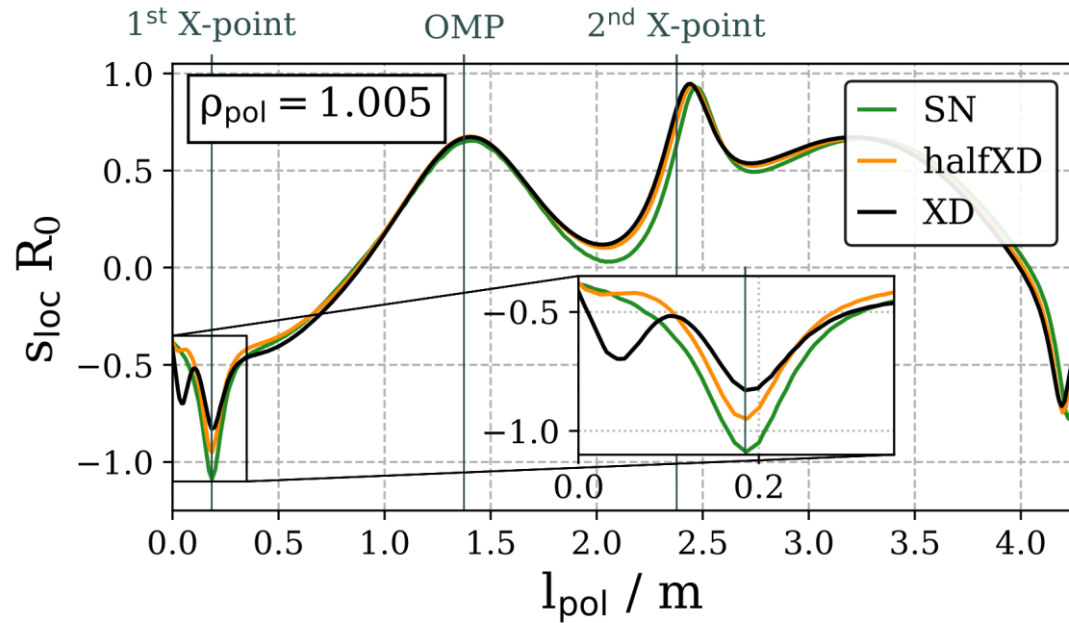
The confined region is unaffected by the in-vessel coils



- Safety factor q_{safety} and integral magnetic shear $s_{\text{int}} = \frac{r}{q} \frac{\partial q}{\partial r}$ are identical for SN, halfXD and XD
→ the confined plasma does not see the coils
- The local shearing rate $s_{\text{loc}} = -\mathbf{e}_y \cdot (\nabla \times \mathbf{e}_y)$ peaks near the two X-points;
in the edge ($\rho_{\text{pol}} = 0.97$) only a slight increase between the OMP and the 2nd X-point remains
- ⇒ any difference found downstream can be attributed to the local divertor geometry

$\mathbf{e}_y = \nabla \Psi / |\nabla \Psi| \times \mathbf{B} / |\mathbf{B}|$ is the binormal unit vector; s_{loc} is normalised to $R_0 = 1.65$ m and plotted vs. the geometric poloidal angle θ measured from the OMP.

Divertor: magnetic shear reduced ~25%, flux expansion up $\times 3$



- Left: s_{loc} along the poloidal arc length l_{pol} of the flux surface $\rho_{pol} = 1.005$, measured from the LFS divertor target
 - around the 1st X-point ($l_{pol} \approx 0.2$ m) the shear decreases close to linearly with the coil current, by $\approx 25\%$ from SN to XD
 - for XD an extra peak appears towards the target, from the strong tilting of the flux surfaces w.r.t. the B_{pol} contours
- Right: poloidal flux expansion f_x at the divertor target (lines) and at the penalization entrance (+ symbols): more than a factor 3 at the strike line, strongly non-linear in the coil current
- **$\Rightarrow$ the shear scales $\sim$ linearly, the flux expansion only jumps for XD — this separates the two candidate mechanisms**

GRILLIX: global full- f edge-SOL turbulence simulations



Plasma: global, drift-reduced, extended Braginskii two-fluid model, full- f , electromagnetic, transcollisional (heat flux limiter, neoclassical viscosity)

Neutrals: 3-moment, diffusive, atomic fluid with $N_{\text{div}} = 5 \times 10^{17} \text{ m}^{-3}$

FCI approach: Cartesian poloidal planes coupled by field-line mapping

→ no coordinate singularity at the separatrix

→ high geometric flexibility across the X-point

Domain $\rho_{\text{pol}} = 0.9 \rightarrow 1.05$; core boundary $T_e = T_i = 300 \text{ eV}$, $n_e = 2 \times 10^{19} \text{ m}^{-3}$ with an adaptive source $\Rightarrow$ adaptively flux-driven, P_{in} is an output rather than an input

→ this is an attached L-mode setup, like validated #36190

Resolution $h_{\perp} = 2\rho_s(100 \text{ eV}) = 1.45 \text{ mm}$, 16 toroidal planes

