Influence of self-consistently determined perpendicular transport coefficients on the numerical prediction of turbulent transport in a full WEST discharge

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Outline

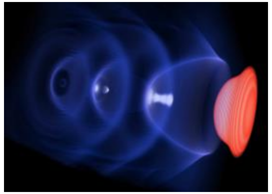
- **Introduction**
  - Plasma simulation codes
  - Heat exhaust
- **Turbulence self-consistent model**
  - Model description
  - Implementation into SolEdge3X-HDG
- **Full discharge simulation**
  - Simulation parameters
  - Simulated plasma profiles
  - Comparison with previous simulation and the experiment via set of synthetic diagnostics
- **Conclusion**

Plasma simulation codes

Increasing description richness

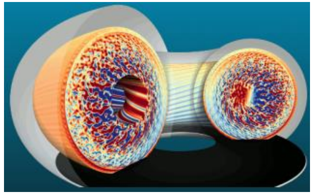
Can give reliable enough predictions for a reasonable cost

PIC



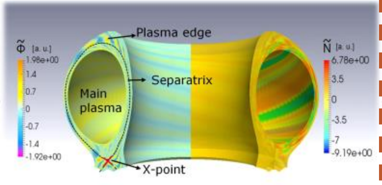
SMILEI

6D/5D kinetic/ gyrokinetic



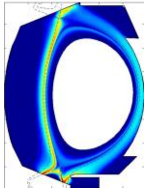
GENE
GYSELA
(QuaLiKiz)

3D Fluid



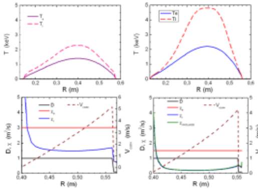
GBS
TOKAM3X

2D Fluid



SOLPS
SOLEDGE2D
EDGE2D

1D core



ASTRA
STRAHL

0D

$$\tau_E \propto I^{\alpha} B^{\beta} P_{\mathrm{SOL}}^{\gamma} \cdots$$

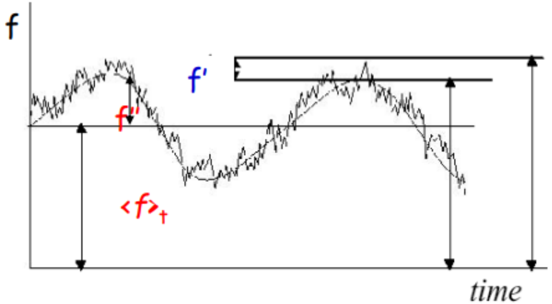
scalings
2-point model

Decreasing computational cost

Transport code: model reduction

- **Model reduction** is based on a time separation and fluid equation averaging:

$$f = \underbrace{\langle f \rangle_{\varphi,t} + f''(t)}_{\text{resolved}} + \underbrace{f'(t)}_{\text{modelled}}$$



Time-averaged part <.>$_t$ + resolved fluctuations f'' + modelled fluctuations f'

- **Perpendicular turbulent fluxes** should be defined

- **Gradient transport model** (Fick's law) is usually employed with an effective D_e

- For example, for the plasma density

$$\langle n' v'_{\perp} \rangle_{\varphi,t} = -D_e^n \nabla_{\perp} \langle n \rangle_{\varphi,t}$$

convective transport due to cross-field drifts

local perpendicular gradient of average density

Heat exhaust

- **Heat and particle exhaust** are one of the main issues for safe fusion plant operation
- **SOL** (Scrape-off layer) **width λ_q** is a characteristic heat flux decay length

➢ Defined by the balance of ‖ and ⊥ transport

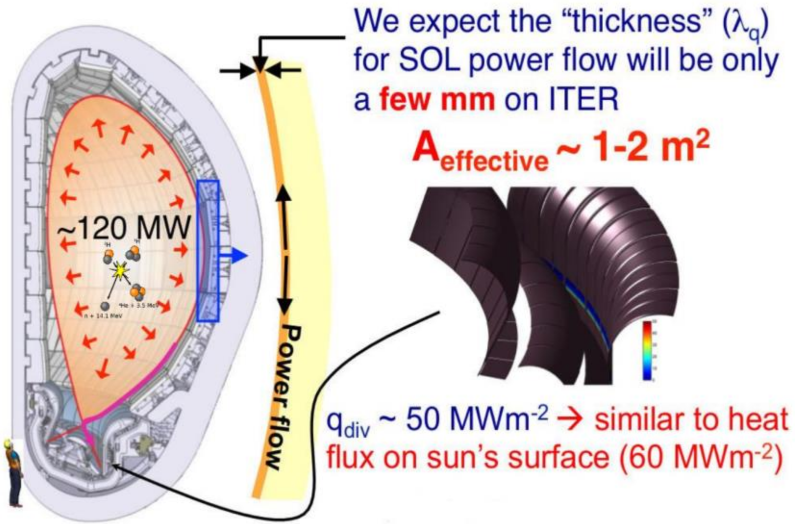
$$\tau_\perp = \frac{\lambda_q}{v_{\perp,\mathrm{turb}}} \approx \tau_\parallel = \frac{L_\parallel}{v_\parallel}$$

D_e ← $\tau_\perp$

➢ **Heat flux** on the divertor targets can be estimated as:

$$q_{\mathrm{div}} = \frac{P_{\mathrm{SOL}}}{2\pi R_0 \lambda_q f_{\mathrm{geo}}}$$

➢ **Both** SOL power (P_{SOL}) and SOL width λ_q (D_e) should be properly estimated before the device operation



Courtesy Loarte ITER

Ways to define effective diffusion

- ★ Adjust by hand or to match experimental values
  - ❖ Depends highly on a machine and experiment parameters
- ★ From **classical** or **neoclassical** theory
  - ❖ But too low values for pure deuterium plasma
- ★ **Quasilinear gyrokinetic simulations** (fast enough, especially with AI QLKNN(K.L. van de Passche, et al. 2021))
  - ❖ To be done during further studies (for the core studies)
- ★ Inspired by fluid mechanics, **simulating plasma turbulence** (Baschetti, et al. 2021, Bufferand, et al. 2021)
  - ❖ Has been **implemented during this study**

S. Baschetti, et al. "Self-consistent cross-field transport model for core and edge plasma transport." Nuclear Fusion 61.10 (2021): 106020.
H. Bufferand, et al. "Progress in edge plasma turbulence modelling—hierarchy of models from 2D transport application to 3D fluid simulations in realistic tokamak geometry." Nuclear Fusion 61.11 (2021): 116052.

