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Introducing electromagnetic effects in Soledge3X

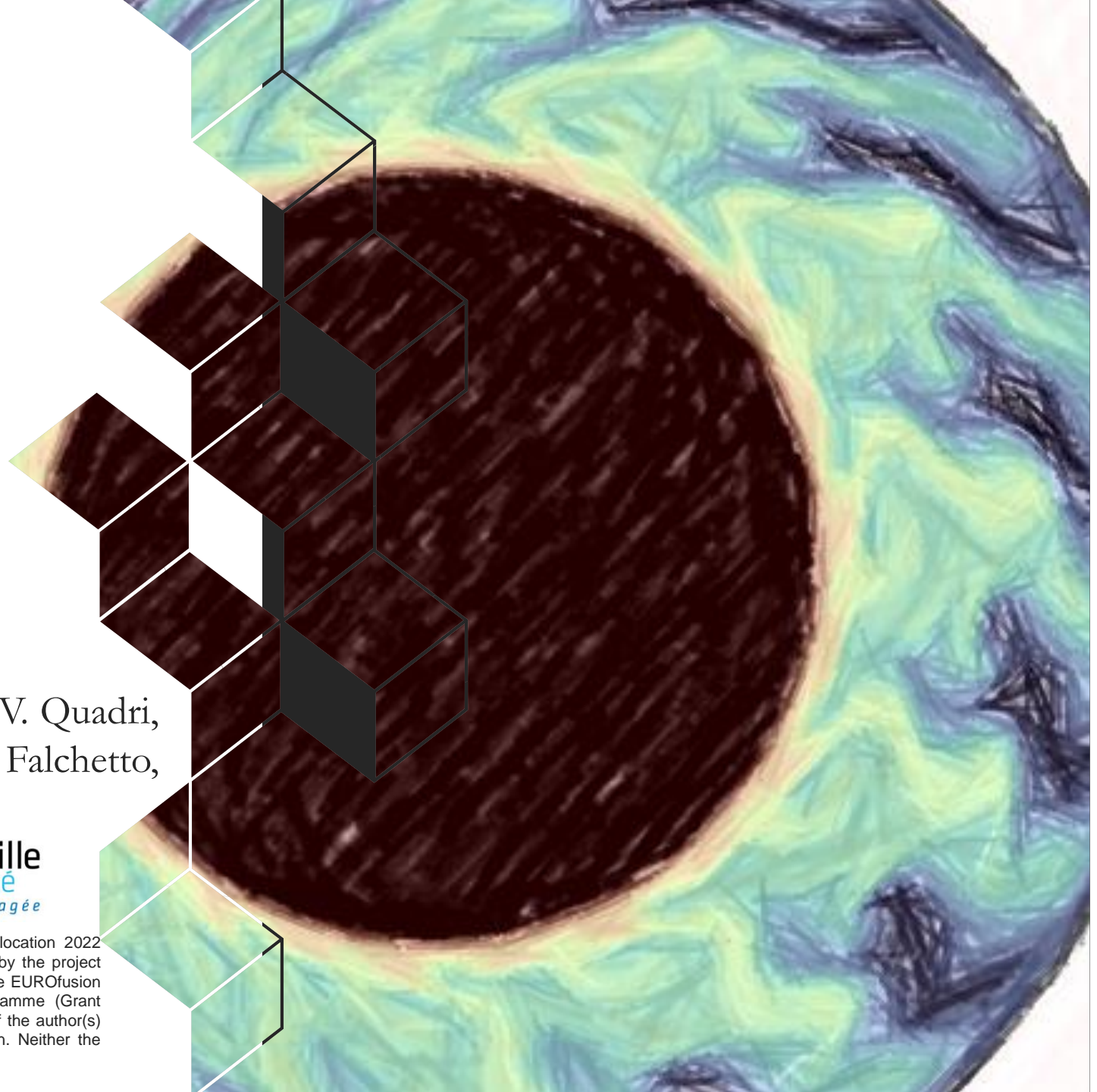
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N. Rivals, G. Ciruolo, H. Yang, K. Galazka, G. Falchetto,
and the SOLEDGE3X team.



