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An electromagnetic model for SOLEDGE3X

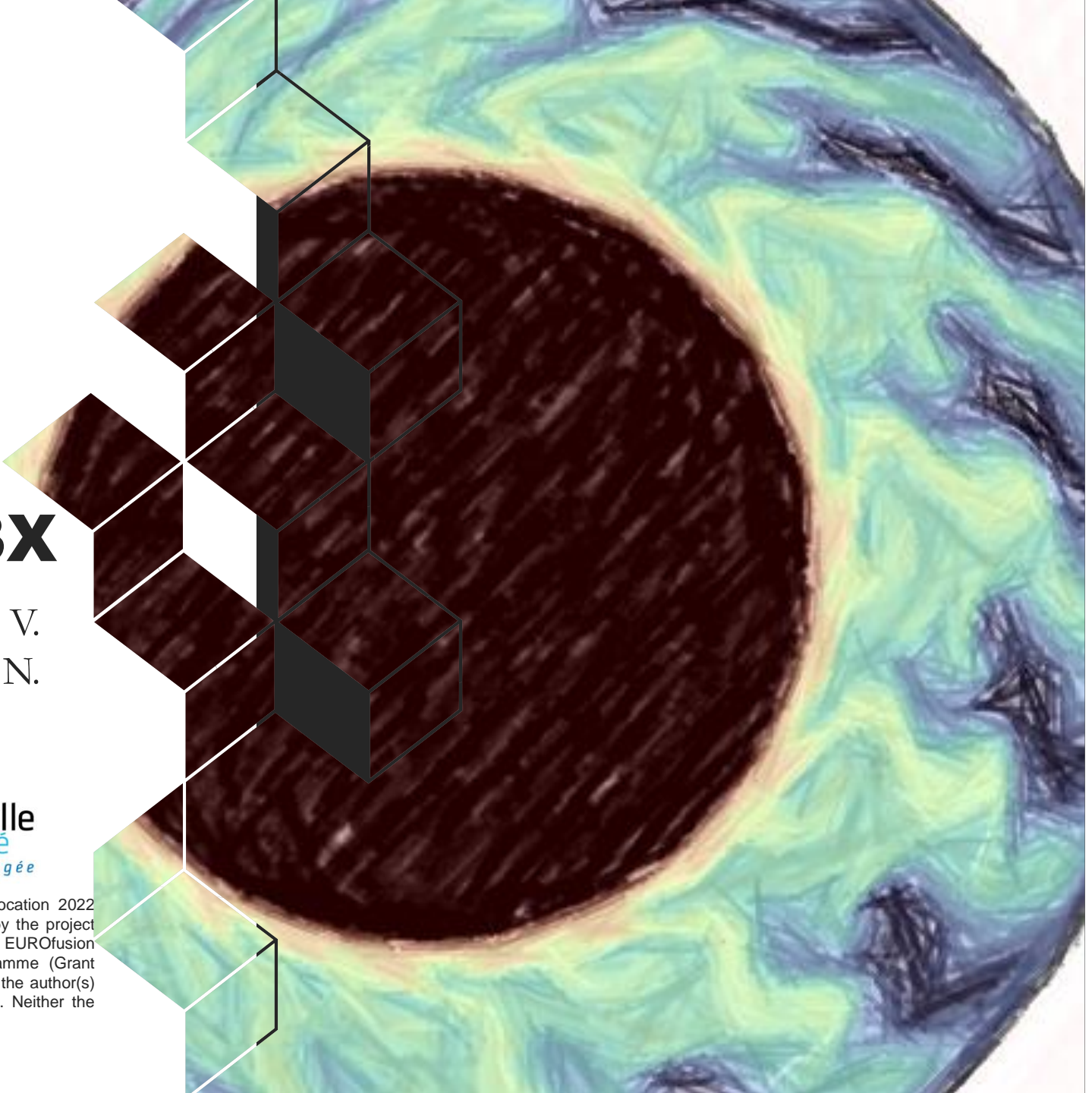
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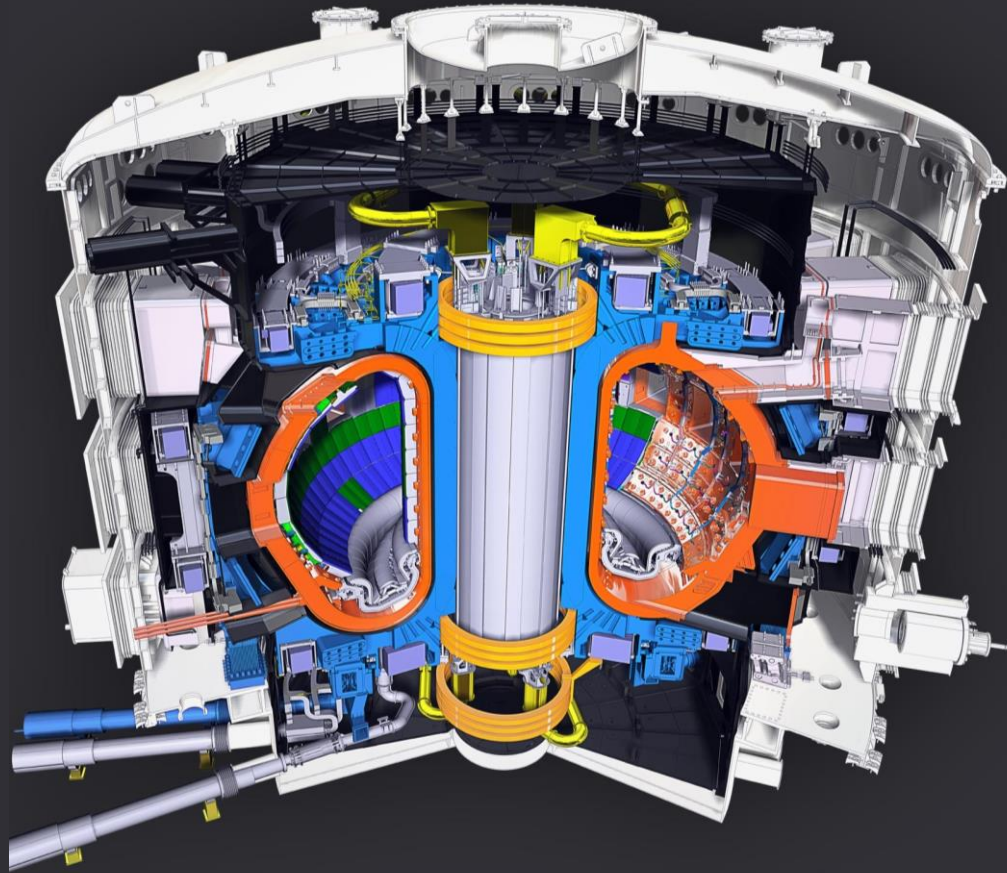
Outline

