# Core-edge transport modeling of a full WEST discharge with SOLEDGE-HDG


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# Context

- **Aim:** turbulent transport modeling and prediction of the entire discharges to investigate heat and particle exhaust
- Most transport simulations are focused on steady state, edge or core plasma:
  - large uncertainties on ramp-up phase with neglecting loads on limiters
  - core and edge plasma are either not coupled or through crude boundary conditions
- In this **work**:
  - two improvements of SolEdge-HDG model are demonstrated
    - revision of transverse turbulent modelling (starting from Baschetti, et al. 2021)
    - modification of the sources: advanced fluid neutrals and additional heating
  - Two physical points addressed:
    - Evolution of heat and particle fluxes at the PFC during the ramp-up
    - Distribution of heat and energy between ions and electrons with respect to different heating regimes

# Outline

- SolEdge-HDG model
- A k-model to go towards a self-consistent transport model
- An advanced fluid neutral model with non-constant diffusion
- Results:
  - Time evolution of heat and particle fluxes at the wall during ramp-up WEST discharge
  - Repartition between ion and electron channels with additional heating
- Preliminary investigation on growth rate modification

# SolEdge-HDG

- Fluid transport code based on Hybridized Discontinuous Galerkin method (Giorgiani, et al. 2018)
- Magnetic equilibrium free high-order meshes
- Solves Braginskii conservative equations for plasma density, momentum, ion and electron energies for deuterium and electrons
- But! How to define the cross-field transport coefficients?

continuity

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

momentum conservation

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

ion energy

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

electron energy

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

# SolEdge-HDG fluid turbulent model revision

- Heuristic model of turbulent model transport (Baschetti et al. NF 2021)

turbulent energy evolution

$$\partial_t k + \boldsymbol{\nabla} \cdot (k v_{\parallel} \mathbf{b}) - \boldsymbol{\nabla} \cdot (D_k \boldsymbol{\nabla}_{\perp} k) = \gamma_I k - c_{\varepsilon} k^2$$

1. parallel transport with plasma parallel velocity
2. Perpendicular diffusion with self-consistently defined D:

$$D_k = k\tau_{\parallel} = k\frac{L_{\parallel}}{c_s} = k\frac{2\pi q R}{c_s}$$

3. The same coefficient is used for plasma transport equations

$$D_k = D = \mu = \chi_i = \chi_e$$

# SolEdge-HDG fluid turbulent model revision

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turbulent energy evolution

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

1. Growth rate due to interchange instability

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

2. Sink rate closure by assumption of energy balance in SOL

$\frac{\chi_e p_e}{\lambda_q^2} = \frac{2\gamma_e p_e c_s}{L_\parallel}$ and $\chi_e = D_k = k\frac{L_\parallel}{c_s}$ and $k = \gamma_I / c_\varepsilon$ ⇒ $c_\varepsilon = \frac{L_\parallel^2}{2\gamma_e \lambda_q^2 c_s^2}\gamma_I$

Scaling

$$\lambda_q = 4 q \rho_L$$

# SolEdge-HDG neutral model

- First introduced for SolEdge-HDG in (d' Abusco, et al. 2022)

continuity neutrals

$$\partial_t n_{\mathrm{n}} - \nabla \cdot (D_{n_{\mathrm{n}}} \nabla_\perp n_{\mathrm{n}}) = -n_{\mathrm{n}} n < \sigma v >_{\mathrm{iz}} + n^2 < \sigma v >_{\mathrm{rec}}$$

- recently modified with self-consistent neutral diffusion coefficient (accepted to Front. Phys.)

depends on mean free path of neutrals

$$D_{n_{\mathrm{n}}} = \frac{eT_{\mathrm{i}}[\mathrm{eV}]}{m_{\mathrm{i}} n(< \sigma v >_{\mathrm{cx}} + < \sigma v >_{\mathrm{iz}})}$$

- Neutral moment and boundary conditions should be modified

$$-D_{n_{\mathrm{n}}} \nabla n_{\mathrm{n}} \cdot \mathbf{n} = -R(-D_n \nabla_\perp n \cdot \mathbf{n} + nu\mathbf{b} \cdot \mathbf{n}) - \Gamma_{\mathrm{puff}} \cdot \mathbf{n}$$

