Report on the meeting

"Self Organisation and Transport in Electromagnetic Turbulence"

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1 Introduction

The aim of this meeting is to allow discussions on recent ideas in turbulent transport and to promote new work and collaborations in the field. When organising this meeting, it was clear from the very beginning that the usual format of a conference does not provide the appropriate framework for in-depth discussions and work on a given subject. Several ingredients were to be implemented in the recipe for success :

◇ the theme of the meeting is focussed on a restricted topic,

◇ a limited number of participants,

◇ a significant participation of PHD and post-doc students,

◇ the participation of astrophysicists in order to enlarge the prospects,

◇ a long duration, at least two weeks,

◇ a very limited number of formal presentations dedicated to introduce the subjects and participants, as well as to trigger discussions and work,

◇ a meeting place with an office for each participant and a computer room.

The final format was a gathering of 27 experts in plasma physics (including 5 astrophysicists and 9 students) during 3 weeks at the University of Provence in Aix-en-Provence. There were less than 3 talks per day. Discussions on predefined topics were organised each week, complemented with meetings for common work. In practice, there was a lot of interaction between participants, in particular between experts in analytic theory and those in numerical simulations. The main discussions were focussed on the dependence of the turbulent flux on the plasma β (electromagnetic effects), subcritical turbulence, scaling laws of turbulent transport, transport of test particles, quench of the α effect (dynamo), relaxation events, structure identifications, dynamics of zonal flows and streamers, and statistical description of turbulence intermittency. The detailed programme can be found on the web site of the meeting http : //festival.theorie.free.fr.

This summary report is organised along the list of topics that have been most discussed, namely electromagnetic effects on $E \times B$ drift turbulence, transport issues, self-organisation, dynamo effect, relaxation events, and predictability. The latter issue was put forward at the most important output of the meeting during the closing discussion.

2 Electromagnetic effects on $E \times B$ drift turbulence

This topic was addressed in several review talks. These sessions and discussions were led by B. Scott. The most basic question is the effect on turbulent transport of a finite plasma beta (β) (gas pressure/field energy). As was also pointed out, the effects of finite magnetic fluctuation activity on the internal dynamics of the turbulence is also important. Finite beta introduces magnetic induction as a replacement for electron inertia and resistive friction in the Ohm's law, and magnetic flutter in the parallel gradient, involving both nonlinear and linear terms. Magnetic induction tends to strengthen the drift wave nonlinear instability, which is the most central mechanism in gradient driven $E \times B$ turbulence. The linear part of magnetic flutter, acting on the background electron pressure gradient, causes stabilization by reducing the pressure/potential phase shift necessary for the energetics. Nonlinear magnetic flutter in turn destabilises at moderate beta (below the ideal MHD threshold) by partially cancelling the linear flutter effect. The net effect is an enhancement of transport in the tokamak edge with rising beta, for both drift wave and ion temperature mode turbulence. Globally consistent flux tube computations which hold the domain size constant while scanning beta do not yield the transport non-monotonicity which would be required to explain tokamak confinement transitions.

In finite beta turbulence the non-linearity in the electron inertia is also very weak. Linear destabilization of shear Alfvèn waves by the ion temperature gradient has been found for scales near the ion gyroradius ρ_i (F. Zonca, G. Falchetto). These AITG modes also extend the domain of non-adiabatic ion dynamics to scales well below ρ_i, placing the usual model for electron temperature (ETG) mode turbulence into question. A new and interesting avenue for investigation of turbulence in magnetically confined plasmas at hot core parameters is thereby opened.

The interaction between turbulence and zonal $E \times B$ flows is also affected by the finite beta, but most subtly for drift modes above ρ_i. The Maxwell stress (nonlinear magnetic flutter acting on the current) remains small compared to the $E \times B$ Reynolds stress. This result is at variance with basic shear Alfvèn modes, but the $E \times B$ stress is itself reduced. Modulational instability analysis of the zonal flows using the wave kinetic equation indicates however that the Maxwell stress is the stronger driving effect for ETG modes. The linear response is mostly electromagnetic in the kinetic limit of faster parallel streaming, directly affecting the Maxwell stress for the turbulence. Zonal field dynamics also enters due to the nonlinear flutter effect in the Ohm's law (A. Smolyakov). Analysis of this effect is only beginning. First results are that it may have a role in the finite beta enhancement of drift wave and ITG turbulence below the ideal MHD threshold, and zonal field generation may then launch non-linearly destabilized micro-tearing or current filamentation at ETG mode scales.