Self-consistent turbulent model

- Turbulent energy equation

$$\partial_t k + \nabla \cdot (k u \mathbf{b}) - \nabla \cdot (D_k \nabla_\perp k) = \gamma_I k - c_\varepsilon k^2$$

turbulent energy [m^2/s^2]

non-local transport

local effects

Diffusion is self-consistently defined based on dimensional analysis (and used also for density, temperature, momentum):

$$D_k = k\tau = \frac{kR}{c_s}$$

Self-consistent turbulent model

- Turbulent energy equation

$$\partial_t k + \nabla \cdot (k u \mathbf{b}) - \nabla \cdot (D_k \nabla_\perp k) = \gamma_I k - c_\varepsilon k^2$$

- In this work growth rate is based on interchange instability with critical gradient approach (Bufferand, et al. 2016)

$$\gamma_I = \begin{cases} c_s \sqrt{\frac{\nabla p_i \cdot \nabla B}{p_i B} - \frac{\theta}{R^2}}, & \nabla p_i \cdot \nabla B \geq 0 \\ -c_s \sqrt{\left| \frac{(\nabla p_i \cdot \nabla B)}{p_i B} - \frac{\theta}{R^2} \right|}, & \nabla p_i \cdot \nabla B < 0 \end{cases}$$

$$c_\varepsilon = \gamma_I \frac{\pi q_{\mathrm{cyl}} R^2}{\gamma_e \lambda_q^2 c_s^2}$$

$$\lambda_q = 4 q_{\mathrm{cyl}} \rho C_\lambda$$

$$q_{\mathrm{cyl}} = \frac{B_t a}{B_p R}$$

$$\rho = \frac{m_i c_s}{eB}$$

$$\theta = 5(1 - T_i/T_e)$$

H. Bufferand, et al. "Interchange Turbulence Model for the Edge Plasma in SOLEDGE2D-EIRENE." Contributions to Plasma Physics 56.6-8 (2016): 555-562.

SolEdge3X-HDG

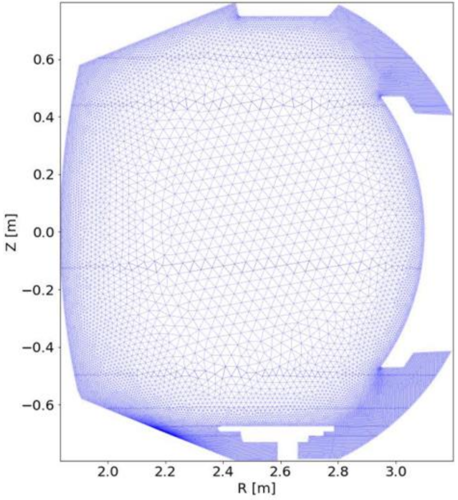
- Fluid transport code based on Hybridized Discontinuous Galerkin method (Giorgiani, et al., 2018)
- Solves Bragiinsky conservative equations for density, momentum and energies for deuterium and electrons
- Simplified neutral fluid model (Horsten, et al. 2018, d'Abusco, et al. 2022)
- **Non-structured, non-aligned**, high-order meshes

★ Full WEST tokamak discharge from start-up to ramp-down has been simulated (d'Abusco, et al. 2022)

❖ Simplified perpendicular transport with constant diffusion

★ Self-consistent turbulent model is now implemented and tested on the whole WEST discharge

★ Modified neutral model with non-constant diffusion



Example of a simulation mesh

G. Giorgiani, et al. "A hybrid discontinuous Galerkin method for tokamak edge plasma simulations in global realistic geometry," J. Comput. Phys., 374, pp.515-532, 2018.
N. Horsten, et al. "Development and assessment of 2D fluid neutral models that include atomic databases and a microscopic reflection model," Nucl. Fusion, 57.11, 116043, 2017.
M.S. d' Abusco, et al. "Core-edge 2D fluid modeling of full tokamak discharge with varying magnetic equilibrium: from WEST start-up to ramp-down," Nucl. Fusion, 62(8), p.086002, 2022.

Turbulent model inside SolEdge3X-HDG tuning

- Diffusion definition $D_k = k\tau = \frac{kR}{c_s}$ ➞ 0 in the region with no interchange instability triggered $(\nabla p, \nabla B) < \Theta / R^2$
- In some regions k value can diverge
- So D_{min}, D_{max} values are limiting diffusion from being too low and too high

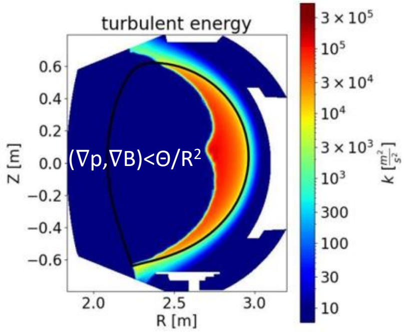
★ SolEdge3X-HDG becomes *unstable for too low diffusion*

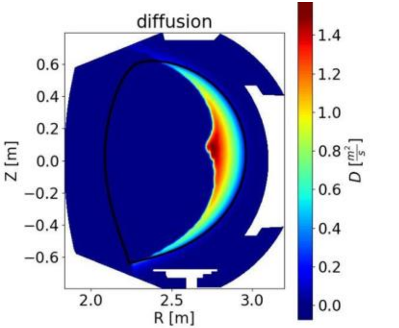
★ Smallest diffusion achieved was D_{min} = 1 m²/s *at given mesh*

