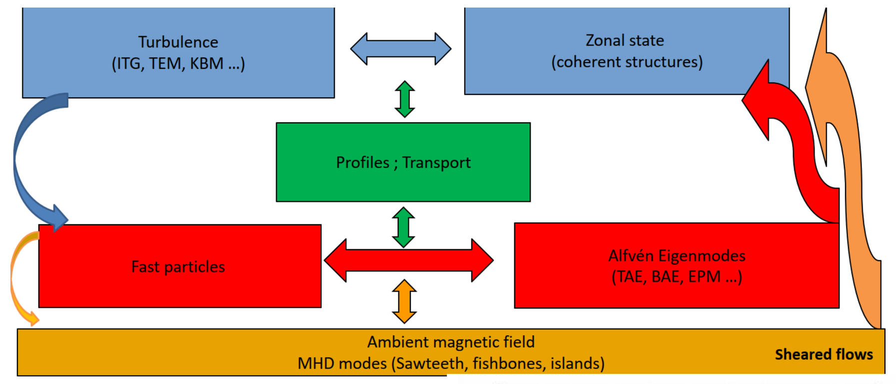
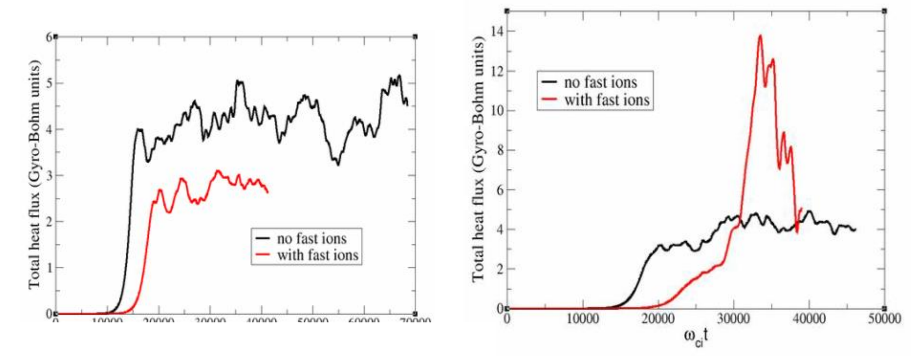
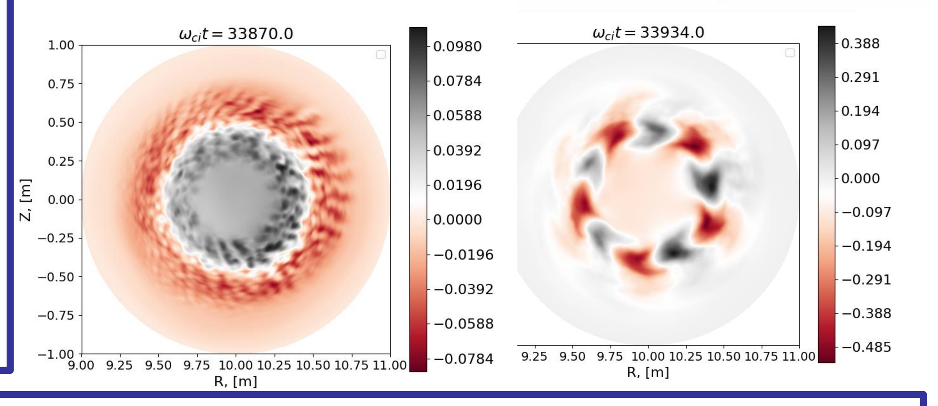
Towards burning plasmas: theory and simulations. TSVV-G Task.







Call for TSVV-G: Physics of Burning Plasmas

Develop a self-consistent description and corresponding simulation tools for the mutual interaction of energetic particles, MHD modes, turbulence, and kinetic plasma profiles in both tokamak and stellarator geometries.

Develop a theoretical understanding and validated interpretative/predictive capabilities (including reduced models) of burning plasma physics in both tokamak and stellarator geometries. The resulting reduced models are to be used in TSVV-H and TSVV-I.

Develop strategies to optimize the deposition of fusion alpha energy into the bulk plasma to enhance reactor performance.