EUROfusion



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Outline

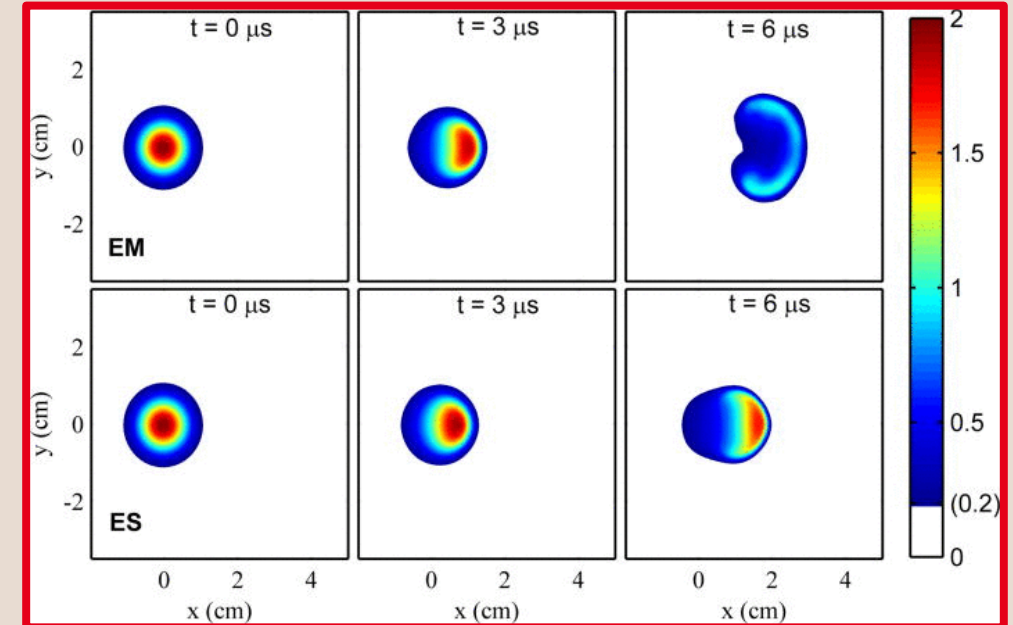
1. **Electrostatic versus Electromagnetic models**
2. **A new vorticity system for Soledge3X**
3. **Verification and validation of the model**
4. **First electromagnetic turbulent simulations**
5. **Conclusions and perspectives**



1 ■ Electrostatic versus electromagnetic models

Do we need electromagnetic effects?

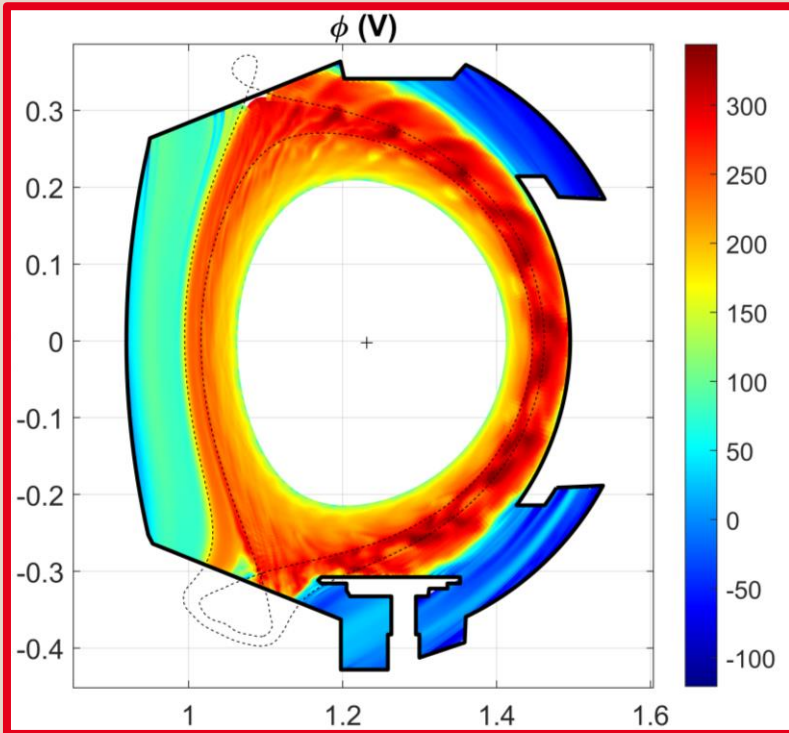
- Non-negligible effects on the plasma
 - Existence of drift Alfvén turbulence [Scott, PPCF 1997]
 - Impact on filament shape in turbulent blob propagation [Lee et al, JNM 2015]
 - Stronger effects for high- β plasmas
- Electron inertia effects are also needed
 - Constrain the shear Alfvén wave speed to physical values [Dudson et al, PPCF 2021]
 - Improvement of the numerical stability [Stegmeir et al, PoP 2019]
- Turbulent simulations on large machines (e.g. ITER) require electromagnetic effects



*Propagation of a plasma blob
from [Lee et al, JNM 2015]
top: electromagnetic, bottom: electrostatic*

$$\text{Key parameter: } \beta = \frac{p}{p_{mag}} = \frac{enT}{B^2/2\mu_0}$$

The electrostatic vorticity equation



WEST turbulent profile

The electric field for $E \times B$ drifts is obtained from the potential: $\mathbf{E}_\perp = -\nabla_\perp \Phi$

■ The potential appears in:

- the vorticity $\Omega = \nabla \cdot \left[\frac{m_i n_i}{e Z_i B^2} \nabla_\perp \Phi + \frac{m_i}{e Z_i^2 B^2} \nabla_\perp p_i \right]$

for the polarization current $\nabla \cdot \mathbf{j}_\parallel \mathbf{b} = -\partial_t \Omega + \nabla \cdot \mathbf{j}_\Omega$

- the parallel electric field $E_\parallel \mathbf{b} = -\nabla_\parallel \Phi$

for Ohm's law $j_\parallel = \sigma_\parallel \left(E_\parallel + \frac{1}{en_e} (\mathbf{b} \cdot \nabla_\parallel p_e + R_{e,\parallel}) \right)$