★ The flat-top stage D_k with typical L-mode scaling $\lambda_q = 4 q_{cyl} \rho$ was only slightly higher than 1 m²/s

★ The experimental decay length can be 2-3 times higher than the scaling (Gaspar, et al. 2021), so we decided to use $\lambda_q = 2 \times 4 q_{cyl} \rho$

Test simulation profiles

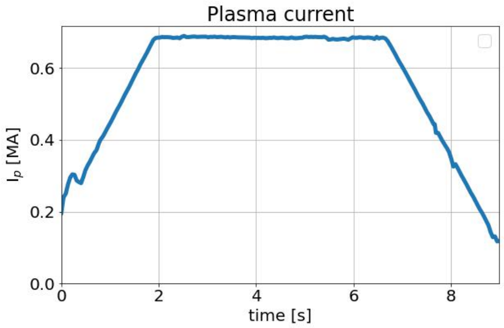


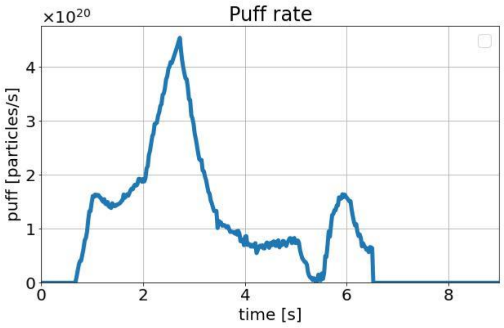


J. Gaspar, Yann Corre, Nicolas Fedorczak, J.P. Gunn, Clarisse Bourdelle, et al.. Divertor power loads and scrape off layer width in the large aspect ratio full tungsten tokamak WEST. Nuclear Fusion, 2021, 61 (9), pp.096027. 10.1088/1741-4326/ac1803. cea-03345900

Full-discharge simulation setup

- WEST **Ohmic** discharge 54487 has been simulated
- **Current** profile and **puff** rate from **WEST IMAS**
- Toroidal magnetic **field** value, **poloidal flux** from **WEST IMAS**
  - *Poloidal magnetic field from database gave hollow profiles* due to lack of resolution in the core plasma
  - It was recalculated using poloidal flux: $B_z = \frac{\partial \psi}{\partial r}\frac{1}{2\pi R}$ $B_r = -\frac{\partial \psi}{\partial z}\frac{1}{2\pi R}$
- **Recycling** coefficient R = 0.998, with R = 0.95 in pump region
- To *avoid too high neutral diffusion values* in far SOL $D_{n_n,max} = 20000$ m^2/s
- Initial solution for first timestep was tuned to approximately have the prefilled particle content in the simulation





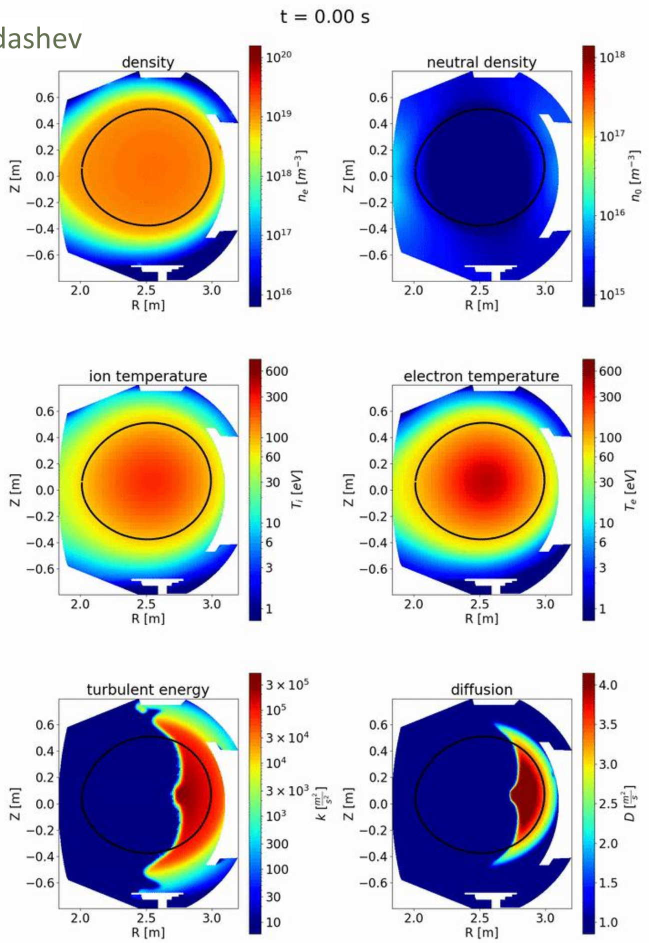
Simulation results

- The simulated turbulent energy **follows the separatrix well** during the whole discharge, including limiter-divertor transition

- Maximum diffusion is generally **higher during the limiter phase** than during flat-top, as expected due to weaker confinement in limiter phase