3 Transport issues

A large number of presentations provided information leading to a better understanding of the physics behind the parametric dependence of transport observed in experimental devices. In the following, the conventional viewpoint is assumed, chiefly for descriptive purposes, that steady state transport can be described in terms of effective transport coefficients as a function of local parameters. It is understood, and largely debated at the meeting, that transient phenomena need not necessarily be describable by means of the same coefficient employed in steady state analysis or by diffusive equations at all. One can write, as usual,

$$\chi = \chi_B \quad F(\rho^*, \beta, \nu^*, \textit{geometrical properties})$$

where χ_B is the Bohm conductivity, ρ^* a gyroradius normalised to the plasma size, β the plasma beta and ν^* the collisionality. The dependence (crucial for machine extrapolation) on the small parameter ρ^* can be arguably written as a power expansion

$$\frac{\chi}{\chi_B} = \alpha_0 + \alpha_1 \rho^* + \alpha_2 [\rho^*]^2 + ...$$

The Bohm vs gyro-Bohm conundrum is equivalent to the question whether the coefficient α_0 is zero (for gyro-Bohm). In an overview on the subject, M. Ottaviani pointed out that in the ion turbulence regime, all fluid codes point to a gyro-Bohm scaling. Gyrokinetic codes has given so far mixed answers. While earlier studies pointed to Bohm scaling for both the correlation length and the effective conductivity, some of the results presented at the workshop gave a more complex picture. In one instance the size of the vortices and the correlation time turned out to be proportional to ρ^* seemingly implying gyro-Bohm, whereas the measured transport was found to be Bohm-like (T.S. Hahm). In another instance it was stressed that when the equilibrium flow is sufficiently high and ρ^* not too small, the third term in the above expansion may become important to the point that apparent Bohm-like weak dependence on ρ^* would ensue (J. Candy). It has also been remarked that in the edge the whole ρ^* expansion may break down due to strong temperature and flow gradients. One also acknowledges that global gyrokinetic studies have not yet been performed in steady state, with input power balanced, on average, by the losses. This may induce some uncertainty in the determination of the conductivity, due to shorter run times with reduced statistics and due to the evolution of the underlying profiles.

Among the geometric parameters, it has been emphasized the importance of the dependence on the gradient scale lengths in determining the form of the profiles. The existence of spatio-temporal transport phenomena (e.g. avalanches) over scales larger than the correlation length measured at a given time might ultimately play a role in the functional dependence on the gradient scale-lengths of the effective transport coefficients (Y. Sarazin, X. Garbet).

On the side of electron turbulence, magnetic flutter transport is found weaker than the $E \times B$ drift transport. This dominance is well known for the ion regime modes and appears to be true for the electron modes up to the limited plasma beta values allowed in tokamaks (overview by W. Horton). The understanding here is limited and the need for more work to understand more fully the closure of the electron heat flux equations was suggested. New closure on the heat flux were discussed and results compared with high resolutions collisionless drift-kinetic simulations were discussed (T. Watanabe). Progress in understanding the formation of streamers in ETG simulations and the streamer/no-streamer transition has been shown. Simulations of ETG discussed in detail were a 3D shearless toroidal FLR fluid simulations which showed streamers in an early stage break up into larger vortex structures in a latter stages of steady state (M. Wakatani). While Zonal flows were not prominent in the 3D fluid simulation, a (2+1/2)D gyrokinetic simulation of a magnetic shear reversal layer showed no Zonal Flows in the shearless region, but showed the turbulence dominated by zonal flows in the regions of appreciable magnetic shear. More work is required to compare the analytic work with the numerical findings. An important point is that for sufficiently long streamers the ion response may not be adiabatic and the equations used in present-day ETG codes may become invalid. This might open a new front of numerical simulations encompassing all the relevant ionic scales.