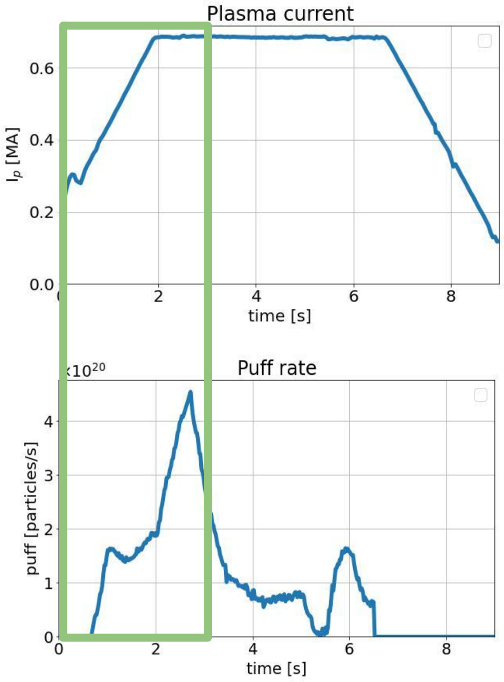
# Simulation set-up

- WEST **Ohmic** discharge #54487
- *Current, magnetic field and puff* rate from **WEST IMAS**
- Recycling R = 0.998
- Two transport models:
  - constant $D = \mu = \chi_i = \chi_e = 0.5\ \mathrm{m^2/s}$
  - variable $D = \mu = \chi_i = \chi_e = D_k = k\frac{L_\parallel}{c_s}$

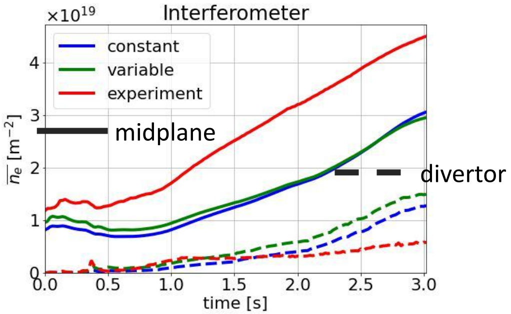
for numerical stability

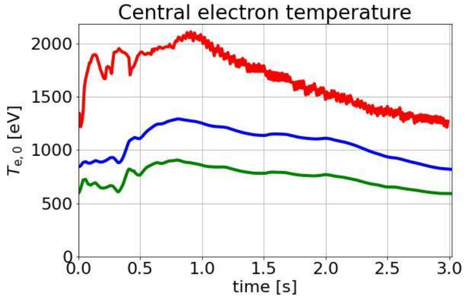
$D_{\mathrm{min}} = 0.3\ \mathrm{m^2/s}$ $\quad D_{\mathrm{max}} = 20\ \mathrm{m^2/s}$ $\quad D_{n_n} = 1000\ \mathrm{m^2/s}$

- Focusing ramp-up (up to t = 3s)

