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PROPOSITION DE STAGE / INTERNSHIP PROPOSAL

Organisme / Institution : Aix-Marseille Université

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Conditions de stage (rémunération, voyage, logement, cantine, …) / internship conditions (salary, travel, lodging, food,…) : gratification (environ 600 euros/mois)

Turbulent transport reduced models with improved physics for tokamak plasmas

The challenge: predictive tokamak turbulence modelling

Fusion reactors deliver high-energy-density baseload CO2-free electricity. In the leading technological concept – the tokamak [1] – hydrogen isotopes deuterium and tritium are heated to high temperatures (~100MK), forming a plasma confined by powerful (>5T) magnetic fields in a toroidal configuration. Significant radial gradients of plasma temperature and density drive instabilities, leading to turbulent losses of plasma heat, particles, and momentum [2]. For a given device, this turbulent transport fundamentally limits the achievable tokamak plasma temperature and fusion power. Consequently, optimizing fusion reactor performance relies on tailoring plasma conditions to minimize deleterious turbulence. Empirical extrapolations were initially used to predict tolerable turbulence levels and net fusion power gain for the next generation of fusion experiments. The emergence of theoretical models capturing the non-linear self-organisation of tokamak plasmas made first-principle-based simulations a key asset in complementing empirical extrapolations. These models are vital for interpreting tokamak experiments, optimizing performance by predictive discovery of new regimes, designing future devices, and developing integrated model-based control required in future reactors where the available sensor suite will be reduced owing to the nuclear environment.

State of the art in tokamak turbulence modelling

Tokamak simulations describe the macroscopic evolution of plasma “radial profiles” of temperature, density, momentum (rotation) and magnetic flux (current) by solving a system of coupled 1D PDEs. The profile evolution results from the balance between the sources (e.g. heating, particle fuelling) and radial transport, the latter itself driven by the free energy in the temperature and density radial gradients. Timescale separation between (slow) profile evolution and (fast) turbulent, heating, and magnetic equilibration processes allows decoupling the system of equations in mathematically and computationally separated modules. The calculation of the turbulent fluxes, performed by one of these modules, is addressed by tokamak turbulence theory.
Recent decades have seen enormous leaps in *direct numerical simulation* of tokamak turbulence, through a combination of increased computational power and powerful theoretical insights. The field of *gyrokinetics* has emerged [3, 4], enabling numerical plasma turbulence simulations successfully reproducing experimental measurements [5]. The gyrokinetic theory exploits the scale separation between the (fast)

gyro-motion and (slow) turbulence evolution to perform a reduction of the Vlasov-Maxwell system of equations and eliminate the gyro-motion from the dynamics. It is the most advanced theory to model turbulence in strongly magnetised plasmas. However, the computational cost – typically 10^4 to 10^6 CPU hours for calculations at a single radial position over turbulence timescales (<1ms) – precludes their routine use in tokamak simulations, which require ~10^3 flux computations for 1s of plasma evolution on devices of the scale of the European tokamak JET.

Reduced turbulent transport models have therefore been constructed to increase tractability and be used in tokamak simulations. They are based on the *quasilinear approximation*, which is proven to be largely valid in the weak turbulence regime in the core of tokamak plasmas [6], and rely on higher-fidelity nonlinear simulations for validating their ansatzes and normalizing factors. The quasilinear approximation relies on a remarkable property of tokamak turbulence: in the non-linearly saturated regime the phase difference between fluctuating quantities, e.g. the plasma density and electric potential, remains close to that obtained for the linear eigenmodes. This implies that the non-linear fluxes, e.g. the particle flux which results from fluctuations of the plasma density and electric potential, can be computed from the *linear response* combined with a *non-linear saturation model*. These are the essential ingredients of any quasilinear model.

However, while extremely useful, the accuracy of existing reduced models is insufficient in several regimes. This is for instance the case in high confinement regimes where transport is sensitive to the magnetic field fluctuations driven by the high plasma pressure to magnetic pressure ratio, β.

Increased accuracy: improve the non-linear saturation models

The self-organisation of complex systems and the non-linear saturation of plasma turbulence are rich and fascinating fields of physics. Capturing this complex physics in a non-linear saturation model is essential for the success of quasilinear transport models.

Two mechanisms are known to play a critical role in the plasma self-organisation into saturated turbulence for fixed profiles: the non-linear generation of radially sheared axisymmetric flows called "zonal flows" which tear apart radially elongated eddies leading to dissipation at small scales [7] and the non-linear energy transfer from unstable modes to stable modes by triad interactions [8]. Recent work suggests that accounting for these mechanisms in "advanced" quasilinear transport models is imperative [9, 10]. Present non-linear saturation models, for instance, have difficulties to capture the turbulence stabilisation observed at high β, as seen in Fig. 1.

We propose to test and further develop these advanced quasilinear transport models by first documenting the validity of their ansatz against existing non-linear simulations, which include β scans, then compare the predicted quasilinear transport fluxes against the non-linear ones.

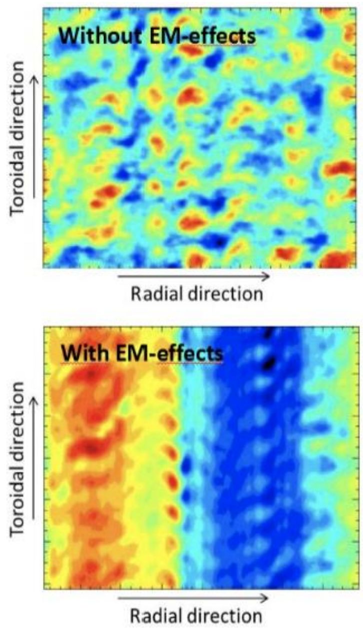

Figure 1 - Streamlines from nonlinear turbulence simulation without (top) and with (bottom) electro-magnetic effects.
At high β, EM effects lead to strong zonal flows, radial stratification and reduced transport.

In practice, an internship on plasma turbulence theory and simulation

- Develop a physical understanding of basic tokamak instabilities, e.g. Ion Temperature Gradient modes and turbulent transport
- Start apprehending the gyrokinetic theory of turbulent transport and the quasilinear approximation
- Get familiar with the state-of-the-art gyrokinetic flux-tube code GKW [11]
- Perform linear simulations with the GKW code
- Compare the structure of the linear eigenmodes to that of their non-linear counterpart (data analysis to be performed in matlab or python)
- Test the quasi-linear model proposed in [10]

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