Test particle dynamics constitutes a somewhat independent area. The new analytic Lagrangian technique of the decorrelation trajectory has been discussed extensively (M. Vlad and F. Spineanu). It gives excellent agreement with the test particle simulations in the notoriously difficult large Kubo number limit. In general, test particle techniques have been extensively used as a complement of numerical simulations as diagnostic tools. It is still an open problem to determine when and to what extent test particle transport is representative of the self-consistent transport obtained from the codes. In certain instances little quantitative agreement is found. A limiting case in this sense is the Hasegawa-Mima equation, where the self-consistent particle transport is strictly zero while test particle transport is finite. Nonetheless, it is clear that the actual motion of charged particles in the turbulent plasma is a chaotic typically far removed from the simple integrable orbits assumed in linear self field calculations.

4 Self-Organization: Zonal Flows and Streamers

The discussions on turbulence self-organization was dominated by the question of structure formation. Two types of structures have been mentioned several times : Zonal Flows (ZF), which are convective cells oriented in the periodic direction, and streamers, which are eddies elongated in the direction of the gradients.

In tokamaks, Zonal Flows correspond to fluctuations of the poloidal velocity. They are always stable linearly. Non-linear electrostatic simulations show that they grow exponentially from a bath of ambient turbulence, before saturating. Recently, there has been a growing interest for these structures since they appear to control the turbulence background. It was pointed out that turbulence is quenched when its linear growth rate becomes smaller than an effective shearing rate ω_{eff} (T.S. Hahm). Here, ω_{eff} accounts for both the mean sheared flow and the ZF, whose shearing efficiency decreases at increasing frequency.

In an overview on the subject, P.H. Diamond described how zonal flows interact with turbulence. This question was illustrated with a generic model coupling the dynamics of drift waves (DW) to that of zonal flows. Here, the key assumption is a scale separation between both: DW develop at small spatial scales and high frequencies, while zonal flows are characterised by small wave numbers and low frequencies. Hence, interactions are non-local in the Fourier space. Such a characteristic is expected to generate turbulence intermittency, as observed in simulations of fluid turbulence. The model relies on the wave kinetic equation, which describes the perturbation to the DW spectrum N_k caused by the emerging zonal flows. In the weak turbulent regime, the impact of ZF appears as a diffusion in k_r, the radial wave vector. In this case, ZF lead to a broadening of N_k, in agreement with gyrokinetic results of ITG (Ion Temperature Driven) turbulence. In such a regime, the necessary condition for the growth of zonal flows is that $\partial_k N_k < 0$.

In the strong turbulent regime, non linear coherent structures can form and propagate ballistically in the radial direction. Part of the DW may then be trapped in local zonal flow, thereby saturating the instability. The trapping criterion is readily fulfilled at low collision frequency ν_{ii}. As ν_{ii} increases, the non linear solutions are shock like, and lead to a diffusive damping of DW. The intermittent character of zonal flow dynamics raises the question of their statistical description. E.J. Kim produced an analytical result that shows that the probability distribution function of Reynolds stress in a 2D electrostatic turbulence is an exponential. This approach clearly open a new route of research in this difficult field.

The saturation level of zonal flows has also received much attention. Three routes have been explored. The first one refers to ion collisions. At vanishing ν_{ii}, gyrokinetic simulations of 3D ITG turbulence reveal that zonal flows remain undamped and stable close to the linear threshold, in agreement with theoretical results. In this case, turbulence is quenched. This up-shift of the non linear threshold with regard to the linear one possibly corresponds to the so-called Dimits shift regime. The effective diffusivity is then observed to scale like $\nu_{ii}^{0.7}$, due to the collisional damping of zonal flows. Also, such a damping is thought to be responsible for the bursting of turbulence, whose time period goes like ν_{ii}^{-1}. This dynamics is recovered in a predator (ZF) - prey (DW) model, where turbulence oscillations are slowly damped as soon as N_k has a finite spectral width (P.K. Kaw). At larger ν_{ii}, this model then predicts a level of turbulence E_{turb} independent of ν_{ii}. Further increasing ν_{ii} is predicted to lead to a state where DW condensate at vanishing k_r, with E_{turb} proportional to ν_{ii}. The second route deals with the stability of zonal flow with regard to Kelvin-Helmoltz (KH) instability. Analytical studies of zonal flow saturation in DW turbulence show that KH instability is primarily driven non-linearly. However, its non linear growth rate is found to be much smaller than the one of zonal flow, which are then expected to dominate. In that respect, the role of KH instability in the collisionless saturation of zonal flow is quite unclear (see previous section). A third mechanism is the coupling of Zonal Flows through geodesic curvature to pressure waves, which are then diffusively mixed by the turbulence. For turbulence in the edge of a fusion device, this limits the self-generated flows to small amplitudes.