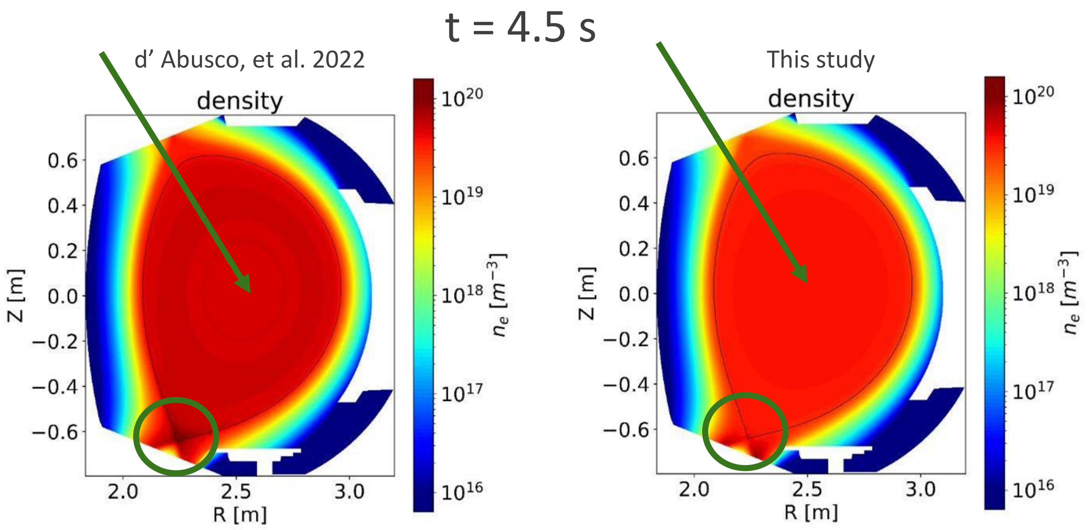
- k-equation defines diffusion in only limited region

- Closure of the k-equation considers SOL physics, whereas **higher turbulence** is simulated in the **core region**



Comparison with previous simulation

- New magnetic field ⇒ no *hole* in density profile
- Increased turbulent transport ⇒ lower core density
- No too high density at the X-point with more attached plasma



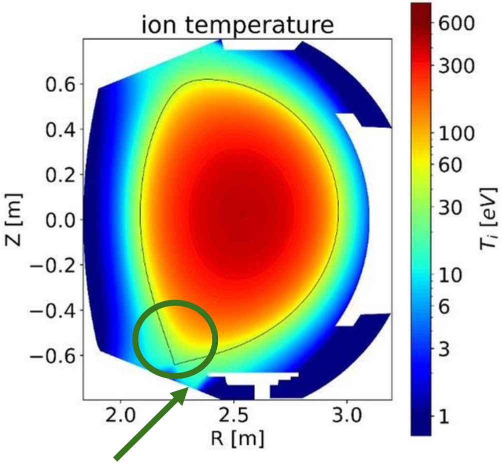
Comparison with previous simulation

- Slightly higher temperature at the separatrix

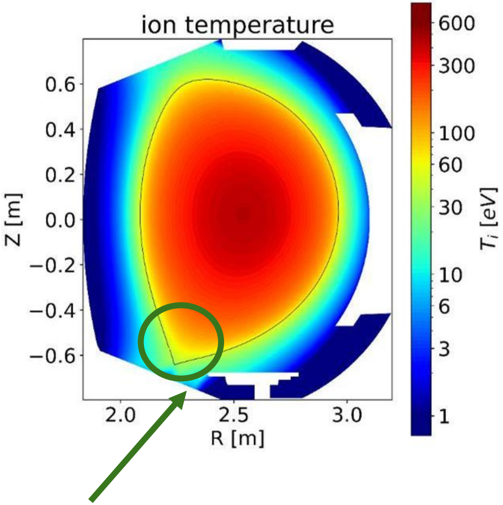
- Lower temperature at the very target

t = 4.5 s

d’ Abusco, et al. 2022



This study

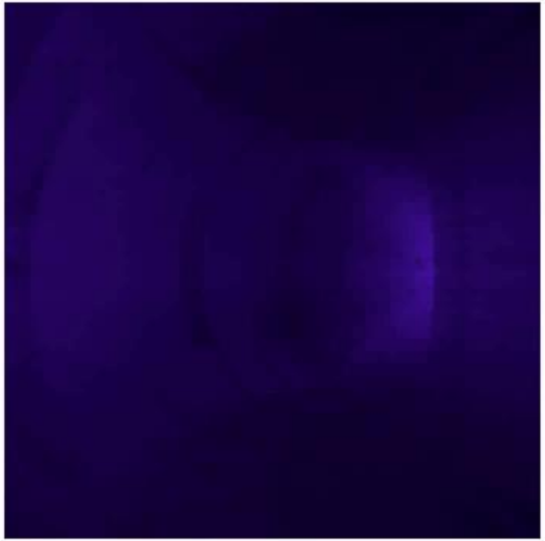


Synthetic diagnostics: visible camera

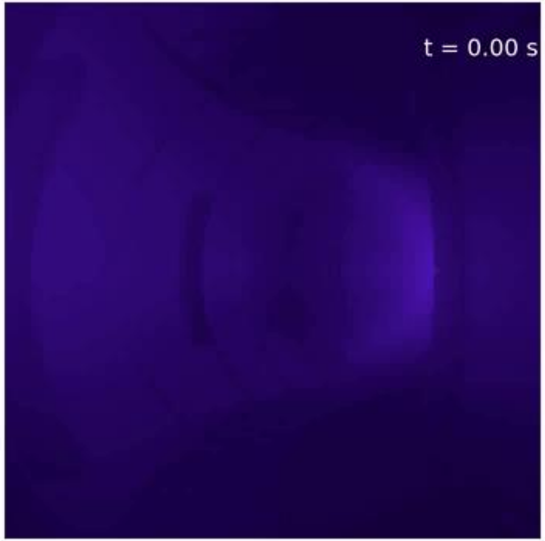
- Deuterium radiation follows the separatrix and different stages of the discharge can be distinguished