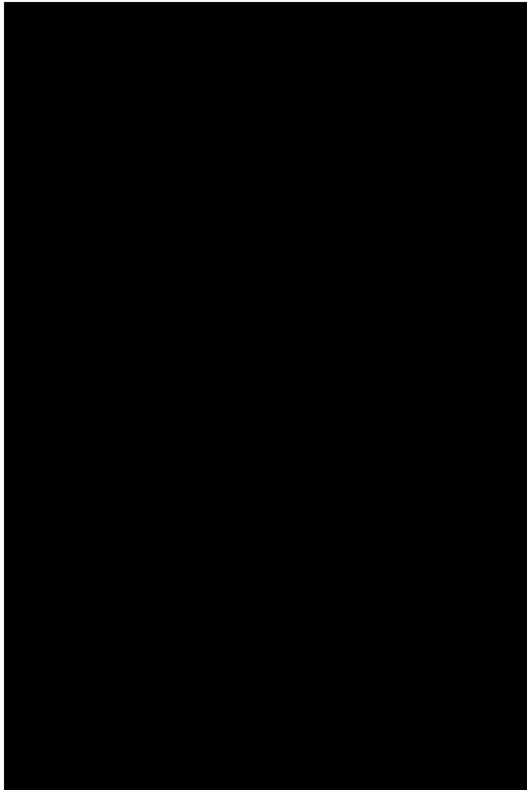


# Evolution of core plasma parameters



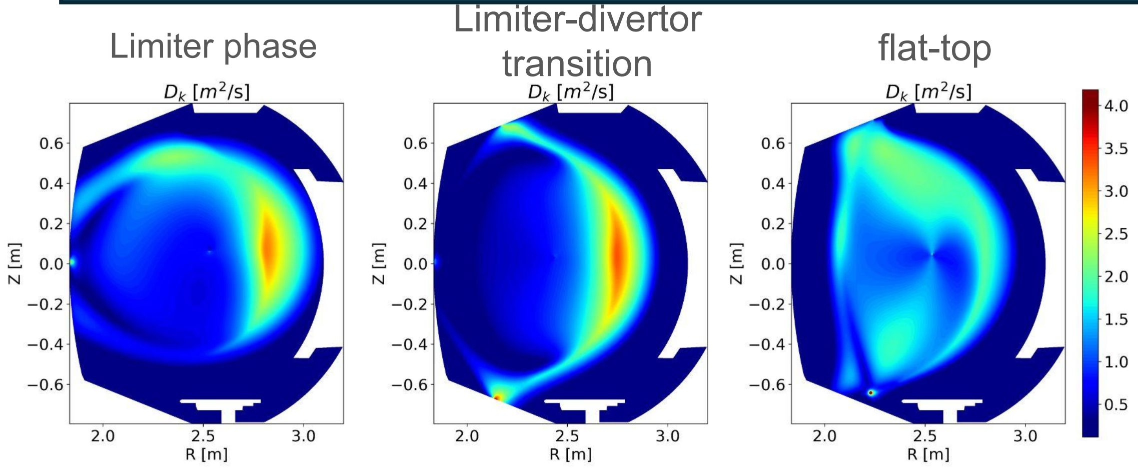



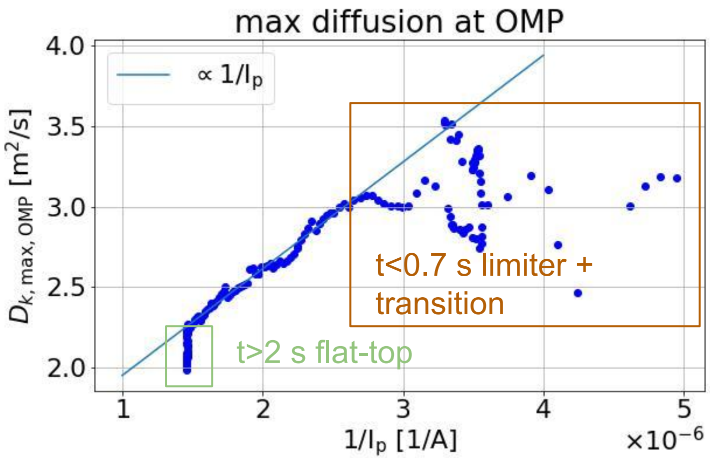

Evolution of poloidal profiles of plasma parameters for simulation with variable diffusion



- Turbulent model causes higher perpendicular transport:
  - wider density profile
  - lower energy content
- Trends are similar, but absolute values are not:
  - should be higher recycling (probably varying)
  - More heating ⇒ take into account higher Zeff