1. **Electrostatic versus electromagnetic turbulence**
2. **A new vorticity system for SOLEDGE3X**
3. **Verification and validation of the model**
4. **Electromagnetic turbulent simulations**
5. **Conclusions and perspectives**



1 ■ Electrostatic versus electromagnetic turbulence

The challenge of simulating tokamaks

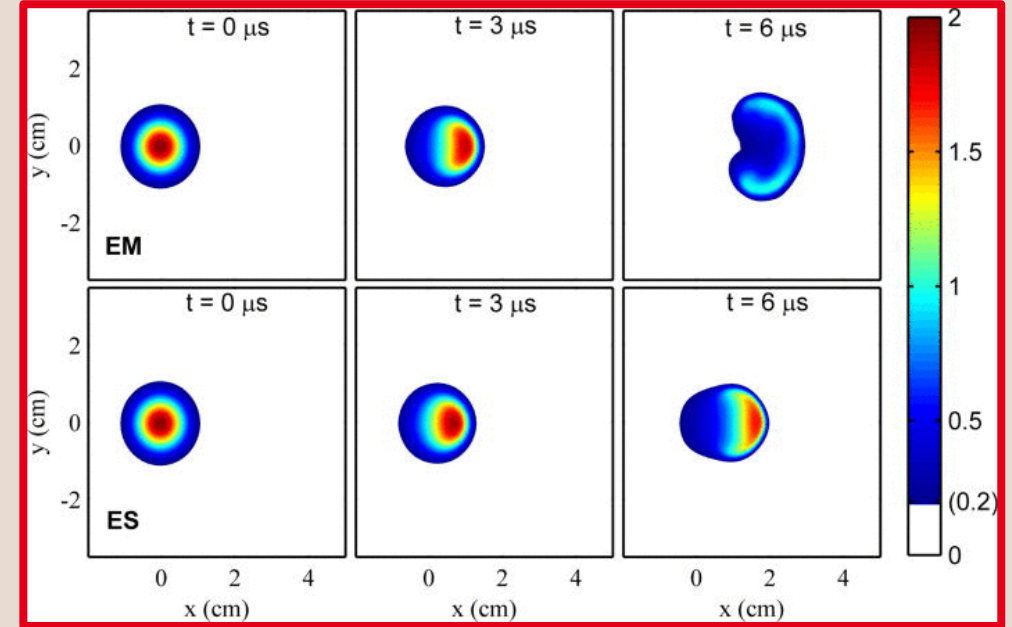


Model of the ITER reactor

- **Dream of a fusion reactor: the tokamak**
 - High heat fluxes on the divertor
 - Challenges of a good plasma confinement
 - Simulations to understand and predict plasma behaviour
- **SOLEEDGE3X is a FVM fluid code for edge plasmas**
 - Solve drift-reduced Braginskii equations
 - Study edge turbulence to understand plasma confinement
 - Turbulence is driven by $E \times B$ drifts
 - Understand and predict heat fluxes on the wall
 - Estimate transport coefficients for reduced models
- **Limitations of the SOLEEDGE3X turbulence**
 - Low electric resistivity in Ohm's law at high temperature
 - In H-mode plasmas electromagnetic effects dominate radial transport

Do we need electromagnetic effects in electrostatic turbulence ?

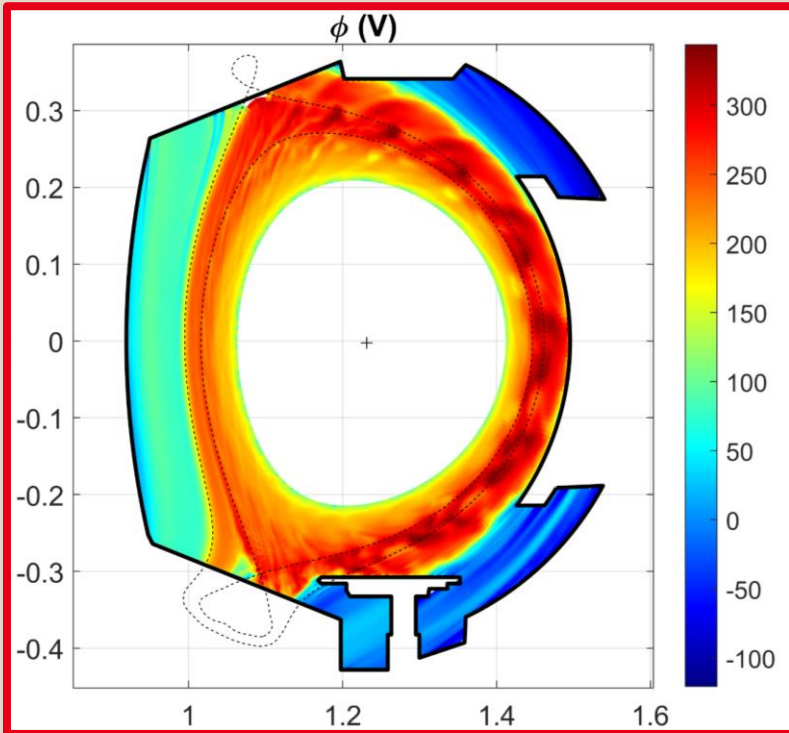
- Non-negligible effects on edge transport
 - EM response to external magnetic field variations (e.g. ripple)
 - Impact on divertor heat transport [Xu et al, NF 2019]
 - EM flutter stabilizes EM turbulent structures [Zhang et al, NF 2024]
- Towards the LH transition
 - Existence of drift Alfvén turbulence [Scott, PPCF 1997]
 - Impact on filament shape in turbulent blob propagation [Lee et al, JNM 2015]
 - Turbulent simulations on large machines (e.g. ITER) require electromagnetic effects
 - Stronger effects for high- β plasmas
- Electron inertia becomes mandatory
 - Constrain the shear Alfvén wave speed to physical values [Dudson et al, PPCF 2021]
 - Improvement of the numerical stability [Stegmeir et al, PoP 2019]