■ The quasineutral assumption $\nabla \cdot \mathbf{j}^{tot} = 0$ leads to the „vorticity“ equation on Φ :

$$\nabla \cdot \left[\frac{m_i n_i}{e Z_i B^2} \partial_t \nabla_\perp \Phi + \nabla \cdot (\sigma_\parallel \nabla_\parallel \Phi) \right] \mathbf{b} = \nabla \cdot \left(\sigma_\parallel \frac{1}{en_e} (\nabla_\parallel p_e + R_{e,\parallel}) \right) \mathbf{b} + \nabla \cdot (\mathbf{j}^* + \mathbf{j}_S + \mathbf{j}_\Omega) \mathbf{b}$$

Ratio between diffusion coefficients: $> 10^6$

High anisotropy \rightarrow poor numerical condition !



2 ■ A new vorticity system for Soledge3X

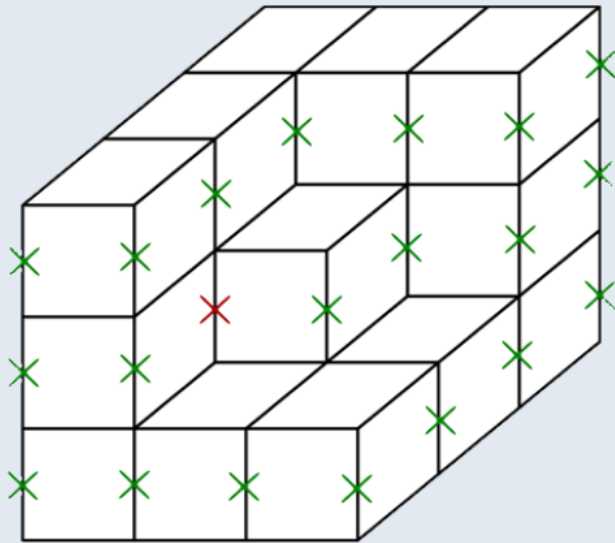
The electromagnetic vorticity equation

Implicit system on 3 fields: electric potential Φ ; parallel magnetic vector potential A_{\parallel} ; parallel current density j_{\parallel}

$$\nabla \cdot \left[\frac{m_{\alpha} n_{\alpha}}{B^2} \partial_t \nabla_{\perp} \Phi \right] = \nabla \cdot (j_{\parallel} \vec{b}) - \partial_t \Omega_{\pi} \quad (1) \quad \text{Vorticity equation}$$

$$j_{\parallel} + \frac{\sigma_{\parallel} m_e}{n_e e^2} \left(\frac{\partial j_{\parallel}}{\partial t} - \vec{\nabla} \cdot (v_e \vec{\nabla}_{\perp} j_{\parallel}) \right) = \sigma_{\parallel} \left(-\nabla_{\parallel} \Phi - \partial_t A_{\parallel} + \frac{T_e}{e} \nabla_{\parallel} \log(n_e) + \frac{1.71}{e} \nabla_{\parallel} T_e \right) \quad (2) \quad \text{Ohm's law}$$

$$\Delta_{\perp} A_{\parallel} = -\mu_0 j_{\parallel} \quad (3) \quad \text{Ampère's law}$$



A_{\parallel} and j_{\parallel} are defined on a poloidally and toroidally staggered grid

No points for A_{\parallel} and j_{\parallel} needed on the sheath:

- Dirichlet $A_{\parallel}^{BC} = 0$ on the sheath and tangential wall BC
- The sheath current is directly enforced in the vorticity equation

$$\left(1 + \frac{\sigma_{\parallel} m_e}{n_e e^2} \partial_t \right) j_{\parallel}^{BC} = j_{sat} (1 - e^{\Lambda - \Phi/T_e})$$

- Neumann $\nabla^{BC} j_{\parallel} = 0$ for the perpendicular diffusion operator on j_{\parallel}

Implementation details

A coupled implicit system is solved on the potentials Φ and A_{\parallel} , the current j_{\parallel} is updated a posteriori

$$\begin{pmatrix} \hat{\partial}_t \hat{\nabla} \cdot [\hat{D}_{\perp} \hat{\nabla}_{\perp} \circ] + \hat{\nabla} \cdot [\hat{D}_{\parallel} \hat{\nabla}_{\parallel} \circ \vec{b}] & \beta_0 \hat{\partial}_t \hat{\nabla} \cdot [\hat{D}_{\parallel} \circ \vec{b}] \\ \hat{D}_{\parallel} \hat{\nabla}_{\parallel} \circ & \beta_0 \hat{D}_{\parallel} \hat{\partial}_t \circ - \hat{\nabla} \cdot [\hat{\nabla}_{\perp} \circ] \end{pmatrix} \begin{pmatrix} \hat{\Phi}^{n+1} \\ \hat{A}_{\parallel}^{n+1} \end{pmatrix} = \begin{pmatrix} \hat{\nabla} \cdot [\hat{D}_t \hat{j}_{\parallel}^n \vec{b}] + RHS^{\Phi} \\ \hat{D}_t \hat{j}_{\parallel}^n + RHS^{A_{\parallel}} \end{pmatrix}$$

with the coefficients $\hat{D}_{\perp} = \frac{\hat{m}_i \hat{n}_i}{\hat{B}^2}$, $\hat{D}_{\parallel} = \frac{\hat{\sigma}_{\parallel}}{1 + \hat{\tau}/\mu}$ and $\hat{D}_t = \frac{\mu}{1 + \hat{\tau}/\mu}$

and the plasma parameters $\beta_0 = \frac{en_0 T_0}{B^2/\mu_0}$ and $\mu = \frac{\hat{\sigma}_{\parallel} \hat{m}_e}{\hat{n}_e \hat{m}_i}$ for a timestep size $\hat{\tau}$.

