Turbulence Modelling

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Particle and heat transport in magnetic fusion devices are controlled by a small scale turbulence. This turbulence is driven by the density and temperature gradients across the magnetic field, as described in *chapter* 3.1. Since the heat transport is basically conductive, the confinement time typically behaves as the plasma size squared divided by the heat diffusivity, *ie* as a diffusion time. Within this frame, turbulence modelling is of interest for three reasons. Firstly, the comparison of models with experimental data allows a better understanding of the turbulent transport in fusion devices. Secondly, the computed turbulent diffusion coefficients can be used to predict the density and temperature in a forthcoming fusion device. Uncertainties on the predicted confinement may be reduced this way. And thirdly, optimized configurations can be designed by calculating magnetic topologies for which the plasma is less turbulent.

Most of the microinstabilities in fusion devices are drift waves, which exhibit large wavelength (meters) along the magnetic field, small wavelength (millimetres to centimetres) in the transverse directions, and correlation times of the order of a few microseconds (10^4 to 10^5 times smaller than a confinement time). Computing drift waves is therefore demanding in space and time resolution. Moreover the calculation has to be self-consistent: the plasma response to an electromagnetic perturbation has to be consistent with this perturbation via the Maxwell equations. Computing the plasma response is the hard part since this is a nonlinear problem. In the simplest version, drift waves are described with two-dimensional fluid equations in a plane perpendicular to the magnetic field. Thus the first modelling attempts in the early 1980s were 2D fluid simulations. However, it was soon realised that 3D effects should be accounted for since the magnetic field is sheared. Moreover, the use of conventional fluid equations is questionable in collisionless regimes since resonant interactions between wave and particles (Landau resonances) are not correctly described. Three numerical techniques are used to overcome this difficulty: fluid codes with improved equations, particle codes and Vlasovian codes. In the first case, dissipative terms are added in fluid equations to account for linear wave-particle resonances, thus preserving the simplicity of fluid codes. However, it is unclear whether nonlinear resonances are well described in this procedure. In particle codes, the exact trajectories of charged particles are computed. At each time, counting particles in velocity space provides the charge and current densities and the coherent electromagnetic field is recalculated. Thus the wave-particle resonances are well described. However, these simulations require a large number of particles (several tens of millions) to reduce the noise down to an acceptable level. Finally, Vlasovian codes solve directly a kinetic equation (Vlasov or Fokker-Planck equation) to determine the distribution function of particles. Integrations over the phase space provide the charge and current densities. This technique is accurate, but demanding in computer resources. As an example, a result from a 3D fluid simulation is shown in *figure* 1. Although particle and fluid codes qualitatively agree, they predict diffusion coefficients which differ by up to a factor of 2. The reasons for this discrepancy are still to be determined. As written before, wave particle resonances are not described in the same way. Also the damping of plasma rotation is not the same, whereas rotation shear is known to be an important ingredient. The prediction capability of diffusion coefficients determined from fluid turbulence modelling has been analysed in the frame of the ITER project. This was done by using the ITER database which includes typical discharges from most of the present devices. For steady-state discharges, the calculated transport coefficients agree with the experimental values within 30%. The error is larger for transient regimes. Though not sufficient, these are encouraging results.

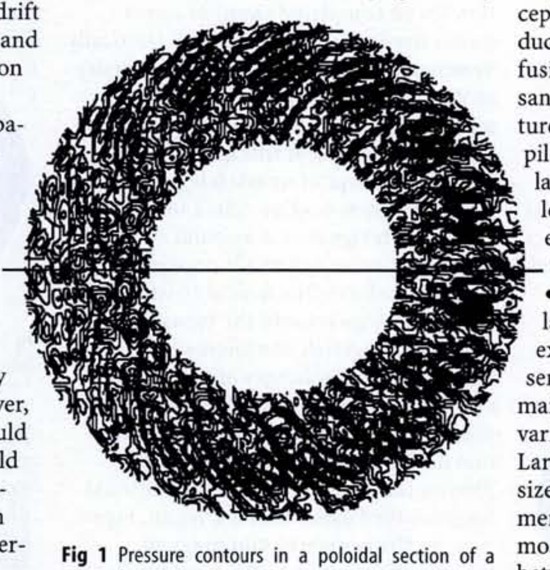

Fig 1 Pressure contours in a poloidal section of a tokamak at a given time for a 3D fluid turbulence driven by a pressure gradient