*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 Φ appears in:

■ Polarization current $j^{pola} = \partial_t \omega$

with the vorticity $\omega = \frac{m_i n_i}{e Z_i B^2} \nabla_\perp \Phi + \frac{m_i}{e Z_i^2 B^2} \nabla_\perp p_i$

■ 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 total charge conservation $\nabla \cdot \mathbf{j}^{tot} = 0$ gives us the system:

$$\nabla \cdot \left(\frac{m_\alpha n_\alpha}{e Z_\alpha B^2} \partial_t \nabla_\perp \Phi + (\sigma_\parallel \nabla_\parallel \Phi) \mathbf{b} \right) = \nabla \cdot \left(\sigma_\parallel \frac{1}{en_e} (\nabla_\parallel p_e + R_{e,\parallel}) \right) \mathbf{b} + \nabla \cdot \mathbf{j}_\perp$$

Ratio between diffusion coefficients: $> 10^6$

High anisotropy \rightarrow poor numerical condition !



**2 ■ A new vorticity
system for
SOLEEDGE3X**

Magnetic induction in the vorticity equation

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

$$\nabla \cdot \left(\frac{m_{\alpha} n_{\alpha}}{e Z_{\alpha} B^2} \partial_t \nabla_{\perp} \Phi \right) = \nabla \cdot (j_{\parallel} \mathbf{b}) + \nabla \cdot \mathbf{j}_{\perp}$$

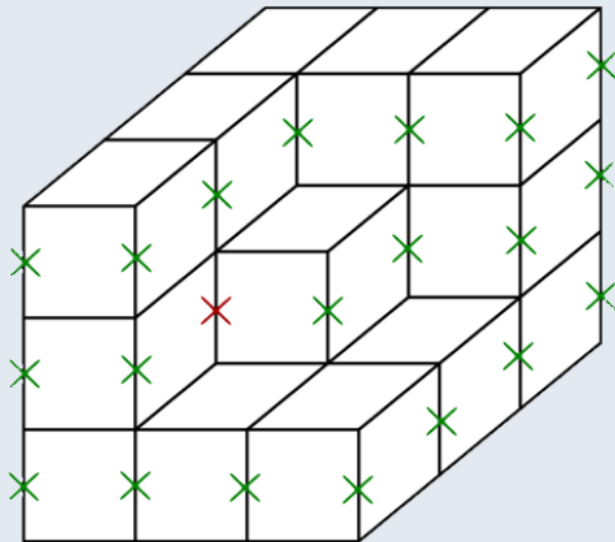
Vorticity equation

$$\eta j_{\parallel} + \frac{m_e}{n_e e^2} [\partial_t j_{\parallel} + \nabla \cdot (j_{\parallel} \mathbf{v}_j)] = -\mathbf{b} \cdot \nabla \Phi - \partial_t A_{\parallel} + \frac{\mathbf{b} \cdot \nabla p_e}{e} + \mathbf{R}_{\parallel, e}$$

Ohm's law

$$\nabla \cdot (\nabla_{\perp} A_{\parallel}) = \mu_0 j_{\parallel}$$

Ampère's law



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

Boundary conditions for A_{\parallel} and j_{\parallel} :

- Dirichlet $A_{\parallel}^{BC} = 0$ on the sheath and tangential wall
- Sheath current $j_{\parallel}^{BC} = j_{sat} (1 - e^{\Lambda - \Phi/T_e})$

Improved matrix condition expected with a finite electron mass

- Parallel diffusion coefficient on Φ : $\frac{1}{\eta_{\parallel}} \rightarrow \frac{1}{\eta_{\parallel} + \mu}$

with $\mu = m_e / (m_u n_e \delta_t)$

Electromagnetic flutter

- Definition of the electromagnetic potential:

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

- Assume small perturbations of the equilibrium magnetic field:

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

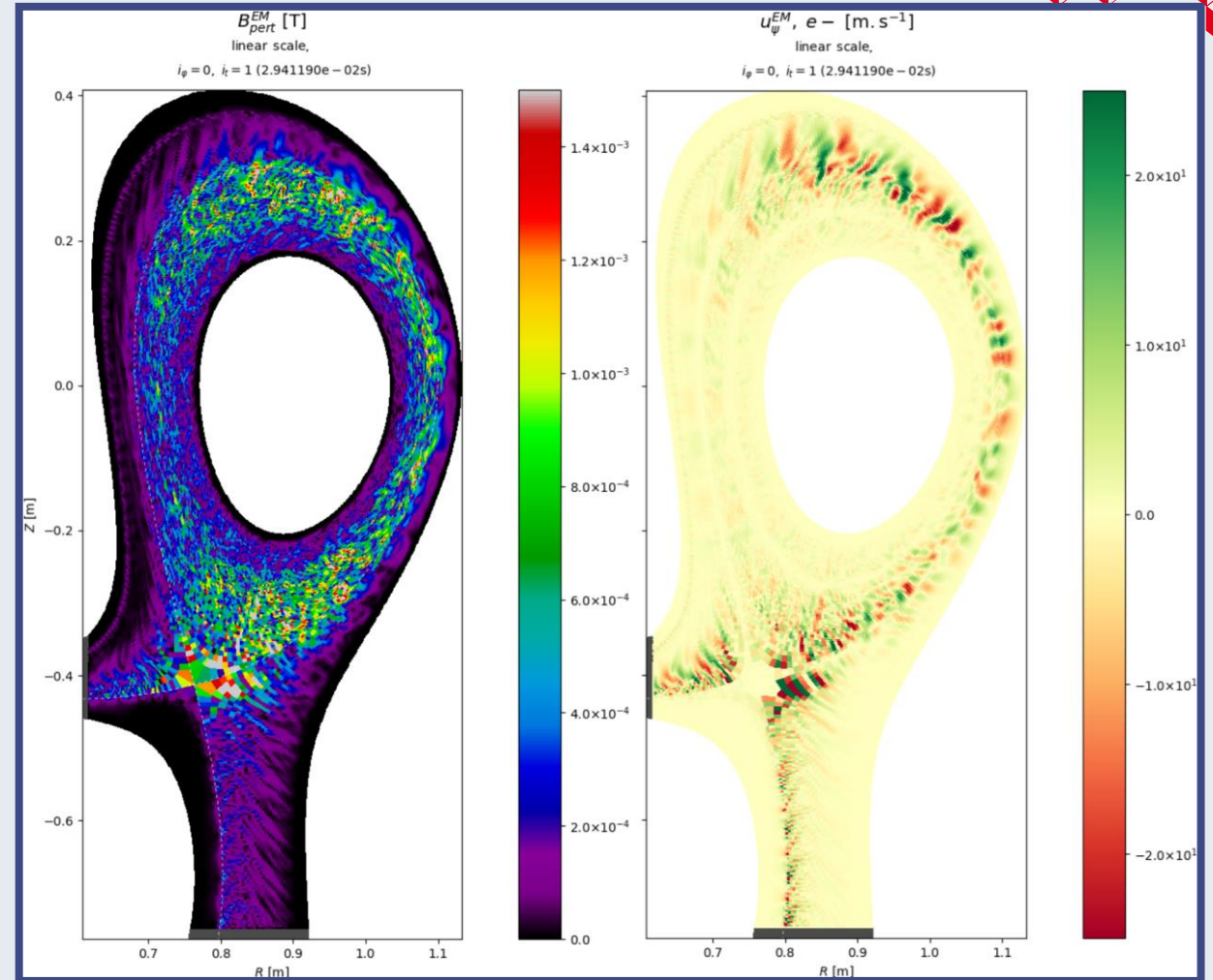
- From the value of the toroidal perturbation field \tilde{A}_{\parallel} :