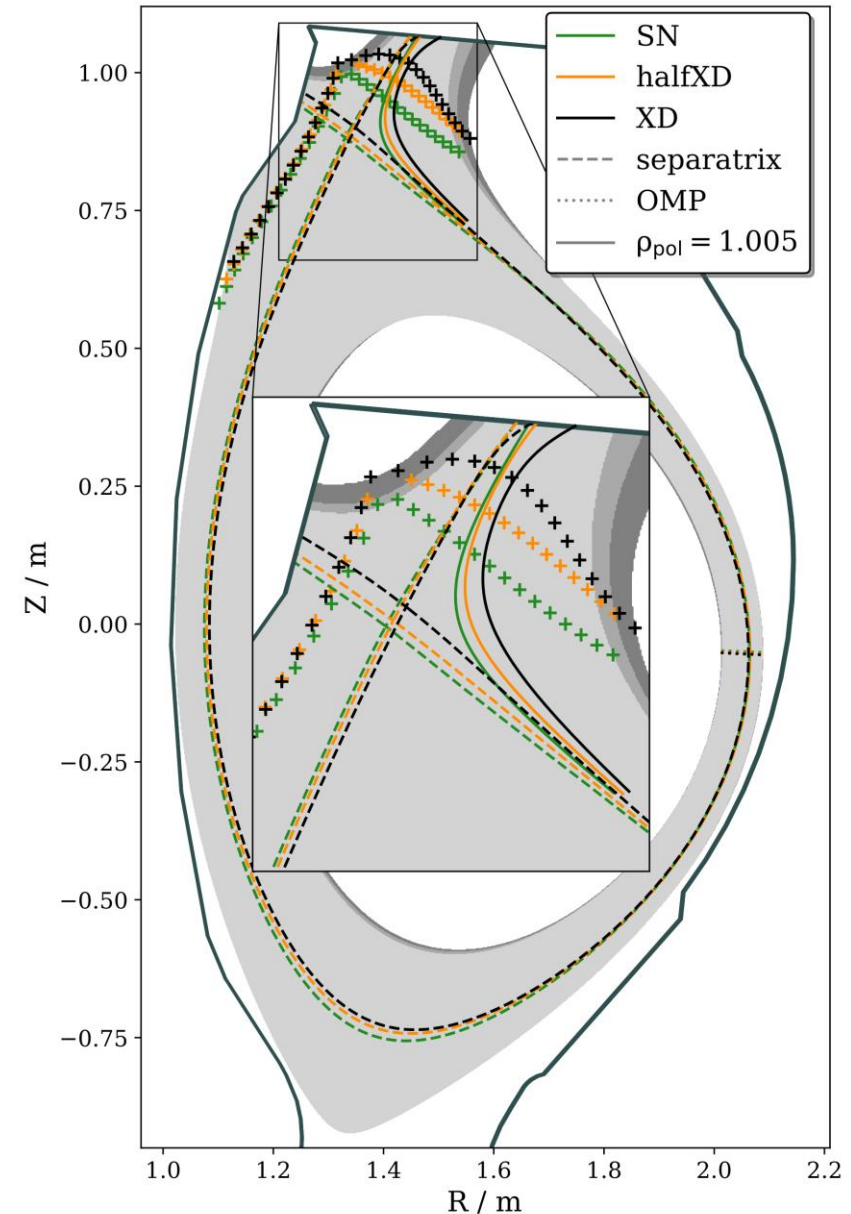
→ ok at OMP, nowhere near enough in the divertor (as always)

Sheath BCs $\varphi = \Lambda T_e$, $u_{\parallel} = c_s$; homogeneous Neumann for n , $\underline{T}_{e\perp}$, $\underline{T}_{i\perp}$, Ω and $j_{\parallel}$

Parallel BCs imposed by penalization (immersed boundary)

→ analysis at the penalization entrance $\chi = 10^{-10}$ (+ symbols in figure)

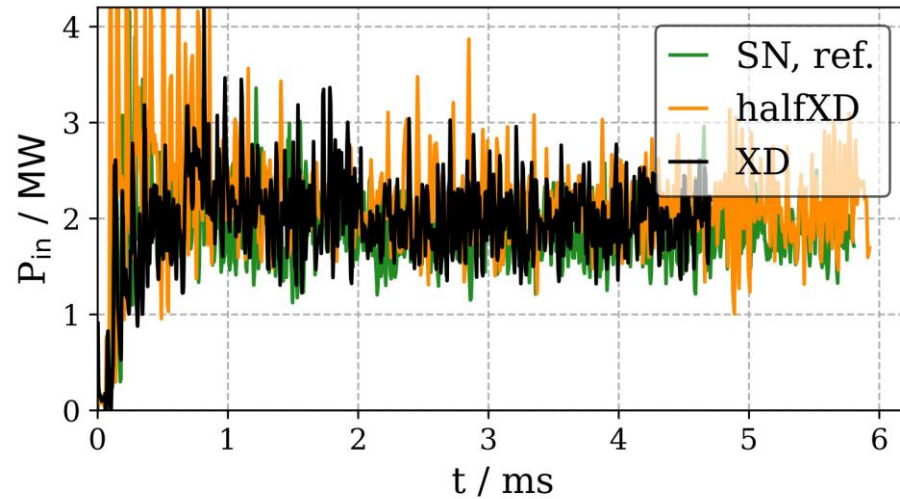
Identical setup for all three equilibria — only magnetic geometry differs



A. Stegmeir et al 2018 PPCF 60 035005 | W. Zholobenko et al 2024 NF 64 106066 |

K. Eder et al 2025 PPCF 67 065034

Global and upstream conditions are identical



Saturated turbulent state; all analyses use $t > 2$ ms

Input power from the adaptive core source: $\langle P_{in} \rangle \approx 2$ MW for all three cases.