Zonal flows appear to be sensitive to magnetic perturbations. On the one hand, 3D fluid simulations of RBM (Resistive Ballooning Modes) edge turbulence show that a stochastic and static magnetic field reduces both the mean sheared velocity and zonal flows. As a result, the magnitude of the turbulent flux is not quenched by the magnetic field perturbation (P. Beyer). On the other hand, the impact of magnetic fluctuations on zonal flows has been investigated analytically in the kinetic regime of shear Alfvèn waves. It is found that magnetic fluctuations tend to inhibit the formation of zonal flows. Indeed, the magnetic stress has an opposite sign to the Reynolds stress, which acts as a drive for zonal flows (A. Smolyakov). This effect was not observed in simulations of drift wave turbulence done during the workshop (see Section 1). A related issue is the generation of zonal flows by macroscopic MHD modes. B. Carreras showed that indeed an MHD mode can generate locally a substantial sheared flow. This offers an explanation for the observation of transport barriers in stellarators and tokamaks near low order rational surfaces.

The interplay between zonal flows and streamers has been addressed by many participants. In an overview on the subject, S. Champeaux showed with a 2D model of drift wave turbulence that zonal flows and streamers appear more likely in some parts of the spectral domain. There exists a range of wave numbers where the coexistence of both structures is possible. This prediction does receive some support from RBM turbulence simulations, which shows an interplay between the two types of structures (P. Beyer). There exists also cases where one structure dominates on the other. The example of ETG modes (M. Wakatani) was already mentioned. This example is quite interesting in many aspects since streamers are found to play an important role in some ETG simulations, but not in others. The difference may actually comes from the dynamics of zonal flows and Kelvin-Helmholtz modes, whose behaviour is sensitive to the details of the model, in particular the damping processes.

5 Dynamo effect

The problem of the spontaneous generation of magnetic fields in conducting fluids (dynamo effect) has been considered in a number of presentations and in the discussions. In fusion plasmas the dynamo effect is considered of some importance only for certain machines in particular in the reversed field pinches. More importantly, some kind of dynamo mechanism is usually considered essential to explain the fields observed in various space/astrophysical objects at all scales, like planets, stars, accretion disks, galaxies and the interstellar medium (ISM). For example, the Earth's magnetic field exists unchanged, in magnitude, since at least a billion years, whereas the estimated resistive decay time for a supposedly-static Earth's core is only $\sim 10^4$. Thus the magnetic field generation from the movement of the core is invoked to explain the observation. The theoretical problem is to determine what kind of motion(s) is/are needed to achieve the observed field. Similar difficulties are met when trying to explain the time-scale of the reversal of the Sun's field (about 11 years). In the ISM, the magnetic energy is of the order of the turbulent kinetic energy of the interstellar matter. Can a turbulent fluid amplify a seed magnetic field to the point that its energy becomes of to the order of the fluid kinetic energy? A different, but related problem is the question of how sufficiently large fields affect the dynamics, and in particular the star formation.

For sufficiently small initial magnetic fields, the back reaction on the fluid is negligible. The problem is linear and it amounts to the calculation of the growth rate for a given flow. One speaks of kinematic dynamo. The kinematic problem has been treated analytically and numerically. An overview was given by Y. Ponty. The results are used to design the handful of experiments around the world dedicated to producing a dynamo by establishing specific flows. One particular question is whether the dynamo can be fast, that is, whether the maximum growth rate can become independent of the resistivity in the limit of small resistivity. This is suggested by concepts based on chaos theory, but numerical verifications are difficult, although indications of possible fast dynamos were shown.

More important for the applications is the question of how to achieve a dynamic dynamo, which includes the retro-action of the magnetic field on the flow, that is sufficiently strong to explain the observations.

Numerical simulations of resistive MHD in three dimensions, where the fluid is stirred turbulently show that the growth of the magnetic field stops at a rather low magnetic energy, typically smaller than the kinetic energy by factor of the order of the magnetic Reynolds number (D. Hugues). This leaves the ISM problem still open.