- Now more radiation is located near the divertor plates and separatrix

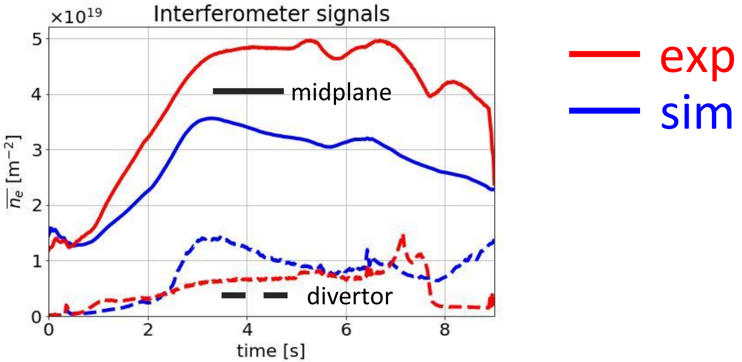
d’ Abusco, et al. 2022, Kudashev, et al. 2022



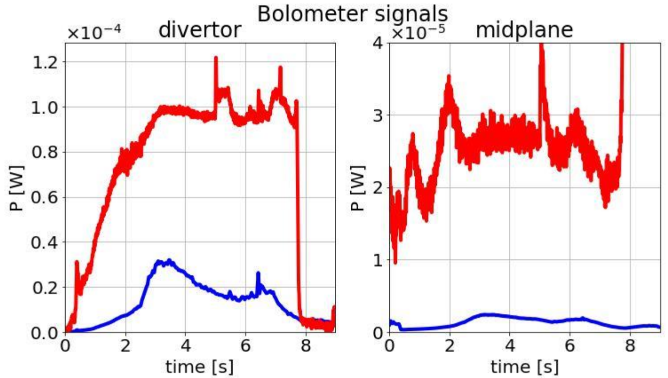
This study simulation



Synthetic diagnostics: bolometer and interferometer



Synthetic bolometer description in (Kudashev, et al., 2022)



- Simulated interferometer data follows the trend of experimental ones
- Lower core density with faster decay length can be explained by too high diffusion values used in simulations

- Absolute value of synthetic signals are much lower due to the absence of impurities
- This effect especially important for channels, covering core regions with synchrotron radiation of the impurities

Conclusion and possible extensions

- **Self-consistent** interchange **turbulence model** has been *implemented* into SolEdge3X-HDG
- **Diffusive** transport is now a **function of space and time** with **non-local** effects due to advection
- **Full WEST discharge 54487 has been simulated** showing numerical robustness of the code to the new implemented features
- Simulated **turbulent energy pattern** corresponds to expected interchange turbulence location on the **LFS separatrix**
- Interchange instability *model is not enough to describe the whole plasma domain*
- We are still in search of new closures and ways to define transport coefficients
- With synthetic diagnostics it will be straightforward to compare new models simulations with the experiments

Thank you for your attention

Decay length

- Simulation values are about 10 mm for pressure, whereas L-mode scaling gives only 3 mm

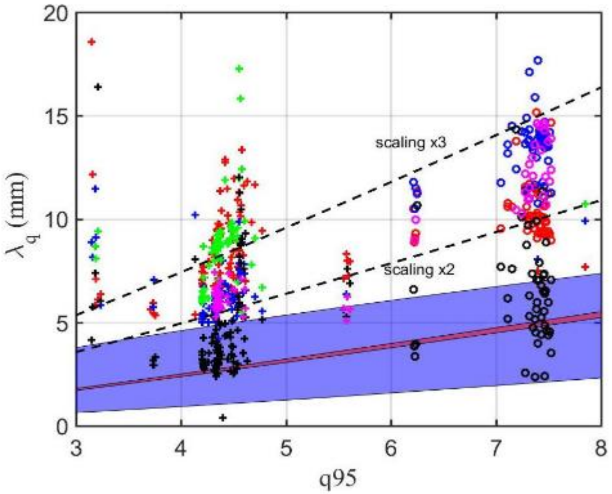
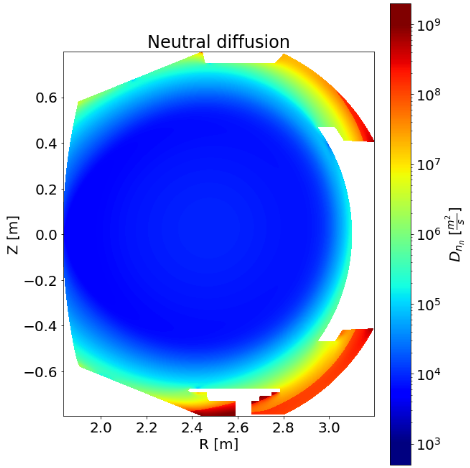


FIG. 5. Heat flux decay length at the midplane λ_q from FBG (red), TC_{Q6A} (blue), TC_{Q1A} (green), LP (magenta) and IR (black) function safety factor q_{95} for deuterium (+) and helium (o) discharges with prediction from L-mode scaling laws from [16] (blue area) the whole set of laws (red area) main scaling law.

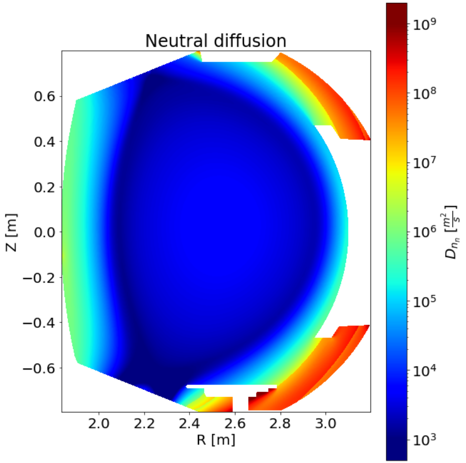
J. Gaspar, Yann Corre, Nicolas Fedorczak, J.P. Gunn, Clarisse Bourdelle, et al.. Divertor power loads and scrape off layer width in the large aspect ratio full tungsten tokamak WEST. Nuclear Fusion, 2021, 61 (9), pp.096027. 10.1088/1741-4326/ac1803. cea-03345900