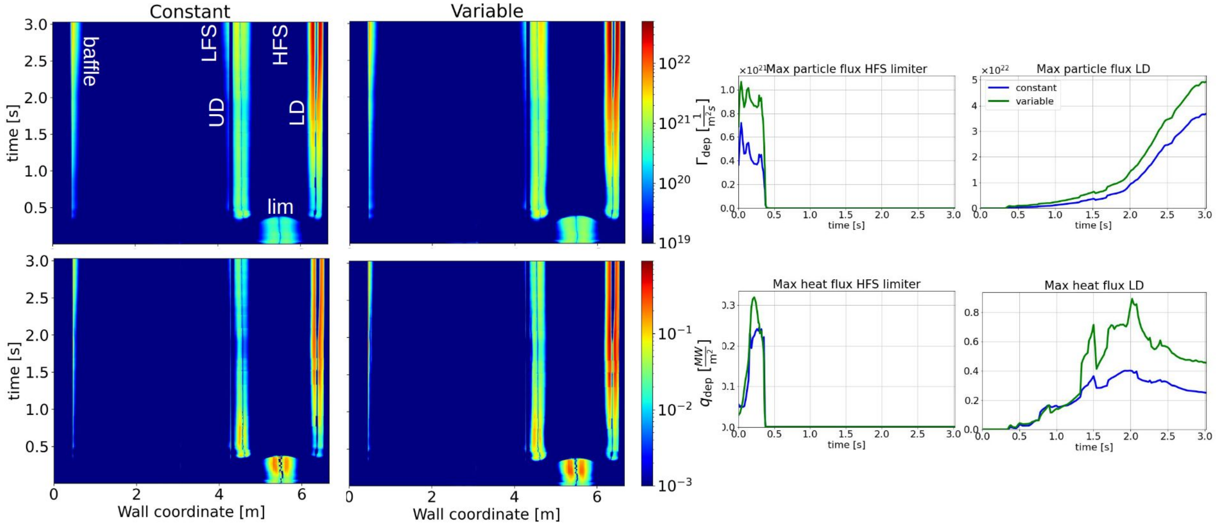
# Predicted diffusion




- The model predicts higher transport at LFS and at regions with high connection length ar plasma edge
- Non-local turbulent transport effects
- During ramp-up of current the maximum value of diffusion decreases as 1/Ip, which corresponds to global confinement scaling

# Evolution of simulated fluxes onto the wall

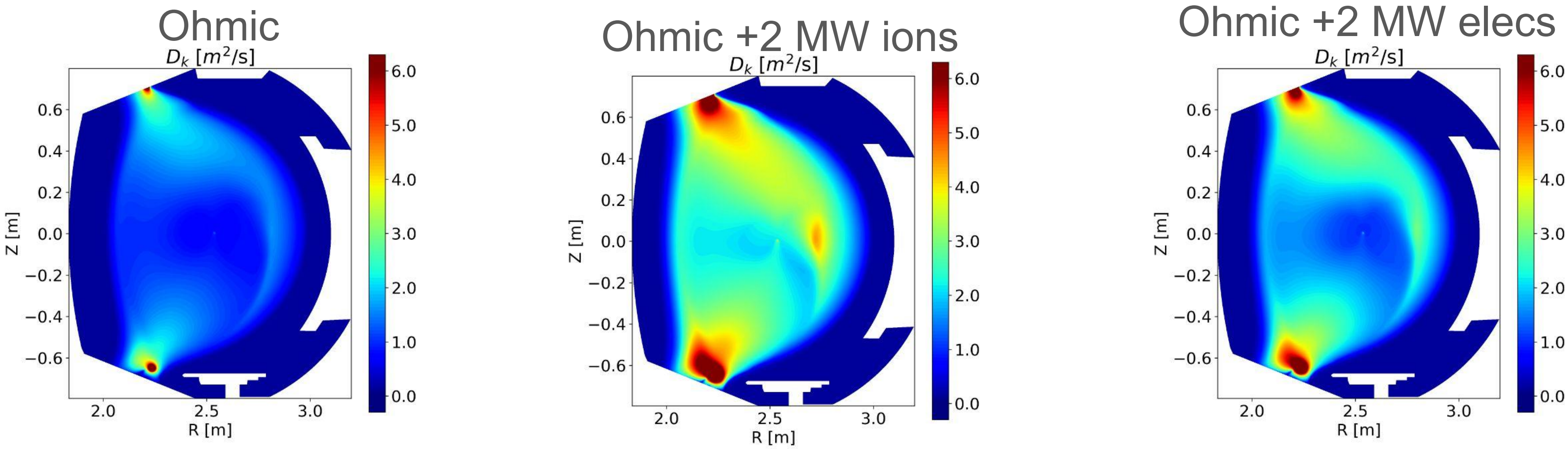



- Increased turbulent transport causes higher and wider profiles particle fluxes
- However, during first 1.3 s peak heat values in both simulations are comparable
- Significant fluxes predicted on baffle and upper divertor (especially during limiter-divertor transition)