	Φ	$\Phi - j_{\parallel}$	$\Phi - A_{\parallel}$	$\Phi - j_{\parallel} - A_{\parallel}$
Number of iterations	165	35	660	117
Solve time per iteration [s]	0.45	0.11	6.36	1.15
Total time [s]	2268	1599	14275	3841

*Simulation results for different combinations of equations (1) – (3) on a 3D limiter case with ~500.000 cells
PETSc: LGMRES scheme with GAMG preconditioner on 96 computing cores.*

No drifts

Electromagnetic flutter

- Definition of the electromagnetic potential:

$$\nabla \times \mathbf{A} = \mathbf{B}$$

- Assume small perturbations of the equilibrium magnetic field:

$$\mathbf{B} = \mathbf{B}_{eq} + \tilde{\mathbf{B}}$$

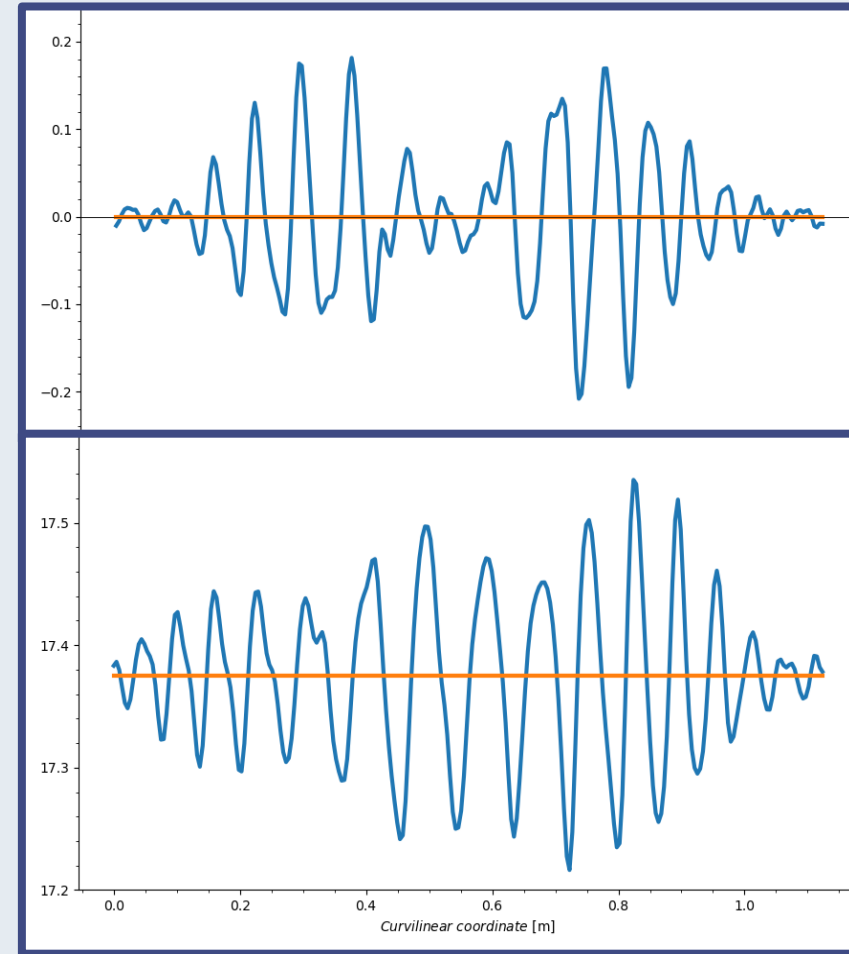
- From the value of the toroidal perturbation field \tilde{A}_{\parallel} :

$$\tilde{\mathbf{B}} = (\nabla \times \mathbf{b}_{eq}) \tilde{A}_{\parallel} - \mathbf{b}_{eq} \times \nabla \tilde{A}_{\parallel}$$

- The perturbation field $\tilde{\mathbf{b}}$ is calculated from \tilde{A}_{\parallel} at the previous timestep

- $\tilde{\mathbf{b}}$ is considered for the advection and the parallel diffusion of the conserved fluid quantities:

- ion density n_i
- ion momentum $n_i v_i$
- electron and ion temperature T_e and T_i



*Fluctuations of the contravariant components of \mathbf{b}
Profile along the poloidal direction in the core
Limiter scenario with developed turbulence*