Neutral diffusion

Limiter phase



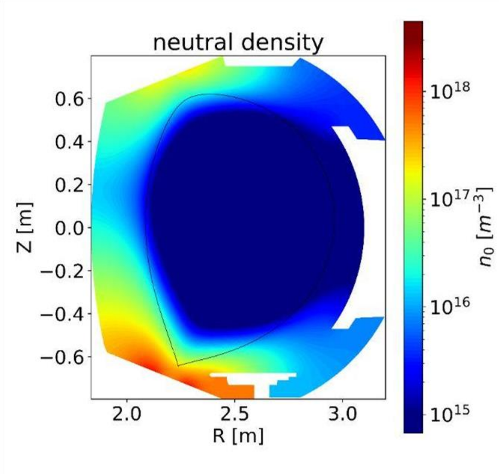
Flat-top phase



Comparison with previous simulation

t = 4.5 s

d’ Abusco, et al. 2022



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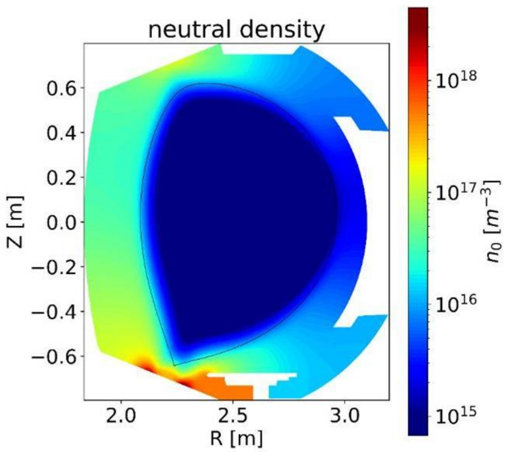
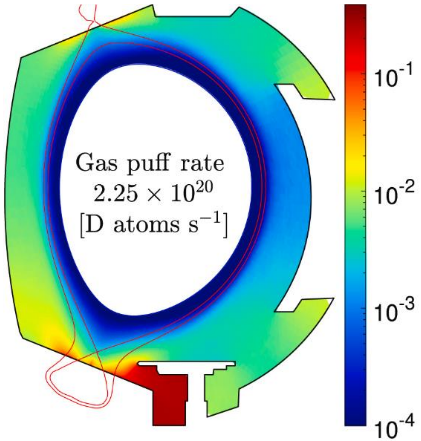


Yang, Hao, et al. "Numerical modelling of the impact of leakage under divertor baffle in WEST." Nuclear Materials and Energy 33 (2022): 101302.



(a) $n_{neu}[10^{19} m^{-3}]$

SolEdge3X-HDG system of equations

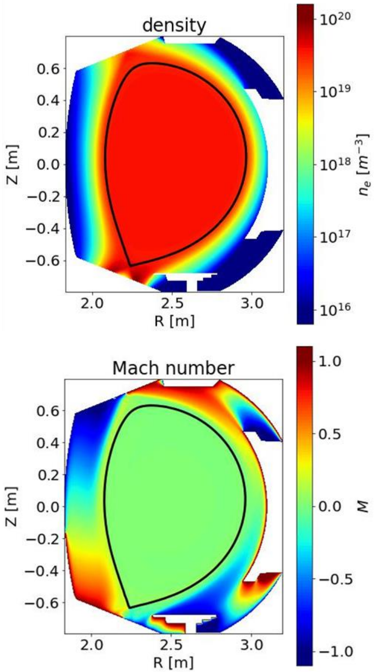
- Quasineutrality is assumed $n = n_i = n_e$
- Continuity equation

$$\partial_t n + \nabla \cdot (nu\mathbf{b}) - \nabla \cdot (D\nabla_\perp n - V_n n \mathbf{b}_\perp) = S_n$$

- Momentum conservation

$$\partial_t(m_i nu) + \nabla \cdot (m_i nu^2 \mathbf{b}) + \nabla_\parallel (k_b n(T_e + T_i)) - \nabla \cdot (\mu \nabla_\perp (m_i nu) - m_i nu V_u \mathbf{b}_\perp) = S_\Gamma$$

- With **b** being magnetic field line direction, $\mathbf{b}_\perp$ perpendicular to magnetic field direction
- m_i ion mass, u is the plasma parallel velocity, T_i, T_e are ion and electron temperatures
- D, μ, V_n, V_u are particle diffusion, viscosity, particle and momentum pinch velocities, all prescribed by the user



SolEdge3X-HDG system of equations

- Ion energy equation

$$\partial_t\left(\frac{3}{2}k_b n T_i + \frac{1}{2}m_i n u^2\right) + \nabla\cdot\left(\left(\frac{5}{2}k_b T_i + \frac{1}{2}m_i n u^2\right)u\mathbf{b}\right)$$
$$- nueE_\parallel - \nabla\cdot\left(\frac{3}{2}k_b(T_i D\nabla_\perp n + n\chi_i\nabla_\perp T_i) - \frac{3}{2}k_b T_i n V_i \mathbf{b}_\perp\right)$$
$$- \nabla\cdot\left(-\frac{1}{2}m_i u^2 D\nabla_\perp n + \frac{1}{2}m_i\mu n\nabla_\perp u^2 - \frac{1}{2}m_i n u^2 V_u \mathbf{b}_\perp\right)$$
$$- \nabla\cdot(k_{\parallel i}T_i^{\frac{5}{2}}\nabla_\parallel T_i\mathbf{b}) + \frac{3}{2}\frac{k_b n}{\tau_{ie}}(T_e - T_i) = S_{E_i}, \quad (3)$$