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

- 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



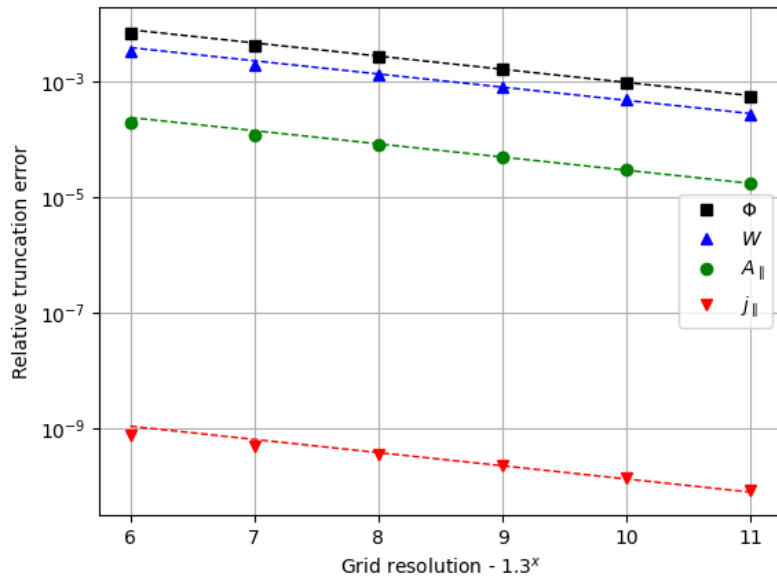
Amplitude of the perturbation field $|\tilde{\mathbf{B}}|$ (**left**) and radial flutter drift velocity (**right**) for a TCV case with $B_t = 0.95T$. The plasma β is $\sim 10^{-3}$ at the core, $\sim 10^{-4}$ at the separatrix and below $\sim 10^{-5}$ in the far SOL.



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}



Estimated numerical errors for different 3D mesh resolutions. The dashed lines indicate the theoretical 2nd order convergence.

Linear validation

Reduced four-field model on a 3D slab:

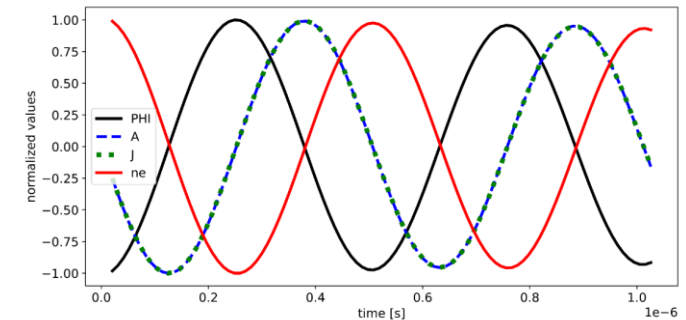
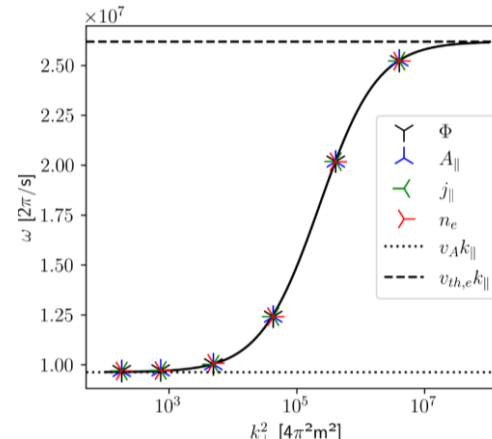
$$\begin{aligned} \partial_t n_e &= \frac{1}{e} \nabla \cdot j_{\parallel} \mathbf{b} \\ \nabla \cdot \left[\frac{m_i n_i}{B^2} \partial_t \nabla_{\perp} \Phi \right] &= \nabla \cdot (j_{\parallel} \mathbf{b}) \\ \frac{1}{\sigma_{\parallel}} j_{\parallel} + \frac{m_e}{n_e e^2} \partial_t j_{\parallel}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