TSVV-G: Hierarchy of models

Theory
- deep insight into the physics ; predictions, ideas, limits for simulations

Low fidelity: theory-driven reduced models (EPWF, ATEP)
- quick execution ; full IMASification
- well-suited for integrated modeling and discharge planning
- able to address transport time scales
- sometimes based on parameters to be derived from higher fidelity or experiment

Intermediate fidelity: hybrid fluid-gyrokinetic models (XTOR-K, HYMAGYC + Struphy)
- computationally more expensive but still very affordable (case-dependent)
- able to address resistive time scales and highly-nonlinear MHD
- IMASified (in some cases) and suited for integrated modeling

High fidelity: global gyrokinetic codes (ORB5/EUTERPE/TRIMEG + GENE and GYSELA)
- computationally most expensive ; most accurate and realistic
- Fundamental for „lower fidelities“

Future steps for gyrokinetic codes (ORB5/EUTERPE, GENE, GYSELA)

Eulerian code GENE and semi-Lagrangian full-f code GYSELA join TSVV-10 PIC codes ORB5/EUTERPE: verification and levereging each others strengths as elements of the overall E-TASC ecosystem

ORB5/EUTERPE applications: (applications to JET, TCV, ASDEX-U, MAST-U)

- Saturation amplitude studies using ORB5: AEs + EPs (+ turbulence)
- Effect of EPs/AEs on turbulence (e.g. via ZF generation): ORB5
- Kink/fishbone instability; effect of ZFs, interaction with turbulence: ORB5 and GENE
- Tearing instability and turbulence in tokamaks (turbulent cascades, island merging vs. Island healing), in realistic geometry and including collisions: ORB5 and GENE
- Electromagnetic turbulence in stellarators, EP physics: EUTERPE

- ORB5/EUTERPE development:
  - adaptive control-variate in ORB5 (PSZS based, supported by neural networks)
  - Field-aligned finite elements in EUTERPE (collaboration with TRIMEG)
  - Further integration of the codes (already parts of a joint project; single git)

- GENE and GYSELA development and applications
  - AE + EP comparison (incl. performance) of GENE and GYSELA with PIC codes (ITPA, NL saturation, etc)
  - Realistic CoM distribution functions in GYSELA (following XTOR CoM distribution functions)
  - AE + EP + turbulence in ITER/DEMO: GENE

Future steps for hybrid fluid-kinetic codes

- XTOR-K: nonlinear MHD + nonlinear full-orbit EP; computationally intensive
- HYMAGYC: linear MHD + nonlinear EP; less computationally challenging than XTOR-K
- STRUPHY: various models + modern math; pythonic

- Fluid-kinetic codes as elements of the Digital-Twin eco-system

- Goal: establishing „user comminuties“ for the codes (across WPs); interest has been expressed (Rui)

- IMASification of XTOR-K (input: chease, profiles; output: mhd ids)
- XTOR-K: performance optimization (GPU-enabling for solver; already enabled for particles)

- STRUPHY: user training

- Applications: nonlinear EP physics of AEs; kink/sawteeth in presence of EPs, kink (sawtooth)/tearing combinations, kink (sawtooth) / AE combinations, flux pumping (sawteethless reactor)

Theory

- Role of the amipolarity in Alfvenic mode saturation (fast-ion vs. bulk-plasma nonlinearities)
- Analytic treatment of phase-space fluxes in nonlinear TAE dynamics, in presence of turbulence. Derivation of sources and collision operators.
- Zonal flow generation by Alfven Eigenmodes (modulational vs. beat-driven regimes)
- Chirping and saturation: scalings with the amplitude, zonal flow effects

Reduced Models

- Extending models to transport time scales, zonal structures
- Integration with EUROfusion tools (transport codes etc) via IMAS-IDS
- Applications to optimization of burning-plasma regimes (**collaboration with DEMO Central Team**)
- **Applications to experiments** (past, ongoing, and planned): JT60-SA, ASDEX-U, JET, ITER, BEST
- **Connecting TSVV-G activities (EP-WF/ATEP code) to burning-plasma operation planning**

CONCLUSIONS:

- ❖ Theory and software stack will be developed for burning plasma applications: gyrokinetic codes, hybrid-MHD codes, integrated modelling
- ❖ GPU-enabling and IMASification of the key tools (assisted by ACHs)
- ❖ Both tokamak and stellarator plasmas will be addressed; simulations of complex physics and in realistic geometries
- ❖ Cross-code verification and comparisons to theory will be carried out
- ❖ Simulations using data from ASDEX-Upgrade, JET, TCV, W7-X
- ❖ Dissemination via publications (wiki, indico), EUROfusion‘s Gitlab (including code documentation), and user training (EP-WF, Struphy, …)

Continuation of TSVV Task 10

New contributors: GYSELA and GENE in addition to ORB5/EUTERPE – all major GK codes represented; cooperation between teams, exchange of experience, favourable environment for scientific discovery
Dissemination: small associations included (Greece and Ukraine)
Interactive user communities for major codes: XTOR-K, HYMAGYC, ORB5/EUTERPE, …

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