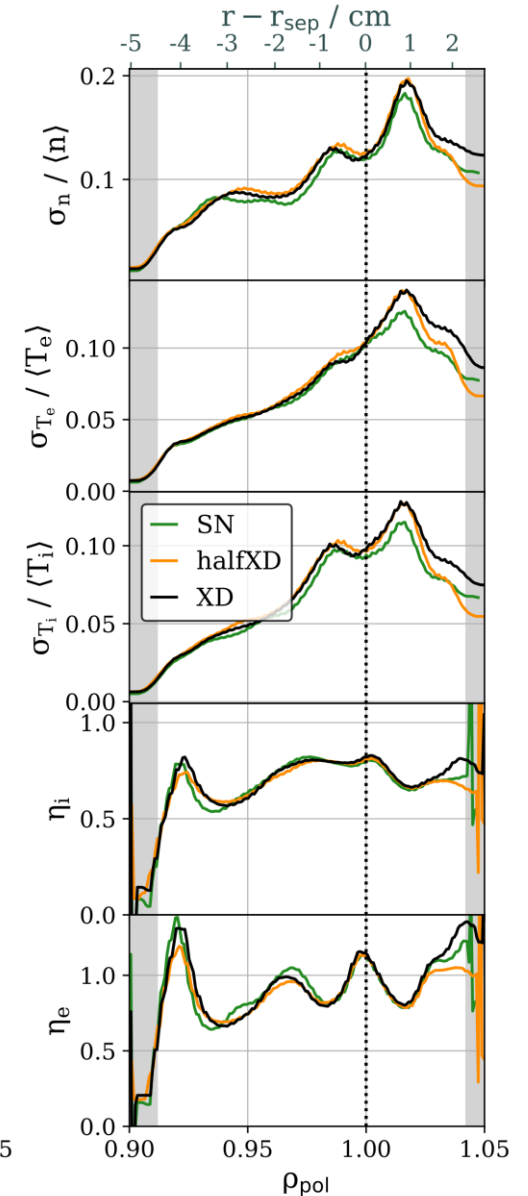
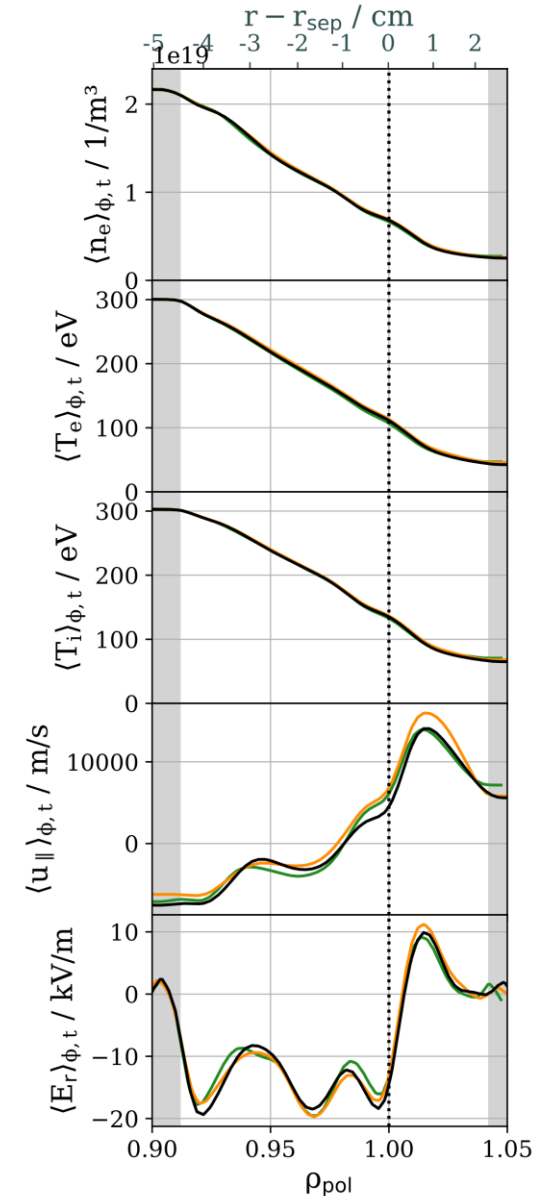
Stored energy, P_{sep} and edge confinement time agree to within $\approx 10\%$

OMP profiles are close to identical — except $u_{||}$, which drops for XD at the separatrix (less transport suppression by magnetic shear)

E_r , and hence the $E \times B$ shearing rate, is the same $\Rightarrow$ no upstream difference in turbulence suppression

$\eta_{e,i} = \partial_r \ln n / \partial_r \ln T_{e,i} < 1 \Rightarrow$ the density gradient is the main free-energy source, ITG modes are suppressed

Fluctuation amplitudes increase in the far-SOL for half-XD and XD



Peak divertor heat flux reduced by more than a factor 3



Heat fluxes evaluated at the penalization entrance ($\chi = 10^{-10}$) and mapped to the target with $f_x(\rho_{pol})$

Includes parallel convective and conductive plus perpendicular $E \times B$, diamagnetic and neutral fluxes