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}

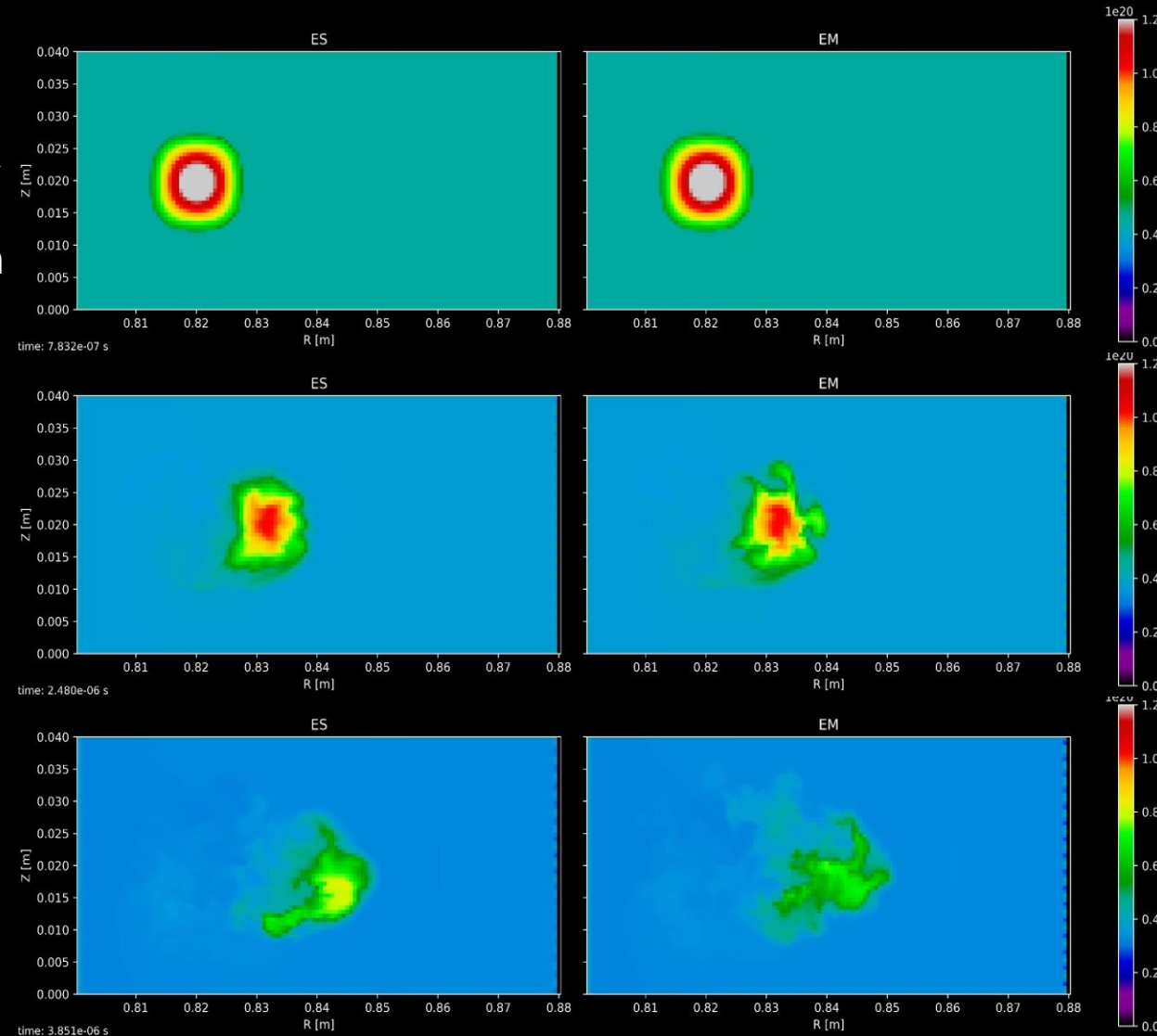
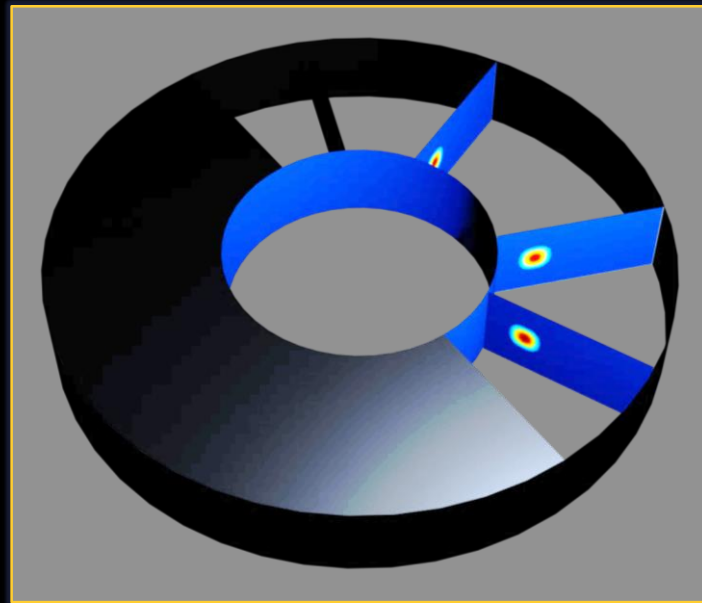