- Electron energy equation

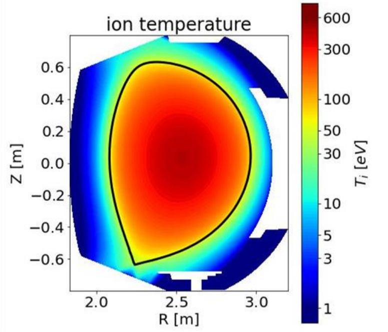
$$\partial_t\left(\frac{3}{2}k_b n T_e\right) + \nabla\cdot\left(\frac{5}{2}k_b T_e u\mathbf{b}\right) + nueE_\parallel$$
$$- \nabla\cdot\left(\frac{3}{2}k_b(T_e D\nabla_\perp n + n\chi_e\nabla_\perp T_e) - \frac{3}{2}k_b T_e n V_e \mathbf{b}_\perp\right)$$
$$- \nabla\cdot(k_{\parallel e}T_e^{\frac{5}{2}}\nabla_\parallel T_e\mathbf{b}) - \frac{3}{2}\frac{k_b n}{\tau_{ie}}(T_e - T_i) = S_{E_e},$$

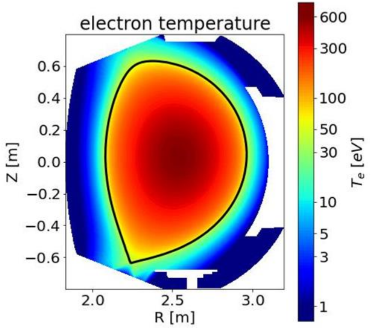
Parallel convection terms

Perpendicular anomalous terms

Parallel transport terms

Temperature exchange





- Inertia of electrons is neglected $enE_\parallel = -\nabla_\parallel(nk_bT_e)$
- D, μ, χ_i, χ_e are particle diffusion, viscosity, ion and electron perpendicular conductivity
- V_n, V_u, V_i, V_e particle, momentum, ion and electron energy pinch velocities, all prescribed by the user

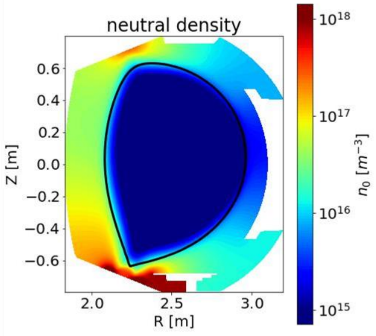
SolEdge3X-HDG system of equations

- Neutrals equation (simplified from Horsten with no neutrals temperature)

$$\partial_t n_n + \nabla \cdot (n_n u \mathbf{b}) + \nabla \cdot (D_{n_n} \nabla n_n) = S_{n_n,iz} + S_{n_n,rec} + S_{n_n}$$

- With diffusion defined:

$$D_{n_n} = \frac{eT[eV]}{m_i n(<\sigma v>_{cx} + <\sigma v>_{iz})}$$



- RHS being ionization sink term, recombination source term and S_{n_n} is particle source defined by puff and recycling at the wall
- Atomic data are splines of OpenADAS (recombination and ionization splines from AMJUEL database
- Other ingredients:
  - Ohmic heating, assuming Z_{eff}=1 and all energy transfers to electrons
  - Bohm boundary conditions imposed on the boundary

Self-consistent turbulent model

- Turbulent energy equation

$$\partial_t k + \nabla \cdot (k u \mathbf{b}) - \nabla \cdot (D_k \nabla_\perp k) = \gamma_I k - c_\varepsilon k^2$$

➢ sink term is obtained assuming stationary point of the RHS (Baschetti PhD, 2019) $k = \gamma_I / c_\varepsilon$

➢ Employing equilibrium of perpendicular and parallel heat transport in SOL $\frac{2\gamma_e \lambda_q^2}{\chi_e} \approx \frac{L_\parallel}{c_s}$

➢ Assuming that heat conductivity is equal to D_k and connection length being $L_\parallel = 2\pi q R$

$$c_\varepsilon = \gamma_I \frac{\pi q_{\text{cyl}} R^2}{\gamma_e \lambda_q^2 c_s^2}$$