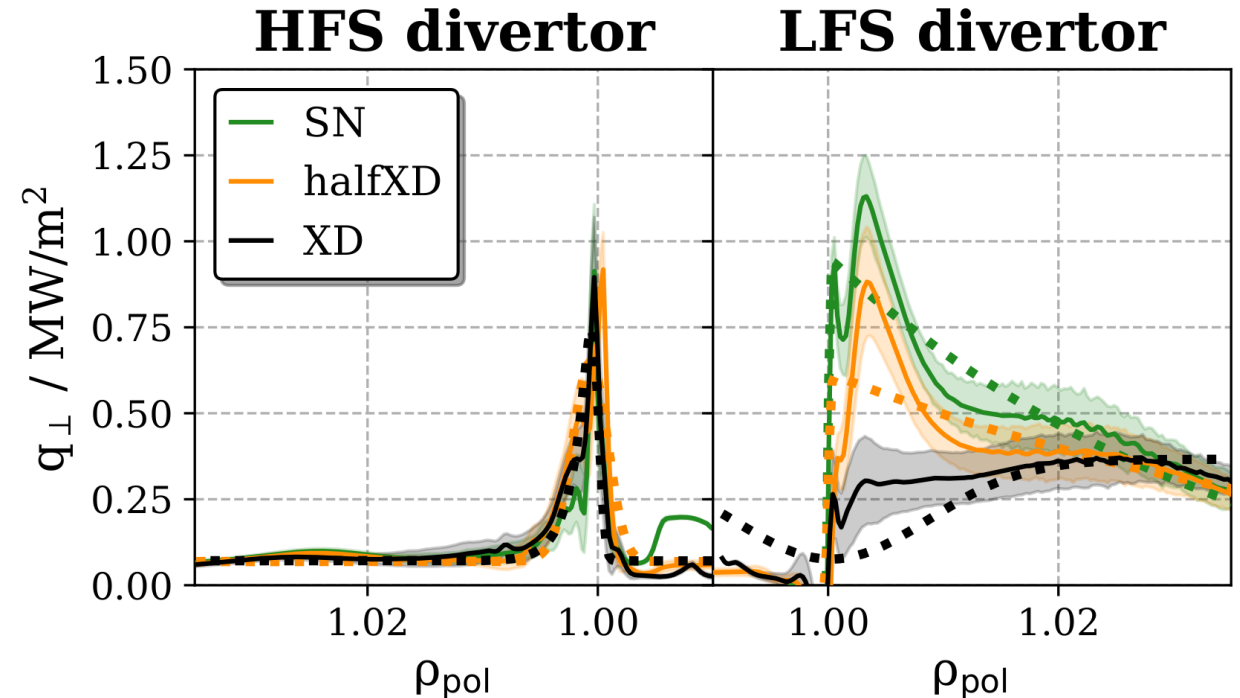
HFS: identical for all three and strongly peaked — turbulence is curvature-stabilised there, no turbulent broadening

LFS: strong inverse dependence on f_x

SN $\rightarrow$ halfXD: peak almost unchanged, shape preserved, λ_q grows

SN $\rightarrow$ XD: peak drops by > 3 , the profile becomes nearly flat $\Rightarrow$ the Eich fit is dominated by the broadening S

The integral power to the targets is unchanged, since the divertor coordinate scales as $s \propto \rho f_x$



	SN	halfXD	XD
λ_q / mm	18.6 ± 1.1	26.1 ± 2.1	0.1 ± 0.6
S / mm	0.1 ± 0.2	0.1 ± 0.3	6.4 ± 0.9

Eich fit: T. Eich et al 2011 PRL 107 215001; T. Eich et al 2013 NF 53 093031

≈20% of the peak reduction is turbulent, not geometric



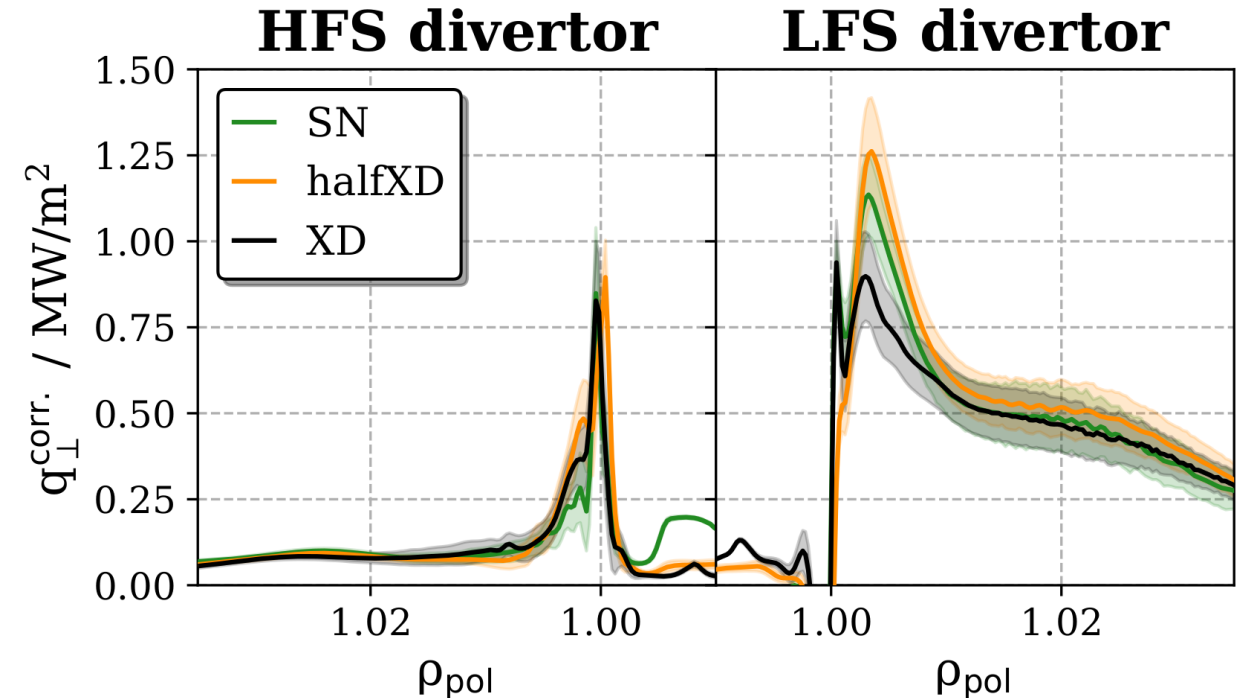
Same profiles, additionally divided by $f_x/f_{x,SN} |_{\chi=0.5}$: this removes the purely geometric spreading and puts all cases on the SN geometry (no longer physical, but comparable)