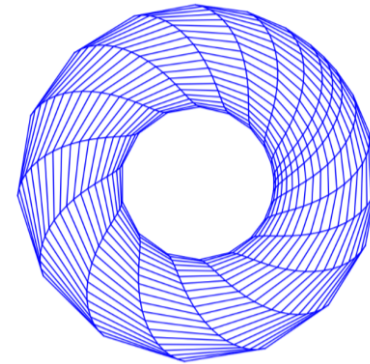
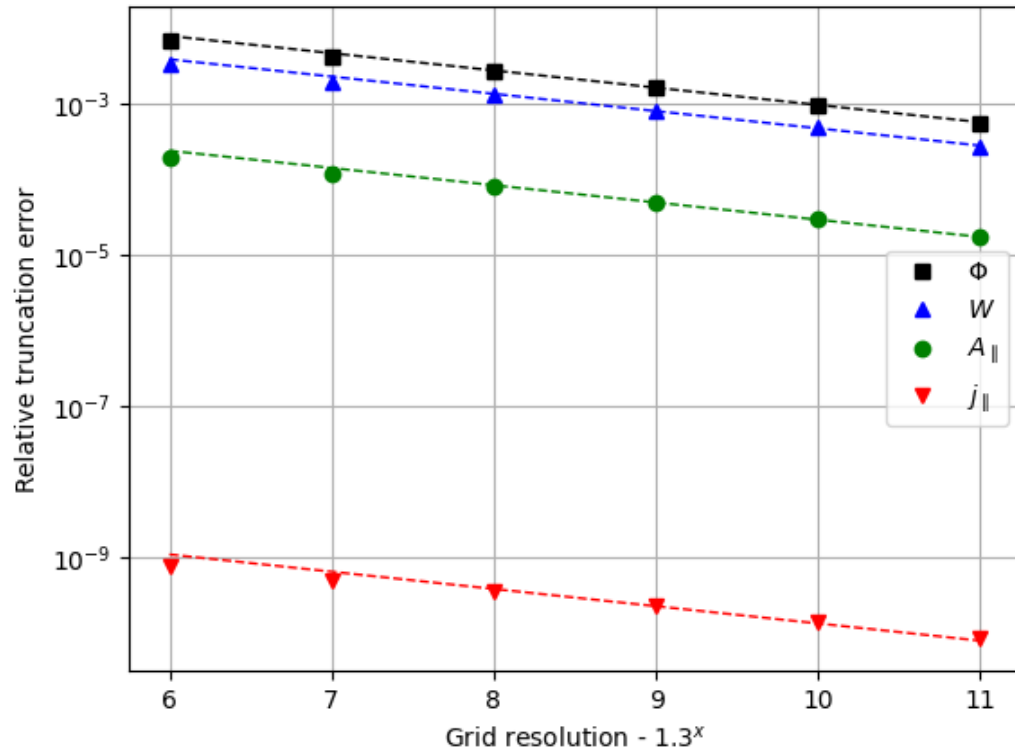
3 ■ **Model verification and validation**

MMS verification

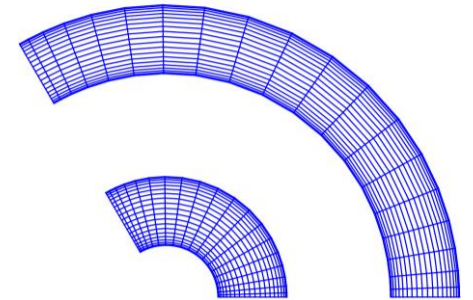
Use the method of manufactured solutions [Roache, SFMA 2019] to check the new system on Φ , A_{\parallel} and j_{\parallel}

Define arbitrary initial profiles and apply analytic source terms to maintain a steady-state solution

The change within one timestep estimates the numerical error



$\psi - \theta$ view



$\psi - \phi$ view

Estimated numerical errors for different 3D mesh resolutions.

The total number of points was increased by a factor ~ 2.2 between each run.

The dashed lines indicate the theoretical 2nd order convergence.

Linear verification

Consider the four-field model on a SLAB domain with uniform magnetic field. Only evolve n_e , Φ , j_{\parallel} and A_{\parallel}