4 ■ Electromagnetic turbulent simulations

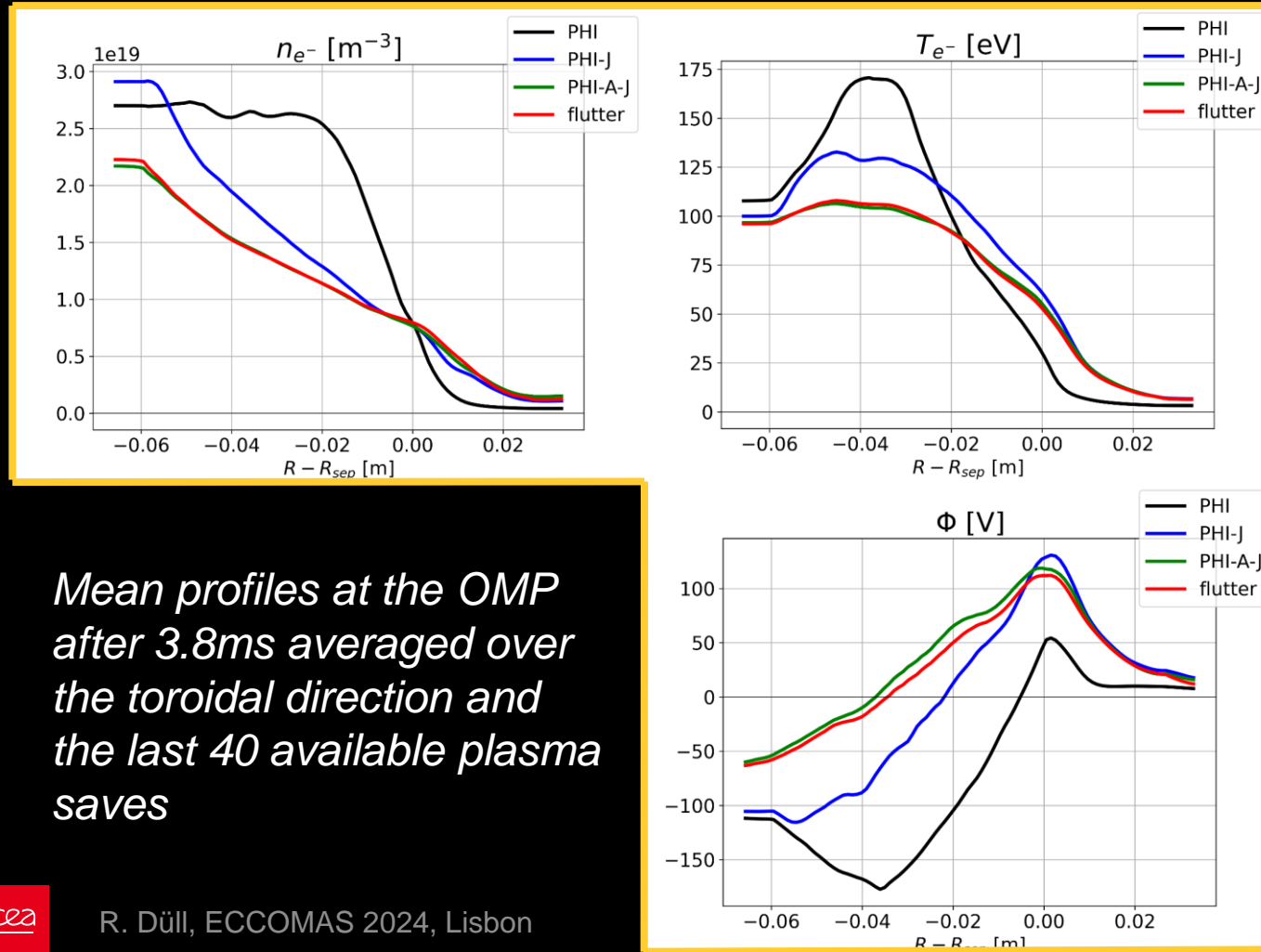
Inductive effects on plasma blobs

- We consider a single blob that evolves in a curved slab geometry.
- The blob is initialized as a local density perturbation of a background plasma with a high $\beta \approx 10^{-2}$ where magnetic induction has a strong impact on the formation of the turbulent filaments.
- As the blob diffuses into the background plasma, its β value decreases and classic drift wave dynamics dominate again



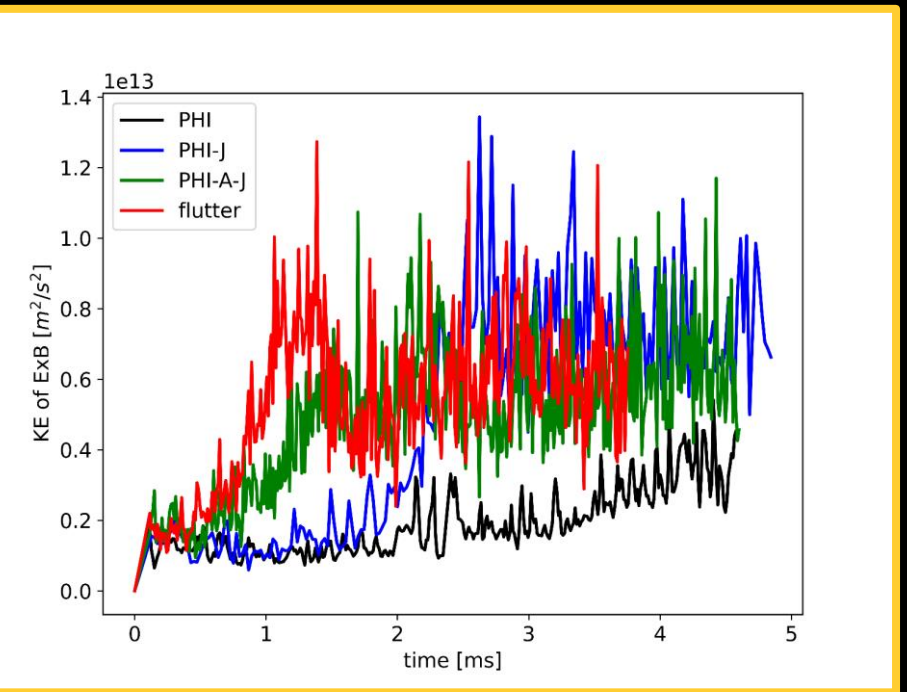
Impact on turbulence with the TCV-X21 case

- Simulation of a quarter of a torus with $\sim 2e6$ cells
- Density feedback on the separatrix to $n_{sep} = 7 \cdot 10^{18} \text{ part}/m^3$
- 200kW ohmic heat source and fluid neutrals with 90% recycling



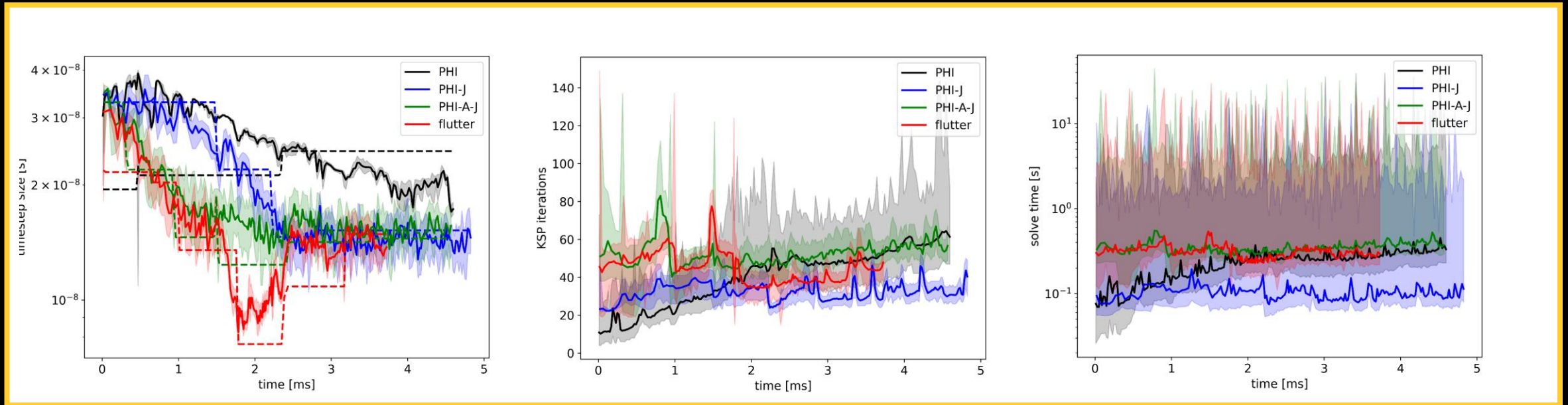
Mean profiles at the OMP after 3.8ms averaged over the toroidal direction and the last 40 available plasma saves