The HFS is unchanged, as expected — the geometry is identical there

LFS: a residual peak reduction of ≈ 20% from SN to XD remains

λ_q is now the same for all three within the error bars $\Rightarrow$ the geometric effect dominates the broadening

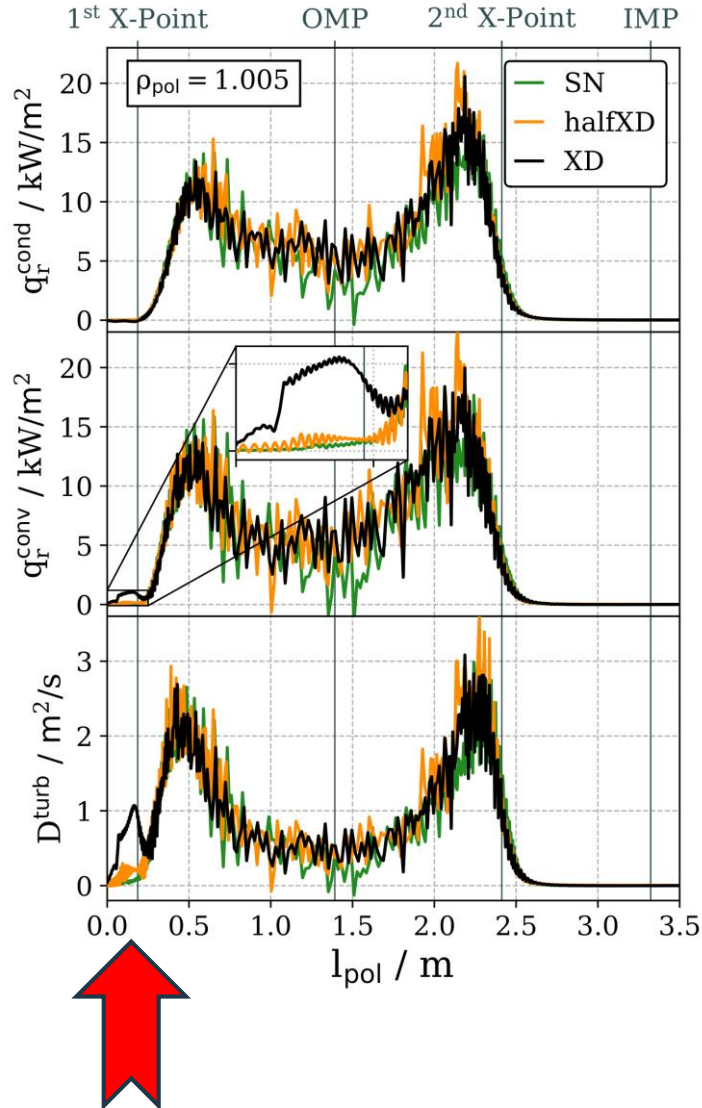
The same ≈ 20% is found without mapping and without normalisation $\Rightarrow$ the extra transport genuinely occurs in front of the penalization region, it is not an artefact of the mapping



	SN	halfXD	XD
λ_q / mm	18.6 ± 1.1	21.1 ± 1.7	18.7 ± 1.4
S / mm	0.0 ± 0.1	0.1 ± 0.3	0.0 ± 0.1

Corrected by the flux expansion of the SN case, evaluated at the physical target ($\chi = 0.5$).