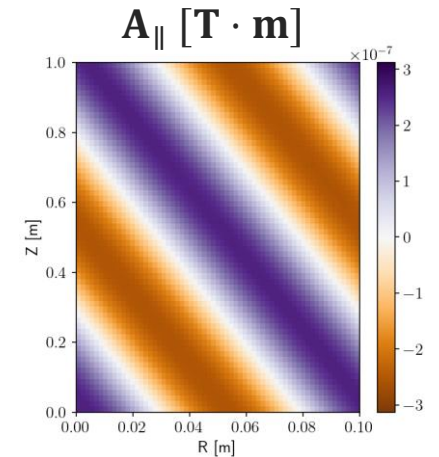
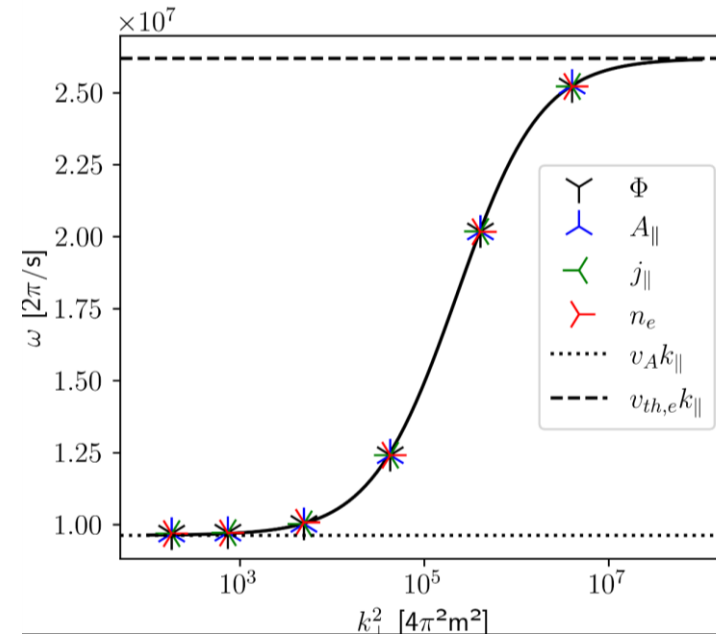
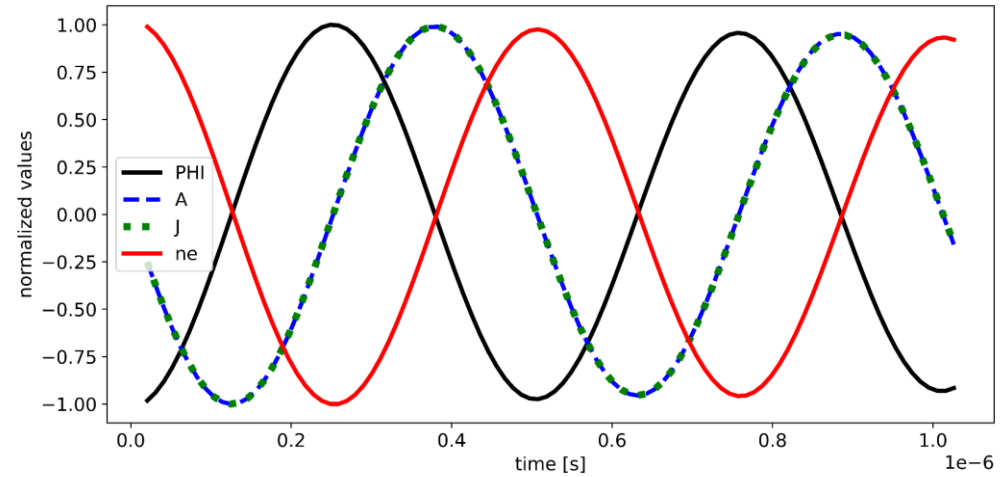
$$\begin{aligned} \partial_t n_e &= \frac{1}{e} \nabla \cdot j_{\parallel} \mathbf{b} \\ \nabla \cdot \left[\frac{m_i n_i}{B^2} \partial_t \nabla_{\perp} \Phi \right] &= \nabla \cdot (j_{\parallel} \mathbf{b}) \\ \frac{1}{\sigma_{\parallel}} j_{\parallel} + \frac{m_e}{n_e e^2} \partial_t j_{\parallel} &= \left(\frac{T_e}{e} \nabla_{\parallel} \ln n_e - \nabla_{\parallel} \Phi \right) \cdot \mathbf{b} - \partial_t A_{\parallel} \\ \nabla \cdot \nabla_{\perp} A_{\parallel} &= -\mu_0 j_{\parallel} \end{aligned}$$

We expect a decaying standing wave with frequency:

$$\omega_0^2 \approx \frac{v_A^2 + K k_{\perp}^2}{1 + C k_{\perp}^2} k_{\parallel}^2$$

The parallel wave speed is bound by:

- Alfvén wave group velocity $v_A^2 = \frac{B^2}{m_i n_i \mu_0}$ for low k_{\perp}
- Electron thermal speed $v_{th,e}^2 = \frac{K}{C} = \frac{e T_e}{m_e}$ for high k_{\perp}