# Steady state additional heating simulation

- Gaussian circle source of 2 MW applied to ions or electrons
- Centered at the magnetic axis of plasma with width of 15 cm
- Equilibrium at t=4.5 s of discussed discharge, steady-state
- Recycling R = 0.998
- Transport model:
    - plasma $D = \mu = \chi_i = \chi_e = D_k = k\frac{L_\parallel}{c_s}$
    - neutrals $D_{n_\mathrm{n}} = \frac{eT_\mathrm{i}[\mathrm{eV}]}{m_\mathrm{i} n(<\sigma v>_\mathrm{cx} + <\sigma v>_\mathrm{iz})}$

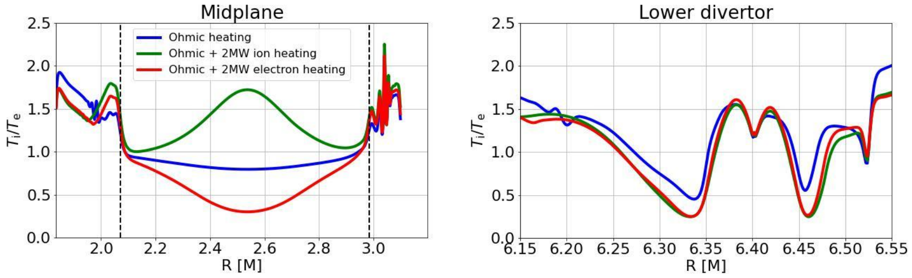
# Turbulent diffusion for different heating




- Additional heating causes significantly higher transport at both divertors
- Since the growth rate is proportional to ion pressure gradient, ion heating leads to more transport increase

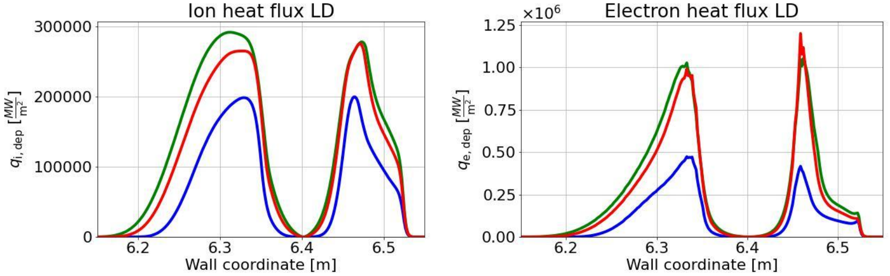
# Ion/electron heat channel distribution

## $T_i/T_e$




- In far SOL heating generally leads to $T_i/T_e$ reduction
- In core the change $T_i/T_e$ corresponds to the heating channel

## Heat exhaust




- Additional heating goes preferentially through electron channel
- Slightly lower heat fluxes for the electron heating are due to lower plasma resistivity and hence lower Ohmic heating

# Conclusions

- On the way of physical model enrichment in SolEdge-HDG:
  - turbulent self-consistent transport model has been revised
  - neutral model now employs self-consistent diffusion coefficient
  - additional heating sources has been implemented
- Simulation of ramp-up of WEST discharge:
  - Turbulent diffusivity scales as 1/Ip and mostly localized at separatrix (LFS), and X-points
  - Heat and particle fluxes are increased compared to constant diffusion simulation
- Additional heating sources simulation
  - Significantly increased turbulent transport near lower and upper divertor
  - Reduction of $T_i/T_e$ in far SOL
  - Additional heating escapes plasma mostly through electron channel