Convective E×B transport increases in the LFS divertor leg

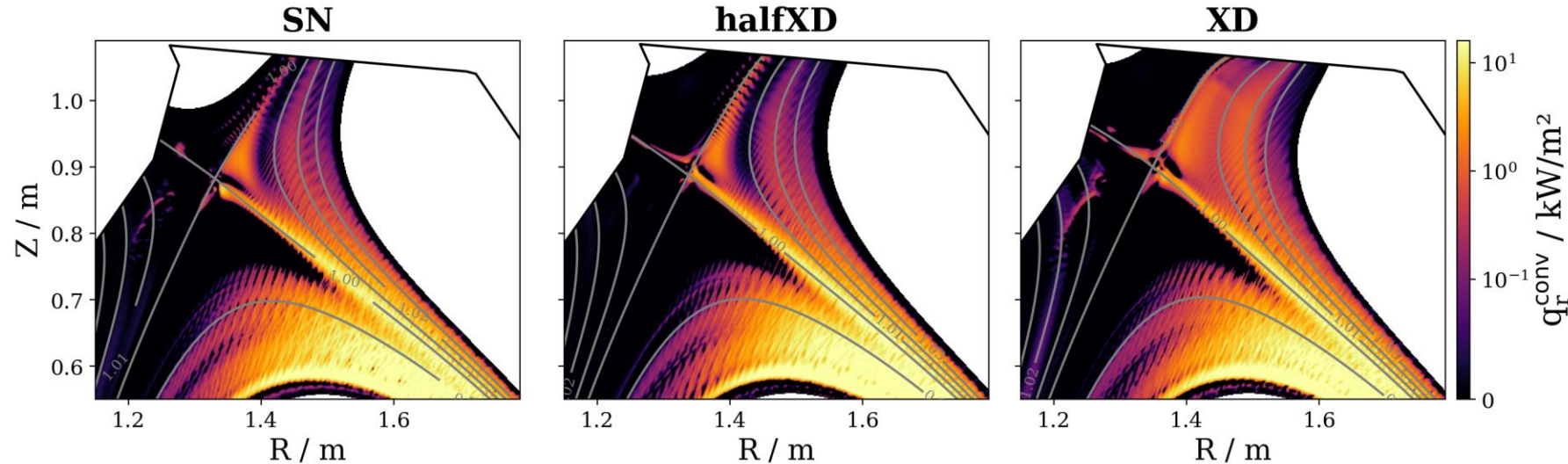


- Turbulent fluxes from correlated fluctuations (full-f: no background / fluctuation split)

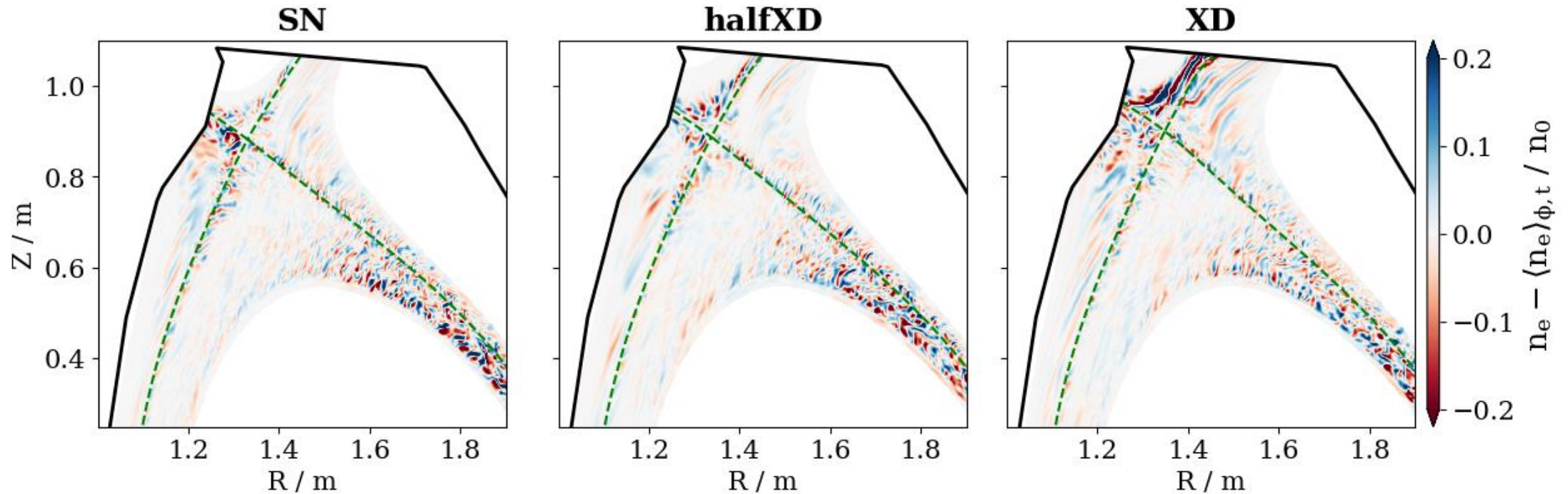
$$\Gamma_r^{\text{turb}} = \langle n' v'_{E,r} \rangle, \quad q_{(e,i),r}^{\text{cond}} = \langle n \rangle \langle T'_{e,i} v'_{E,r} \rangle, \quad q_{(e,i),r}^{\text{conv}} = \langle T_{e,i} \rangle \Gamma_r^{\text{turb}}$$

$$D_r^{\text{turb}} = \frac{\Gamma_r^{\text{turb}}}{\langle \partial_r n \rangle}$$

- Conductive channel identical; the convective one differs only in the LFS divertor leg ($l_{\text{pol}} < 0.3$ m): zero for SN and halfXD, finite for XD, where D_r^{turb} reaches OMP values
- Shear falls linearly SN→XD, but f_x only jumps for XD ⇒ flux expansion is the driver**
- 2D map (log): increase and broadening across the whole XD divertor leg