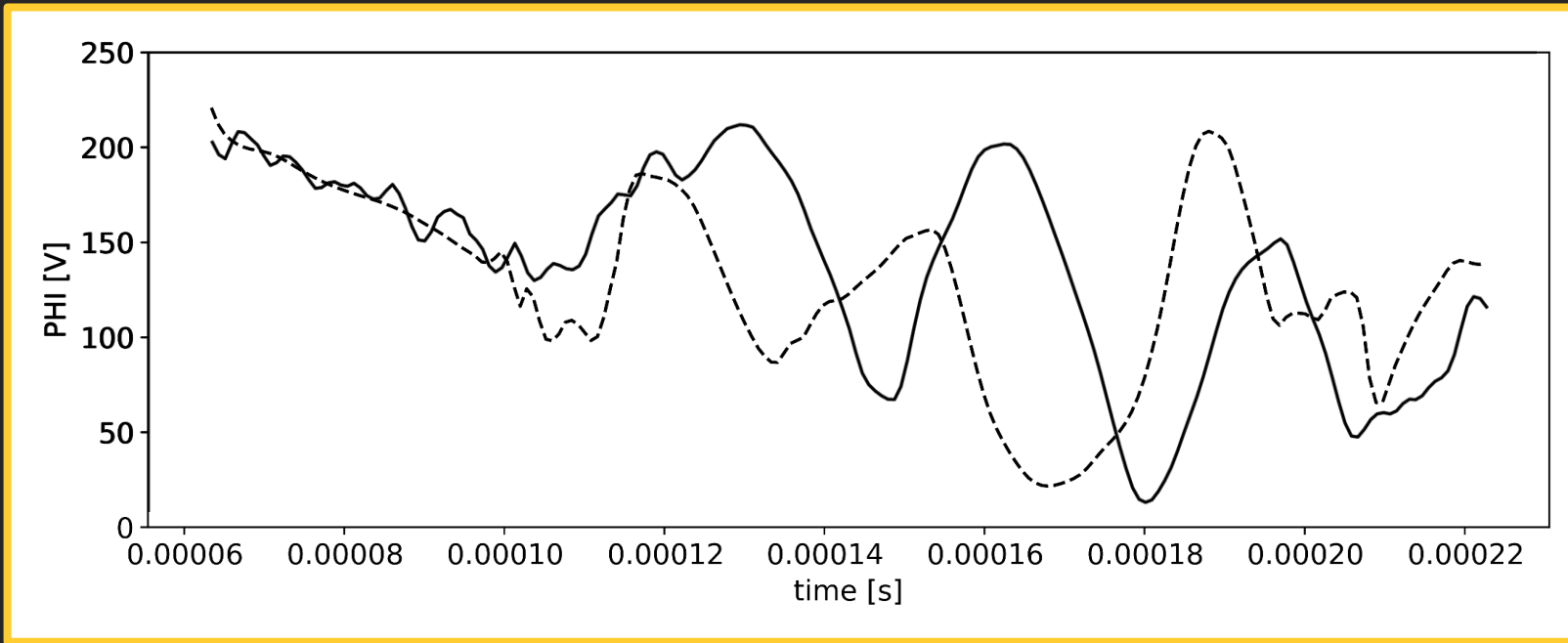
Simulation on a 3D SLAB with 63 points per dimension
Good agreement with [Stegmeir et al, PP 2019]



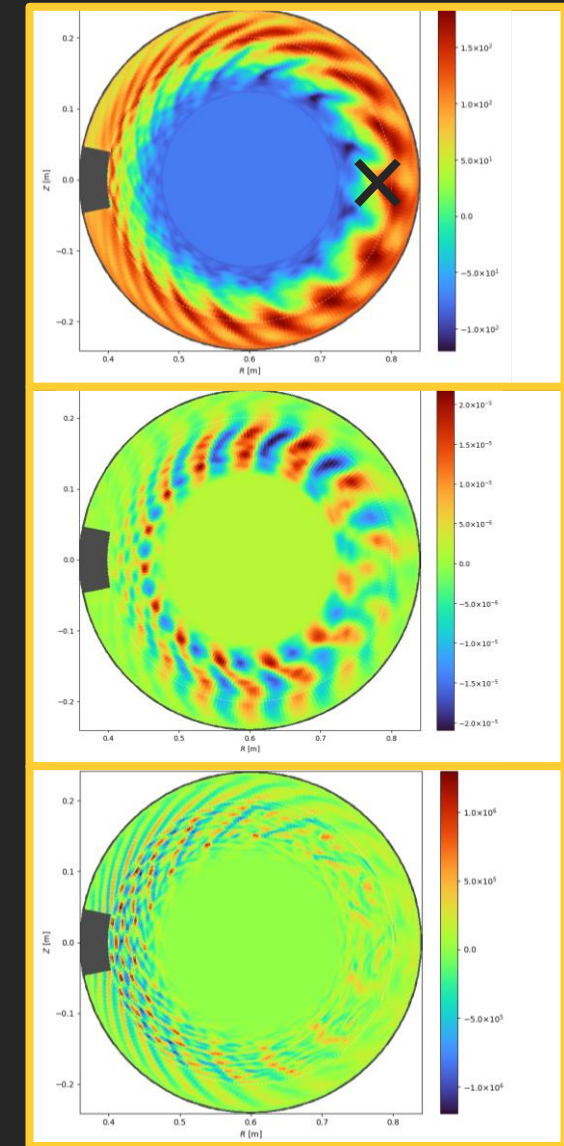
4 ■ First electromagnetic turbulent simulations

Electromagnetic profiles

- Simulations on a limiter geometry with a constant density and energy source at the core



Time evolution of the electric potential at one point in the domain
dashed line: electrostatic scenario
full line: electromagnetic scenario



Φ [V]