# Perspectives: drift-wave instability and parallel losses

- We start from set of 2 equations:

continuity equation

$$\partial_t n_e + \nabla\cdot\Big(n_e\big(\boldsymbol{v}_E + \boldsymbol{v}_{*,e}\big)\Big) + \nabla\cdot\Big(-D_\perp \nabla_\perp n_e\Big) = S_n - \nabla_\parallel \Gamma_{\parallel,e}$$

parallel losses

divergence of total current

$$\nabla\cdot\Big(\boldsymbol{J}_{pol} + \sum_{\text{species }\alpha}\big(q_\alpha n_\alpha \boldsymbol{v}_E + q_\alpha n_\alpha \boldsymbol{v}_{*,\alpha}\big)\Big) = -\nabla_\parallel J_\parallel$$

electric drift

diamagnetic drift

$$\boldsymbol{J}_{pol} = \frac{\boldsymbol{B}}{B^2}\times m_i \frac{d}{dt}\Big(n_i\big(\boldsymbol{v}_E + \boldsymbol{v}_{*,i}\big)\Big)$$

polarization current

- Leaving 1st order terms in 1st equation and up to 2nd order in the 2nd
  Linearizing, low β limit, Boussinesq approximation for density, cold ion limit:

$$\partial_t n + D_B \boldsymbol{b}\cdot\big(\nabla\phi \times \nabla\bar{n}\big) - D_\perp \nabla_\perp^2 n = S_n - \sigma_{n,n}\, n + n_0 \sigma_{n,\phi}\, \phi$$

$$\partial_t W - \nu_\perp \nabla_\perp^2 W - 2D_B \boldsymbol{b}\cdot\Big(\frac{\nabla B}{B}\times\frac{\nabla n}{n_B}\Big) = -\sigma_{\phi,n}\frac{n}{n_B} + \sigma_{\phi,\phi}\,\phi$$

vorticity

$$W = \rho_s^2 \nabla_\perp^2 (eU/T_e)$$

# Perspectives: linearization of loss terms

- We want to linearize parallel losses in a simple form:

$$-\boldsymbol{\nabla}_{\parallel}\boldsymbol{\Gamma}_{e\parallel,e} = -\sigma_{n,n}n + n_0\sigma_{n,\phi}\phi$$
$$\frac{1}{en_B}\boldsymbol{\nabla}_{\parallel}\boldsymbol{J}_{\parallel} = -\sigma_{\phi,n}\frac{n}{n_B} + \sigma_{\phi,\phi}\phi$$

Confined region?

yes → Electron collisions

no → Collision length much smaller than connection length? $\frac{L_{coll}}{L_{\parallel}} \ll \sqrt{m_e/m_i}$

yes → Electron collisions

$$\sigma_{n,n} = \sigma_{\phi,n} = \sigma_{n,\phi} = \sigma_{\phi,\phi} = C_{\parallel} = \frac{T_e k_{\parallel}^2}{\nu_e m_e}$$

no → Sheath limited regime

$$\sigma_{n,n} = \sigma_{n,\phi} = \sigma_{\phi,\phi} = C_{\parallel} = \frac{c_s}{L_{\parallel}}$$
$$\sigma_{\phi,n} = 0$$

# Perspectives: adding more physics to turbulent model

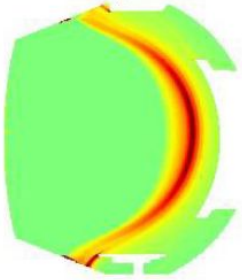
- Current growth rate does not include interchange instability damping

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

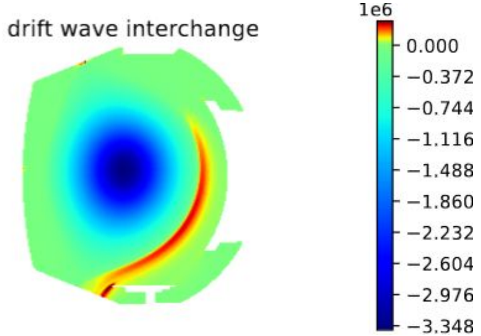
$$\gamma = \frac{-A + \sqrt{\frac{g_r + |g|}{2}}}{\tau}$$