Beyond the quantitative estimate of diffusion coefficients in a fusion plasma, several topics are actively investigated. The main subjects are the following:

- Transport transients occurring on a time scale smaller than a confinement time have been observed in several devices. Such fast events are hardly explained with standard diffusive models. Two explanations are available at the moment: mode coupling and self-organized criticality. As explained in *chapter* 3.1, the toroidal geometry introduces a coupling of the radially localised Fourier modes, leading to a dynamical system similar to a set of coupled oscillators. Not surprisingly, this coupling opens the route to propagating waves similar to phonons. Simulations have shown that these waves can induce fast transients. However, this effect competes with the decorrelation effects due to nonlinear effects. The concept of self-organized criticality was introduced to model sandpile automatons. A fusion device exhibits some similarities to sandpiles, with the density and temperature gradients corresponding to the sandpile slope. Fast transport relaxations similar to avalanches are observed in turbulence simulations provided that there exists an instability threshold. An example is shown in *figure* 2.
- The use of dimensionless scaling laws reduce the uncertainties when extrapolating the performances of present devices towards a next step. The main dimensionless parameter which varies in such an extrapolation is the Larmor radius normalised to the plasma size. Thus the dependence of the confinement time on this parameter is one of the most investigated subjects. Discrepancies between theoretical expectations and experimental results have been identified

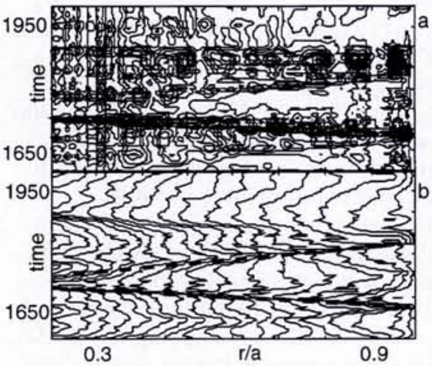

Fig 2 Isoflux ***a*** and isobars ***b*** as a function of radius and time for a 2D fluid simulation. Dashed lines indicate fast transport events, similar to avalanches in sandpile automatons

and have to be understood. Again, mode coupling and self-organization are candidates since they may affect the turbulence correlation lengths.

- The understanding of improved confinement is crucial to design optimized configurations. Most of the simulations show that high shears of magnetic field and plasma flow improve the confinement, in agreement with experiments (see *chapter* 3.1 for details). The stabilising effect of shear flow is observed both in linear and nonlinear regimes, as shown in *figure* 3. Interestingly, a drift turbulence usually self-regulates by generating a shear flow. Also the magnetic topology can be optimized to stabilize a large class of drift waves. This property has also been evidenced numerically, in agreement with recent experiments in tokamaks where the magnetic shear has been reversed. Thus several mechanisms have been identified to explain transitions of the confinement which are observed in fusion devices (*eg* the transition from Low to High confinement regime). However, a full simulation of the LH transition has still to be done.

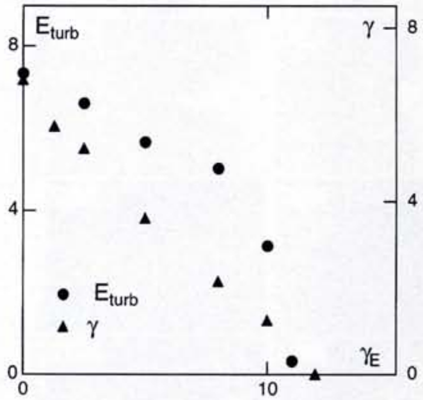

Fig 3 Turbulence level E_{turb} and growth rate γ versus flow shear rate. The growth rates are multiplied by 100 and the time unit is a minor radius divided by the acoustic speed

These encouraging results open the way towards the computation of optimized magnetic configurations with a low level of turbulence.