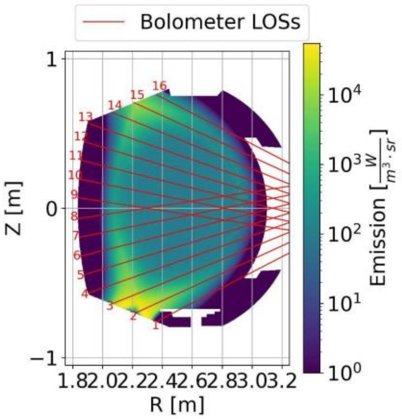
with

$$\lambda_q = 4 q_{\text{cyl}} \rho C_\lambda$$

$$q_{\text{cyl}} = \frac{B_t a}{B_p R}$$

$$\rho = \frac{m_i c_s}{eB}$$

Synthetic diagnostics

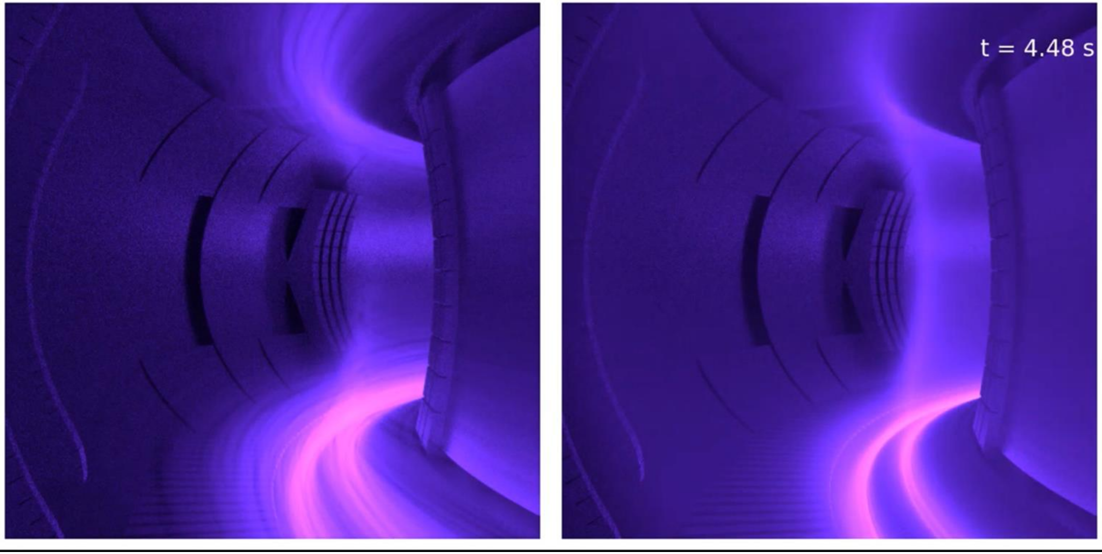


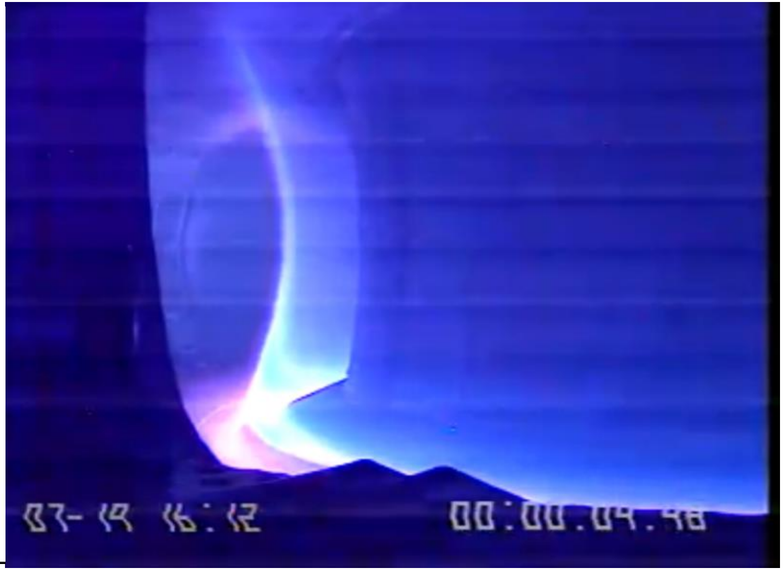
Bolometer LOS

Visible camera digital twin:

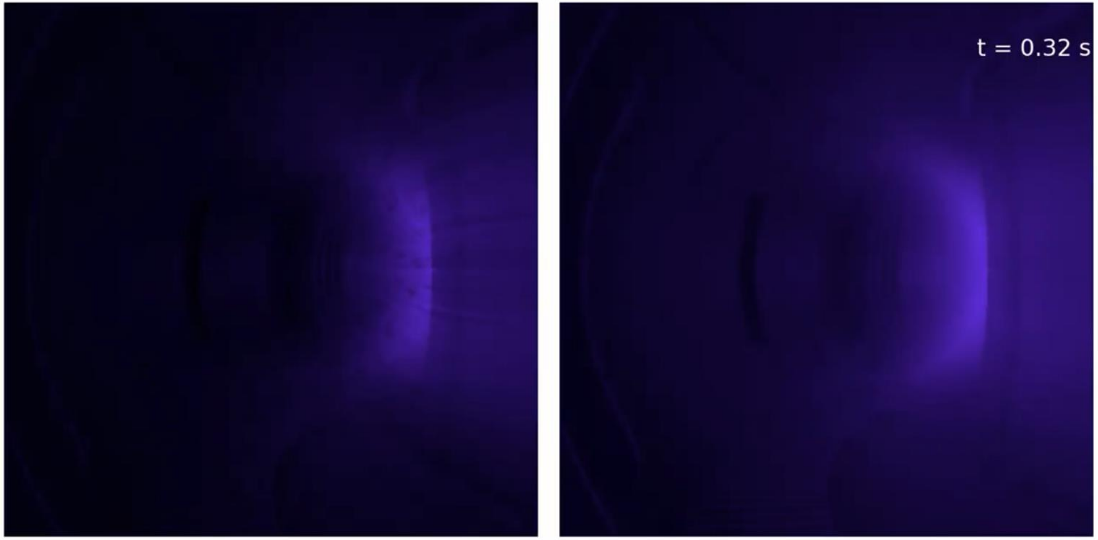
- Deuterium Balmer lines (α, β,γ, δ, ε)
- Rough tungsten PFC model
- Simplified pinhole camera
- No optical elements considered

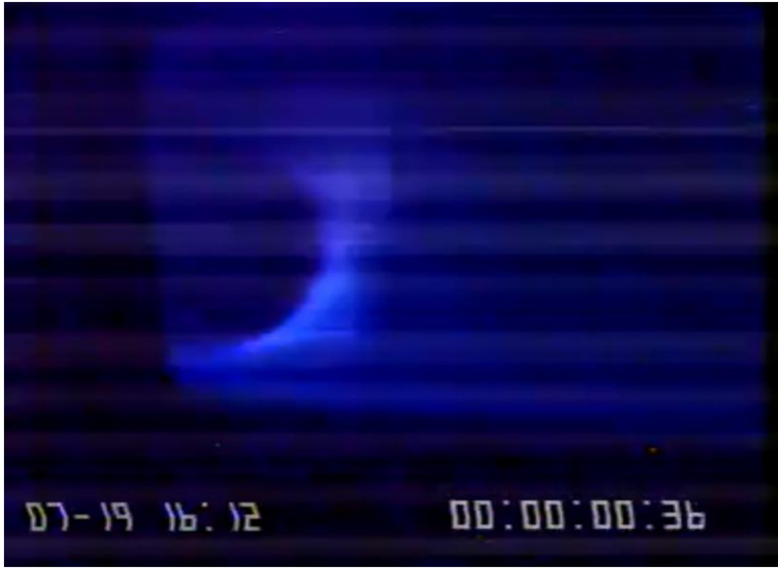
Visible camera (flat-top)





Visible camera (limiter)





Previous simulation