Preliminary estimation on fixed plasma background

old model



new model



# Perspectives: stability analysis

- Making fourier transformation and solving dispersion equation:

$$\gamma = \frac{-A + \sqrt{\frac{g_r + |g|}{2}}}{\tau}$$

$$A = \frac{a_n + a_\phi}{2}$$

$$g_r = A^2 - a_n a_\phi - \frac{b_{nr} b_{\phi r} - b_{ni} b_{\phi i}}{C_\parallel / \Omega_i}$$

$$g_i = -\frac{b_{nr} b_{\phi i} + b_{ni} b_{\phi r}}{C_\parallel / \Omega_i}$$

$$\frac{1}{\tau} = \sqrt{C_\parallel \Omega_i}$$

polarization current

parallel losses

$$a_n = \frac{D_\perp}{D_B d_\perp} + (C_\parallel / \Omega_i)^{1/2}$$

$$a_\phi = \frac{\nu_\perp}{D_B d_\perp} + d_\perp$$

electric drift

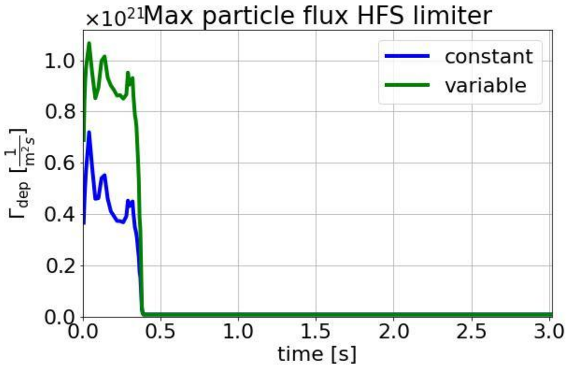
$$b_n = \frac{\rho_\star}{\sqrt{2} d_\perp^{1/2}} \left( \widehat{\boldsymbol{e}}_R \cdot \frac{a \boldsymbol{\nabla} \bar{n}}{n_B} - \widehat{\boldsymbol{e}}_z \cdot \frac{a \boldsymbol{\nabla} \bar{n}}{n_B} \right) + i (C_\parallel / \Omega_i)^{3/4}$$

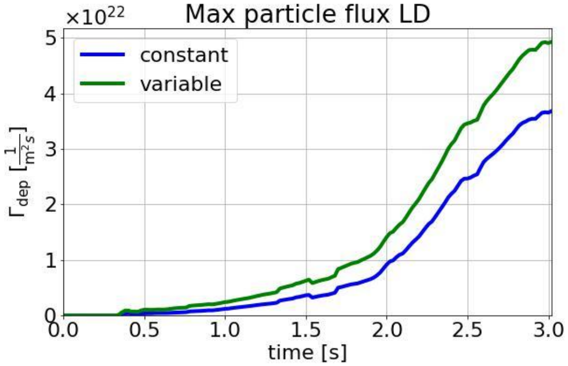
$$b_\phi = -\sqrt{2} d_\perp^{1/2} \rho_\star \left( \widehat{\boldsymbol{e}}_R \cdot \frac{a \boldsymbol{\nabla} B}{B} \right) + i \frac{C_{\parallel,*}}{C_\parallel} d_\perp (C_\parallel / \Omega_i)^{3/4}$$

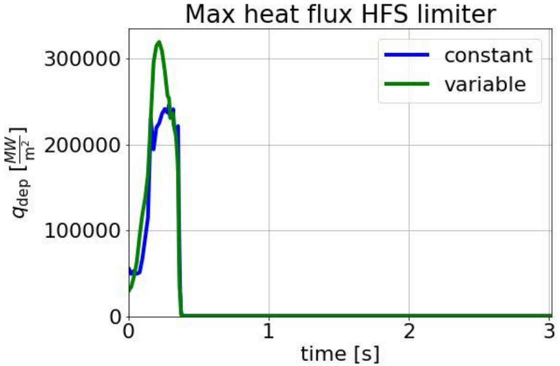
diamagnetic drift

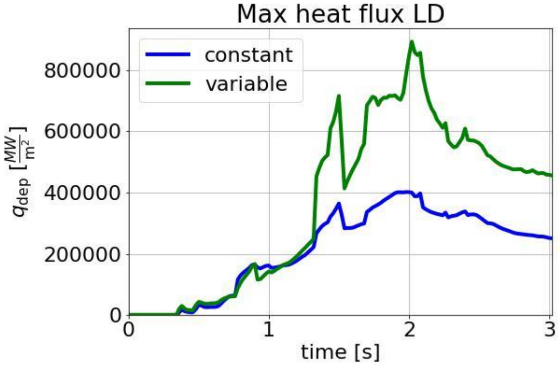
- Parallel losses act generally as a damping term
- Drifts are driving the instability
- Though interplay between different terms should be studied in details