The Fast Ignitor

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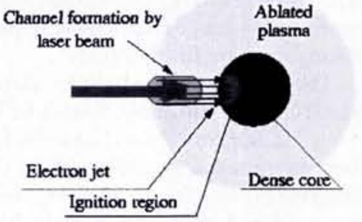

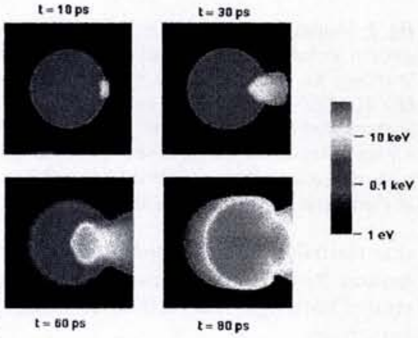

Fig 1a Fast ignition by an external laser beam; **1b** two-dimensional hydrodynamic simulation of fast ignition and burn of a precompressed (300 g/cm^3) deuterium-tritium core; the ignition spot of only 1 mg mass is heated by an energy pulse of 20 kJ deposited in 20 ps. In this simulation transport through surrounding ablation plasma was not considered. (*S. Atzeni et al Nucl. Fusion 37 1665 1997*)

The fast ignitor is a new concept in inertial confinement fusion—to ignite precompressed fuel by an additional external laser pulse of high power. It was proposed by M. Tabak *et al* (*Phys. Plasmas* 1 1626, 1994). The advantage of this method is that fuel ignition is separated from fuel compression and does not depend any more on Rayleigh-Taylor unstable hot spot formation in the centre of the imploding capsule. It is actually this hot spot formation which sets the stringent symmetry conditions in the standard ICF implosion scheme. Aiming only for high compression without central ignition relaxes both symmetry and peak power conditions. On the other hand, one has to deal with new problems concerning the ignitor beam, and these are not yet sufficiently understood.

The idea of the fast ignitor is sketched in *figure* 1a. The energy of the external laser pulse has to be transported to the imploded high-density core through overdense plasma surrounding the core. This transport occurs partially through a propagation channel which the laser beam bores into the ablated plasma, and then via relativistic electrons which the laser drives in the form of an electron jet and which heat the ignition spot. Here, we report on two-dimensional hydrodynamic simulation of fuel ignition and burn (*figure* 1b) and on three-dimensional particle-in-cell (3D-PIC) simulations of laser channelling and electron jet formation (*figure* 2).

The goal is to create the hot ignition spot very rapidly during the 100 ps of fuel stagnation after implosion, hence the name 'fast ignitor'. Though the general idea has been discussed since the 1960s, it is only now that the new laser technique of chirped-pulse amplification provides a tool to generate the required petawatt pulses (10^{15} W). Again, the energy to be invested in the ignition spot scales roughly like $1/\rho^2$, and one needs highly compressed fuel to keep this energy at an acceptable level. An actual simulation of fast ignition and burn is shown in *figure* 1b in terms of the temperature evolution. A remarkable result of these simulations is that one can also ignite pure deuterium using a DT ignition spot.

The fast ignitor concept involves the interaction of laser light with plasma at intensities of 10^{20} W/cm^2, at which laser-driven plasma electrons become relativistic. This modifies the index of refraction and leads to self-focussing of the light beam. Light can propagate in a plasma up to a critical density. A light pulse incident on the plasma can self-focus into a narrow propagation channel having a diameter of 1-2 wavelengths. Another relativistic effect is: the laser pulse drives electrons by means of the $(v/c) \times B$ force in the direction of light propagation. This creates huge currents (of the order of 10^{12} A/cm^2) comoving with the light. Self-generated magnetic fields of the order of 100 MG pinch the current, and this fur-