1 Core transport studies in fusion devices

Pär Strand[*†], **Andreas Skyman**[*] **and Hans Nordman**[*]

[*] *Department of radio and space science, Chalmers university of technology, EURATOM-VR association*
SE-412 96 Göteborg, Sweden
[†] *EFDA Task Force on Integrated Tokamak Modelling*

elfps@chalmers.se
http://www.chalmers.se/rss/EN/research/research-groups/transport-theory/

Introduction

Comprehensive first principles modelling of fusion plasmas is a numerically challenging: the complicated magnetic geometry and long range electromagnetic interactions between multiple species introduce complex collective behaviour in the plasma. In addition, steep density and temperature gradients combined with an inhomogeneous magnetic field drives instabilities, resulting in non-linear dynamics and turbulence.

The turbulence in magnetically confined fusion plasmas has important and non-trivial effects on the quality of the energy confinement. These effects are hard to make a quantitative assessment of analytically. The problem investigated in this article is the transport of energy and particles, in particular impurities, in a Tokamak plasma. Impurities from the walls of the plasma vessel cause energy losses if they reach the plasma core. It is therefore important to understand the transport mechanisms to prevent impurity accumulation and minimize losses. This is an area of research where turbulence plays a major role and is intimately associated with the performance of future fusion reactors, such as ITER.

With the rapid growth and increased accessibility of high performance computing (HPC) over the last few decades, plasma modelling has matured towards an increased predictive capability. Particular emphasis has been put on simulation of drift wave physics, widely accepted as the main source of transport in the plasma core. Theory, reduced physics as well as first principles modelling, and software are developed in a coordinated European effort to produce a virtual Tokamak, a tool that will become indispensable, both when it comes to developing and running ITER, and in the planning of future reactors aimed at energy production [1].

Physical background

To arrive at a set of equations that are both meaningful and solvable, some approximation is necessary. The advances in high performance computing have allowed fusion modellers to move from fluid descriptions of the plasma to kinetic descriptions as the basis for turbulence modelling. In *kinetic theory* the plasma is described through distribution functions of velocity and position for the plasma species. Hence, kinetic equations are inherently six-dimensional, however, magnetically confined particles are constrained to tight orbits along field lines. This motivates averaging over the gyration, reducing the problem to five-dimensional *gyrokinetic* equations[1]
This is a considerable gain, and the foundation of most current plasma codes. In

this project, GENE, a European code developed by IPP-Garching[‡], has been used. GENE employs a second order accurate explicit finite difference scheme, and has demonstrated excellent parallel performance using in excess of 10000 cores[2].

Modelling plasmas

As mentioned above, gradients drive turbulence. Here, plasma core turbulence induced by the so called *ion temperature gradient* (ITG) mode[3], has been studied. Parameters were taken from discharge #67730 of the *Joint European Torus* (JET). A slice of the simulation domain, illustrating the turbulence, is shown in figure 1(a).

The GENE code employs a fixed grid in five dimensional phase space and a flux-tube geometry. For a typical simulation for main ions and one trace species, with electrons considered adiabatic, a resolution of $n_x \times n_{ky} \times n_z = 48 \times 48 \times 32$ grid points in real space and of $n_v \times n_\mu = 64 \times 12$ in velocity space is necessary. A normal run with these parameters uses a minimum of 8000 CPU hours and 384 cores. Incorporating kinetic electrons increases the demand for high resolution in all of phase space, but most notably in velocity space, and also requires a shorter time step. Typically, such simulations require 40000 CPU hours, occupying 1024 cores.

The computations produce tens of gigabyte of data to be analysed. The nonlinear data presented in figure 1(b) is the result of approximately twenty runs on the HPC cluster *Akka*, and from the discussion above, it is readily understood that HPC is vital for this kind of study.

Transport in ITER-like plasmas

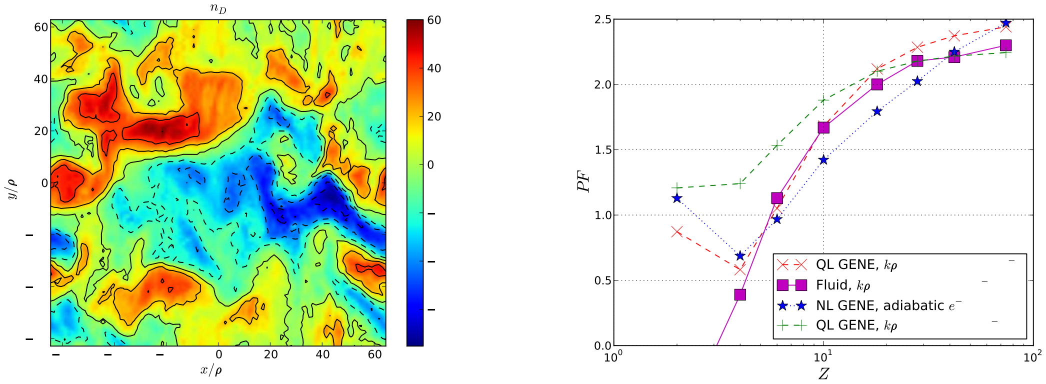
In general, transport of a species with atomic number Z can locally be described by a diffusive and a convective contribution. The former is characterized by the diffusion coefficient D_Z, the latter by a convective velocity or "pinch" V_Z. The *zero flux peaking factor*, defined as $PF_0 = -RV_Z/D_Z$, is important in reactor design because it quantifies the balance of convective and diffusive transport. This can be understood from equation (1), where Γ_Z is the impurity flux, n_Z the density of the impurity species and R the major radius of the tokamak [2]. For the regime studied ∇n_Z is regarded as a constant, such that $-\nabla n_Z/n_Z = 1/L_{n_Z}$. Setting $\Gamma_Z = 0$ in equation (1) yields the interpretation of PF_0 as the gradient at which the impurity flux vanishes.

$$\Gamma_Z = -D_Z \nabla n_Z + n_Z V_Z \Leftrightarrow \frac{R\Gamma}{n_Z} = D_Z \frac{R}{L_{n_Z}} + RV_Z \tag{1}$$

A positive sign of PF_0 indicates a net inward transport. This might lead to an accumulation of wall impurities in the plasma core, which can seriously hamper the efficiency of the fusion device. Understanding under what circumstances a negative peaking factor can be achieved is therefore an important issue for ITER and future fusion reactors.

Time series were generated by GENE on the *Akka* HPC cluster for multiple values of L_{n_Z}, and from these Γ_Z was extracted. The parameters D_Z and RV_Z were estimated and the peaking factor calculated as their quotient. This was repeated for several different nuclear charges Z. Results have been reported in [2], [3] and [4].

Investigating where different models are in agreement is one of the aims of this kind of study: it is the first step towards an understanding of the physics that



(a) crossection of the Deuterium density profile showing turbulent features

(b) zero-flux peaking factor for different Z according to three different models with adiabatic and one with kinetic electrons

Figure 1: Results from the non-linear simulations on Akka

underlie their differences. In figure 1(b) the non-linear results from *Akka* are compared with quasi-linear kinetic results and results from a fluid model developed at Chalmers[3]. As can be seen, the three models are in good qualitative agreement with one another for $Z > 4$ (Be). This owes to the domination of the single strong ITG mode for these particular parameters, and it cannot be guaranteed to hold for other cases. Also in figure 1(b), the quasi-linear result with kinetic electrons is shown for comparison. From that one expects kinetic effects to be most pronounced for low Z. At the time of writing, the fully kinetic non-linear case is still being simulated.

Publications

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