Total kinetic energy of the ExB drift velocity over the full simulation time



Numerical implications

- Simulations run on MARCONI with 768 cores on 16 nodes
- PETSc iterative solver: GMRES with multigrid GAMG preconditionner



Electron inertia reduces the computing time

Magnetic induction only slightly decreases the performance compared to the electrostatic reference

- 1 – optimal timestep size (to match the CFL condition)
- 2 – number of iterations of the implicit solver
- 3 – CPU time spent on the vorticity system per timestep

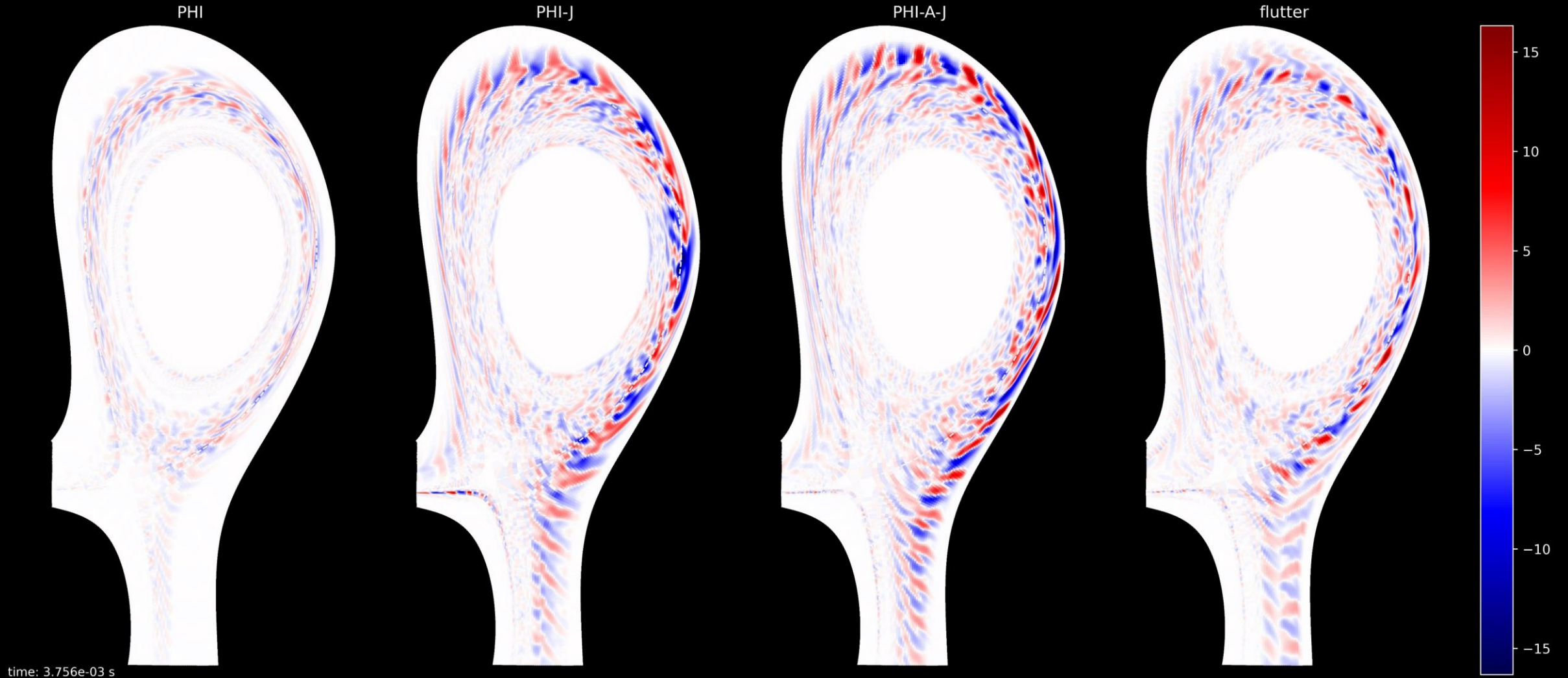


5 ■ Conclusion

Conclusion

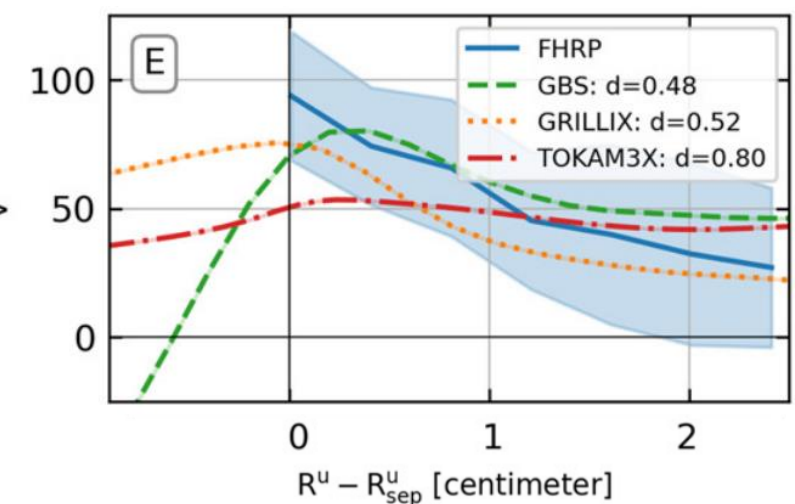
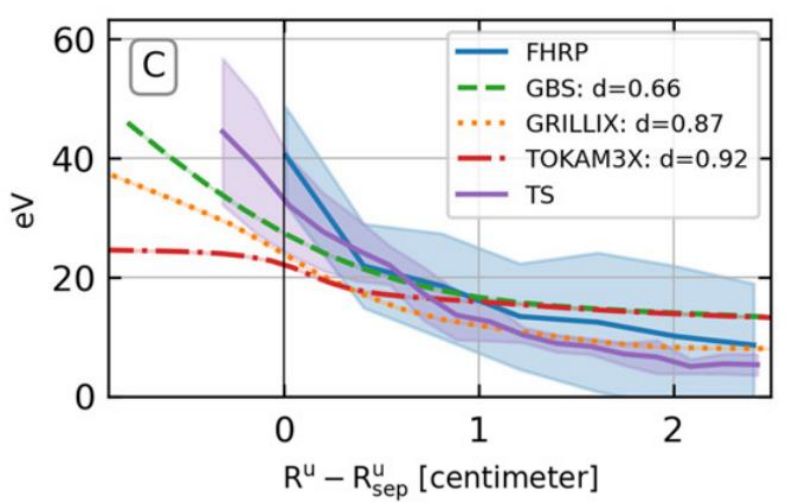
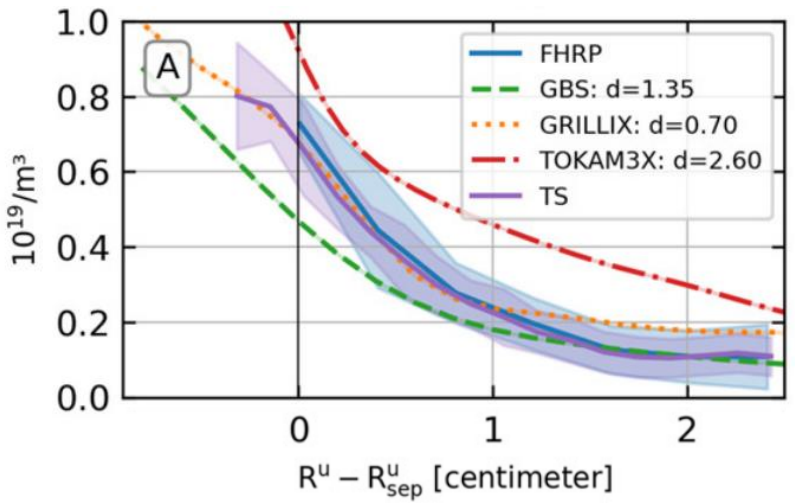
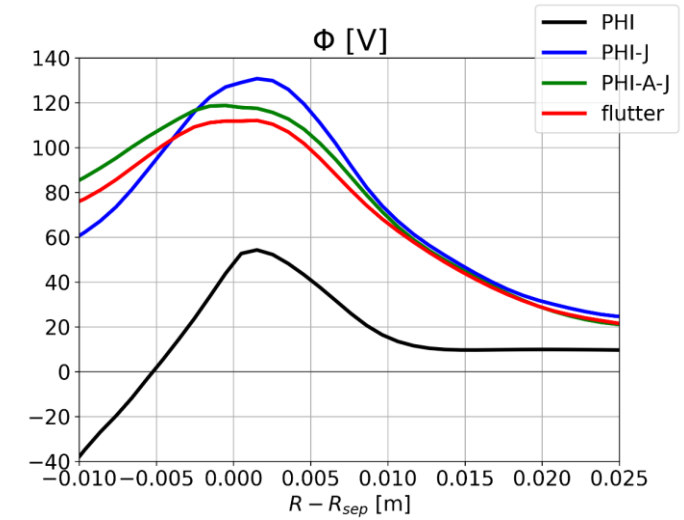
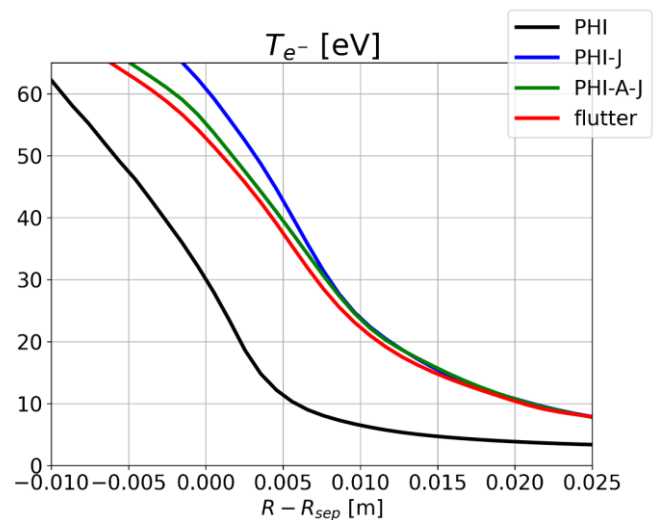
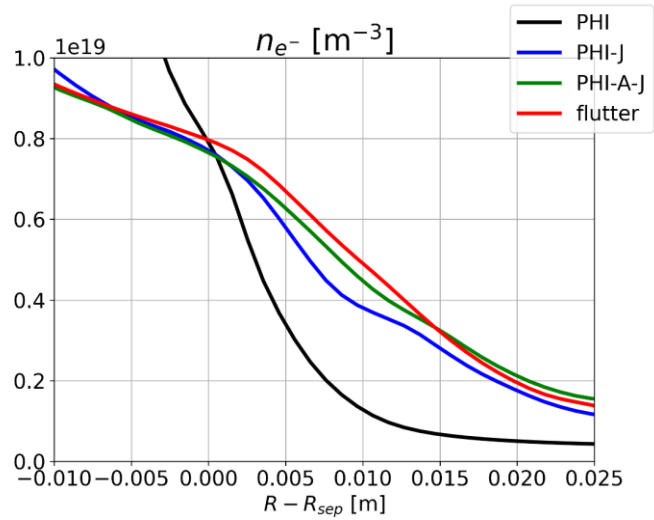
- Addition of two new fields to the SOLEDGE3X model:
 - the parallel electromagnetic vector potential A_{\parallel} known from Ampère's law
 - generates magnetic induction in the parallel electric field
 - causes small perturbations to the magnetic equilibrium
 - A finite electron mass to reduced Ohm's law causing inertia of the parallel current density j_{\parallel}
 - improves the numerical stability
 - constrains the Alfvén wave speed
- Verification via the Method of Manufactured Solutions and validation on a linear test case
- Even at low β , electromagnetic effects impact drift-wave turbulence
 - Magnetic induction affects blob propagation and filament formation
 - Flattening of mean profiles and increased turbulent transport
 - Flutter only has a local impact on filament shapes
- Additional numerical costs for electromagnetic effects remain within limits

Backup: Turbulent profiles



Toroidal perturbations of the electron temperature T_e [eV] after 3.8ms simulated time

Backup: Comparison with the TCV-X21 case



TOP: Our profiles BOTTOM: TCV X21 [Oliveira et al, NF 2022]