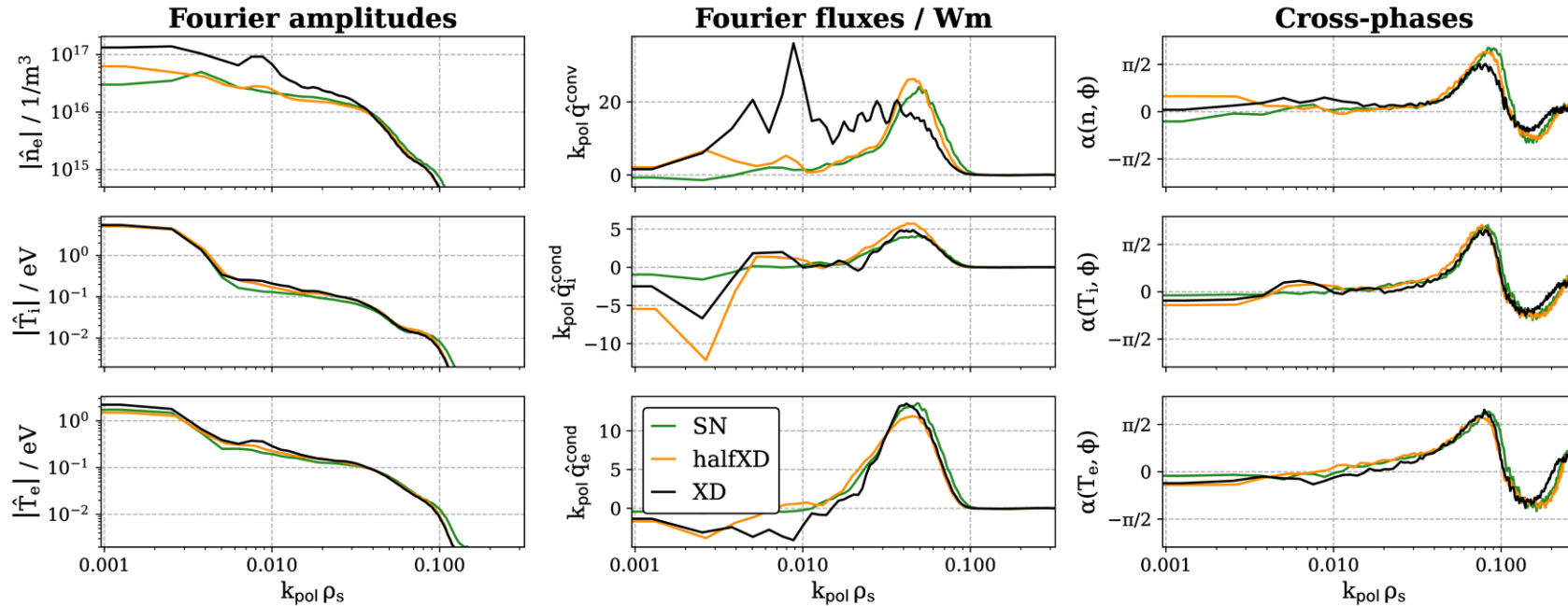


Larger divertor filaments and flux-surface-aligned streamers



- Snapshots of the relative density fluctuations. Upstream the filaments are comparable between the three configurations
- In the LFS divertor region the XD filaments grow in amplitude and in size: the physical expansion of the flux surfaces lets larger radial structures fit into a region of fixed radial background gradient
- Flux-surface-aligned streamers form, connecting the X-point region to the divertor target — as also observed with gas-puff imaging on TCV
- Together with the reduced magnetic shear (weaker filament decorrelation) this explains the enhanced radial $E \times B$ advection found above

Turbulence analysis: Fourier spectra and cross-phases



- Flux-surface-aligned FFT on the LFS divertor segments:

$$\hat{\Gamma}_r(k) = k|\hat{n}||\hat{\phi}| \sin \alpha_{n,\phi} \quad \alpha \approx 0 \text{ drift wave, } \alpha \approx \pm\pi/2 \text{ interchange}$$

- Confined region: broadband drift waves, $\alpha \in [0, \pi/8]$, identical for all three
- Divertor SOL: high $\nu_e \propto n_e T_e^{-3/2}$ decouples the pressure from $\phi \Rightarrow \alpha \in [\pi/4, \pi/2]$, interchange drive; temperature spectra and cross-phases are unaffected by XD geometry
- Only for XD does q^{conv} broaden and peak at much smaller $k_{\text{pol}}\rho_s \approx 0.01$ — larger density amplitudes plus a finite cross-phase, partly cancelled by conductive pinches ($q^{\text{cond}} < 0$) $\Rightarrow$ net $\approx 20\%$**

Conclusions



First self-consistent turbulence simulations of the new AUG upper divertor — a prediction made before the measurements exist, and therefore material for later validation

Identical GRILLIX setup for SN / halfXD / XD, scanning the in-vessel coil currents gives an increase of the divertor flux expansion by more than $\times 3$ at the strike line

Global energy content and upstream profiles are unchanged $\Rightarrow$ all differences are local to the divertor

LFS peak heat flux reduced by more than $\times 3$ in the XD; the profile becomes nearly flat and the Eich fit is dominated by $S \approx 6.4$ mm, while the integral target power is unchanged