# Max fluxes for varying equilibrium



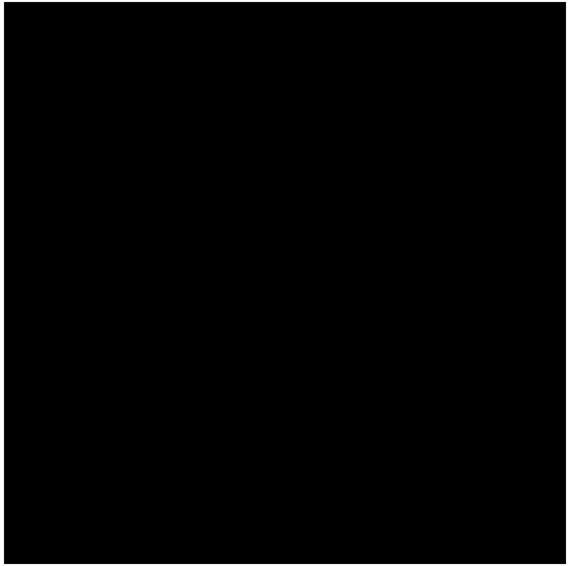



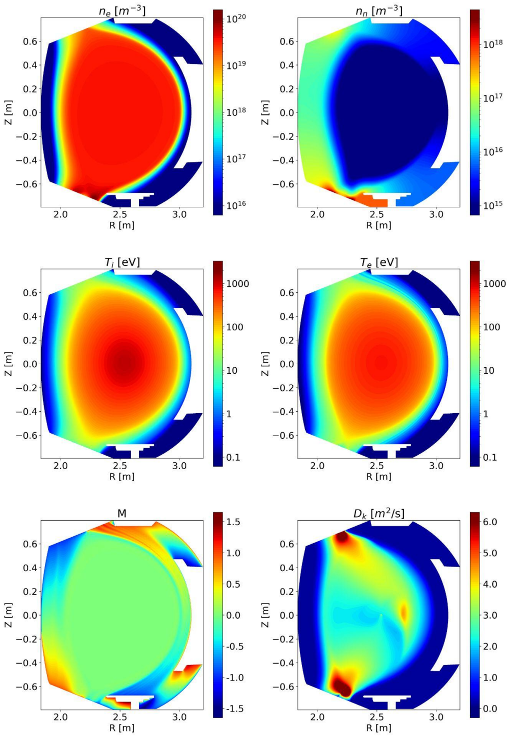
# SolEdge-HDG

- Fluid transport code based on Hybridized Discontinuous Galerkin method (Giorgiani, et al. 2018)
- Magnetic equilibrium free, high-order meshes

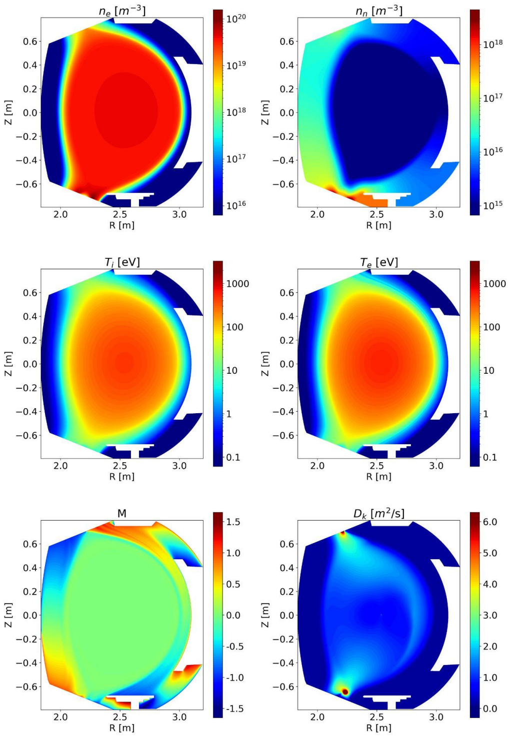


# Overview poloidal profiles

Ohmic +2 MW ions




Ohmic




Ohmic +2 MW elecs