The notion was discussed that resistive MHD may not be an adequate model for the space plasmas under consideration. In particular the extension of MHD that was proposed takes into account the effect of friction with neutrals, but other possibilities, like the use of a generalized Ohm's law were mentioned. As the conventional turbulent α effect seems to impeded by the alignment of the velocity fluctuations with the perturbed magnetic field (so called "Alfvèn effect"), a central question is whether an alternative route takes place via an inverse cascade of helicity (E. Vishniac).

6 Relaxation events

There are many examples in magnetic fusion physics where relaxation processes with following characteristic features are observed :

− slow increase of a mean parameter followed by its fall,

− recovery and cycling of this rise and fall at an average frequency determined by the input source,

− probabilistic nature of time series with properties determined by distance from threshold.

Examples are sawteeth events near the $q \sim 1$ surface in tokamaks, ELMs near tokamak edge, dithering near L-H transitions, internal reconnection events in small aspect ratio tokamaks, dynamics of ITB's (internal transport barriers) etc... . The conventional paradigm for such phenomena is usually presented in terms of a continuous transition through a linear instability and the subsequent nonlinear effects. A concrete example, namely modelling of ELMs was discussed in a detailed review talk by J. Connor. He pointed out that recent work has identified the importance of current gradients and kink like effects (over and above the pressure gradient effects) for the instability related to Type I ELMs. Similarly, it appears that in many instances the peeling mode effects have to be considered in addition to the conventional instabilities due to ballooning modes. But there was a general feeling that the detailed nature of the nonlinear amplitudes, frequencies etc of the ELMs are still not predictable from any of these theories .

At the meeting there was also a detailed discussion on the need for a paradigm shift for the theoretical description of such nonlinear relaxation phenomena (K. Itoh, S. Itoh, P. Kaw, A. Das). It was felt that a new approach based on threshold bifurcation effects with hysterisis, which has proved quite successful in modelling fluctuations in far from equilibrium driven dissipative systems, would be appropriate.

For example, one could consider a two parameter model with 1D dynamics :

$$\begin{aligned}
\partial_t T &= \partial_x\{\chi(\partial_t T)\} \; + \; S \\
\partial_t \chi &+ \chi \, / \, \tau = \; Q \, / \, \tau \\
Q &= \chi_{max} \quad if \quad |\partial_x T| \; > \; K \\
Q &= \chi_{min} \quad if \quad |\partial_x T| \; < \; \eta K
\end{aligned}$$

This model couples the global parameter T to the fluctuation parameter χ. It has multiple time scales, the important ones being the source function S, χ_{max} and τ. There is a threshold parameter K and a hysterisis parameter η. Each time the collapse occurs there is propagation of avalanche like fronts in the 1D space-time. These equations belong to a class of time dependent Ginzburg-Landau equations and describe relaxation/transition phenomena in a wide class of problems.

It was felt that it is time to advertise that the old paradigms have outlived their utility. Experimentalists and modelers should be encouraged to look for characteristic signatures of the bifurcation paradigm. These signatures are multiple time scales, hysterisis, evidence of propagating fronts, probabilistic characteristic of the time series etc. Similarly, theorists can be urged to look for deductive derivations of the above phenomenological models starting from a more complete fluid or kinetic description of the basic plasma.

7 Conclusion

The question of predictability was present all along this meeting. As mentioned in the previous sections, intermittency is found to be a central issue in plasma turbulence. The main reason for intermittency seems to be the dynamics of structures such as zonal flows and streamers and their interaction with the turbulence background (however intermittency coming from dissipative scales cannot be excluded). Electromagnetic effects certainly enhance this tendency.

Another paradigm that was questioned is the mean field approach. The main justification of a mean field theory is scale separation. As zonal flows and streamers tend to be mesoscale (sometimes macroscopic) structures, this assumption certainly deserves to be revisited. Gaussian statistics and scale separation are the main hypothesis behind most of the turbulent transport models that are used in fusion plasmas. The use of conventional transport models was therefore questioned during the meeting, and particularly during the closing session.

Among the possible improvements and alternative routes, the development of a statistical theory has been mentioned several times. The calculation of a mean turbulent flux would then be replaced by the determination of a probability distribution function. This is clearly a formidable task and only a few works have been done in this domain.