After removing the geometric effect, $\approx 20\%$ peak reduction remains, caused by enhanced convective turbulent $E \times B$ transport

Mechanism: larger density fluctuation amplitudes and a finite cross-phase at $k_{\text{pol}} \rho_s \approx 0.01$, partly compensated by conductive pinches

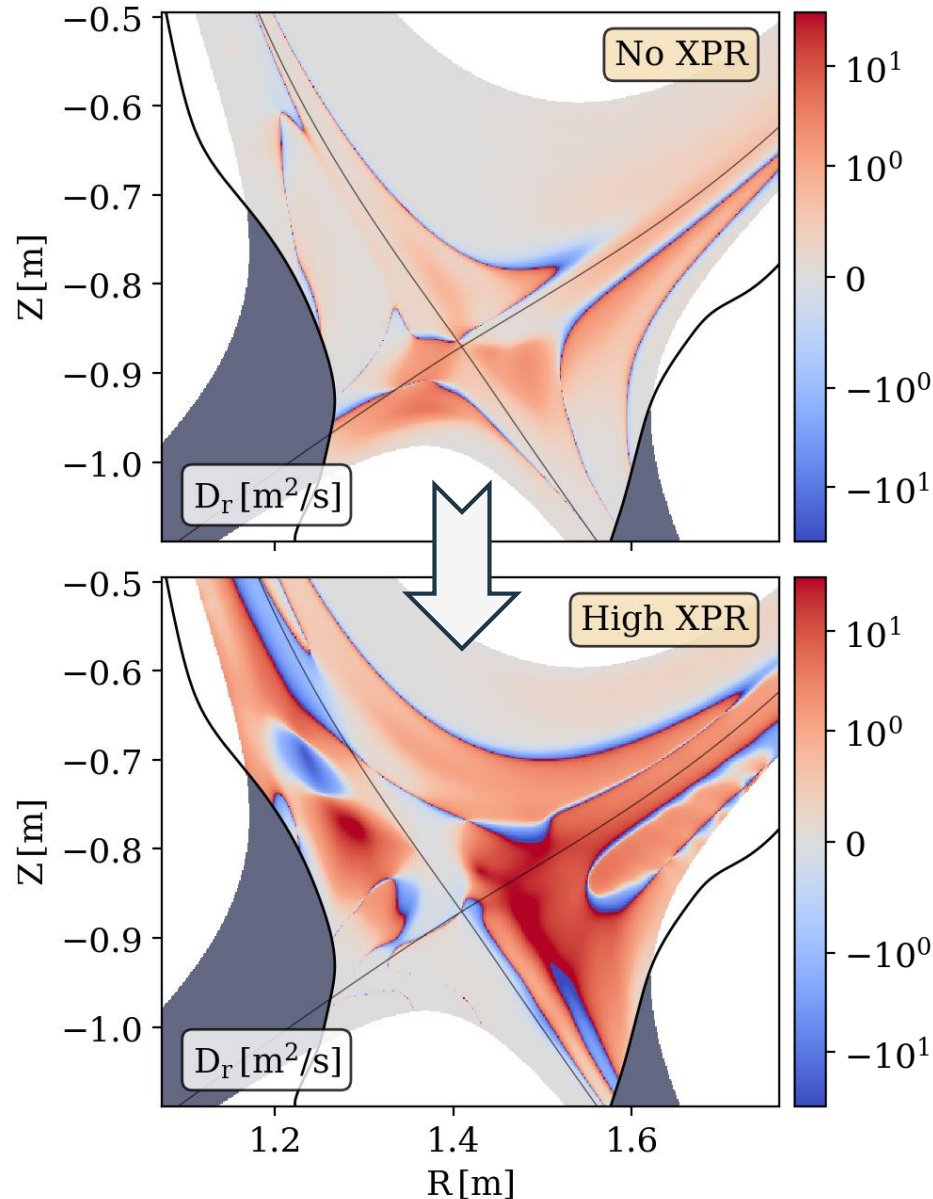
In attached L-mode the turbulent merit of the X-Divertor is therefore small compared with the purely geometric one

The strong spatial variation of D^{turb} shows that fixed anomalous coefficients are inadequate for divertor design studies

Experimentally falsifiable: scale-resolved density fluctuation amplitudes vs. divertor flux expansion, e.g. with spatially resolved gas-puff imaging

For details, see: J. Pfennig-Bär et al 2026 Nucl. Fusion **66** 036004

Outlook: detached ADCs are the case that matters



A reactor divertor must be detached — so the attached L-mode studied here is not the relevant operating point

In detached conditions parallel transport is strongly reduced, which shifts the competition between parallel and perpendicular transport in the SOL towards the latter, i.e. turbulent, channel

⇒ divertor turbulence is expected to gain importance, considerably larger contribution than the $\approx 20\%$ found here

⇒ detached advanced divertor configurations must be simulated (e.g. X-point radiator?)

Numerics and physics to improve on the way there:

- (better) converged resolution in the cold divertor, enabled by GPUs
- (hybrid fluid–) kinetic molecular neutral gas with recycling

Experiments in the new AUG upper divertor will allow a direct validation of these predictions

Other ADC configurations (e.g. SF) are of course also of interest

Thank you for your attention!