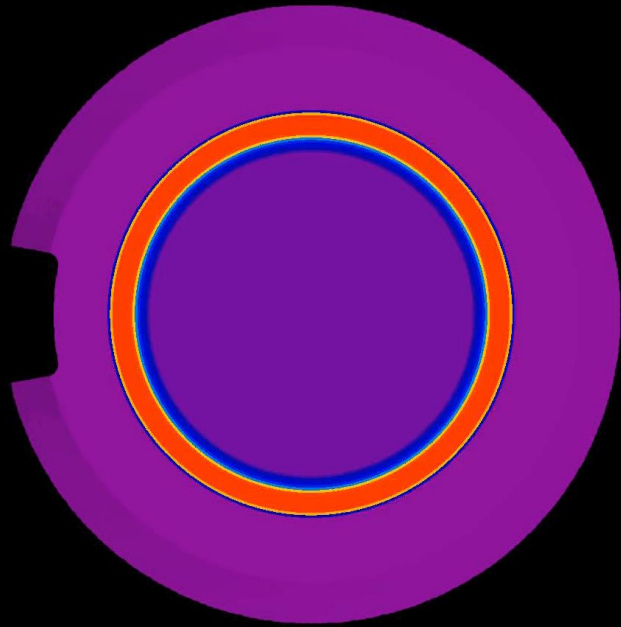
\tilde{A}_{\parallel} [Tm]

j_{\parallel} [Am⁻²]

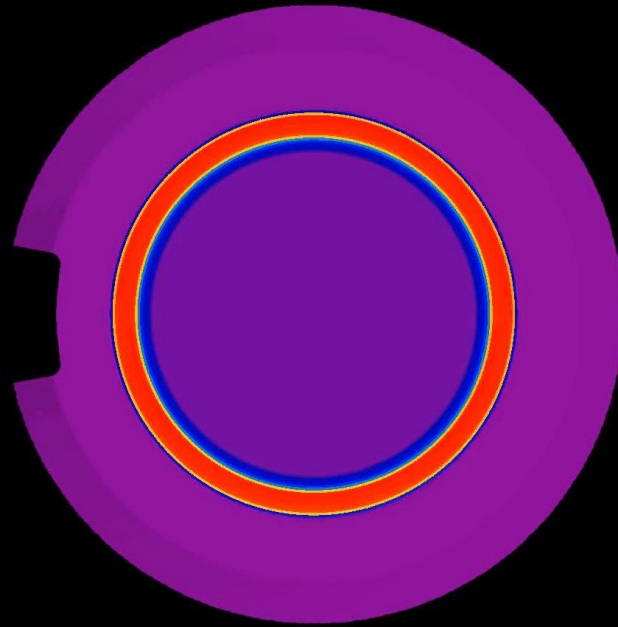
Snapshots at the first poloidal plane with fully developed turbulence

Videos of a turbulent run

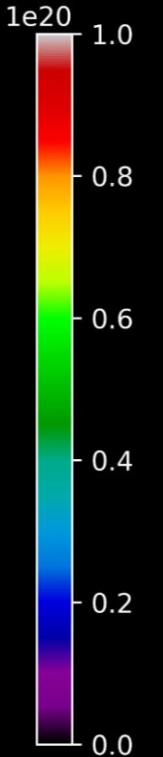
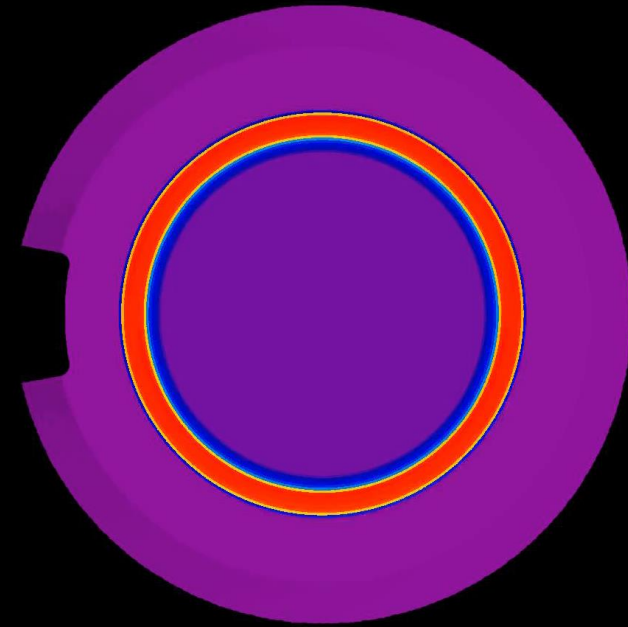
Electrostatic
scenario



Electromagnetic
scenario



Electromagnetic
scenario with flutter



Evolution of the ion density $n_i [m^{-3}]$



5 ■ **Conclusions and perspectives**

Conclusions and perspectives

- Addition of two new fields to the Soledge3X model:
 - the parallel electromagnetic vector potential A_{\parallel}
 - the parallel current density j_{\parallel} with finite electron mass
 - improves the numerical stability
 - constrains the Alfvén wave speed
- Validation of the new model
 - Verification via the Method of Manufactured Solutions
 - Dispersion relation verified by simulations
- Perspectives for future work
 - Extensive investigation of electromagnetic effects on the turbulent transport
 - Evaluate the impact of β on the plasma
 - Extend to X-point geometry