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CONFERENCE REPORT

Summary: Third IAEA Technical Meeting on Theory of Plasma Instabilities

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1. Introduction

This meeting had a slight emphasis on fast particle physics, but also addressed a wide range of other topics of relevance to stability in fusion plasmas: large scale plasma instabilities, micro-stability and turbulence. S. Cowley was invited to give a talk on gyro-kinetic theory in the vicinity of a black hole, to stimulate inter-disciplinary discussion. Indeed, micro-stability and turbulence dominated the agenda, with about half of the presentations being in this area. There was an approximately equal split of the remaining presentations between energetic particles and magneto-hydrodynamic instabilities. We present a summary of selected presentations in each of these areas in the following three sections.

2. Micro-instabilities and turbulence

Sixteen oral contributions addressed progress in the understanding of micro-instabilities and turbulence. Some of the key results are briefly reviewed here.

The zonal flow/geodesic acoustic mode (GAM) physics, often controlling the level of turbulence, was further investigated in several papers. A probabilistic transport model was extended by S. Bouzat to include the effects of the $E \times B$ velocity shear, leading to an enhancement of the confinement time. A paper by J.W. Connor included the flow shear effects in the ballooning mode formalism. The wave number representation is a convenient way to include the effect, and shows that the influence of flow shear varies depending on the mode under consideration. G. Darmet presented results on the phase space intermittency in flux-driven gyro-kinetic simulations. Quasi-periodic relaxations governing the system are observed in phase space where zonal flows have a significant influence on the distribution function. Y. Kishimoto discussed numerical simulations of turbulent transport near the critical gradient including the zonal flow and GAM mode. A new type of intermittency near the critical gradient (referred to as GAM intermittency) was observed in global Landau-fluid ion temperature gradient (ITG) turbulence simulations. The GAM intermittency nonlocally transfers and/or convects turbulence energy to a wider radial region than that of steady state zonal flows through GAM propagation and damping.

There is increased interest in the extension of electrostatic models to include electromagnetic effects. A study of the micro-tearing mode for the MAST tokamak parameters was presented by D. Applegate. This mode is unstable for sufficiently high values of the plasma β (where β is the ratio of thermal to magnetic energy) and is found to be mainly connected with the physics of passing electrons. Investigations have shown that magnetic drifts and the electrostatic potential play an important role in the drive of the mode. E.J. Kim presented a paper on transport theory in electromagnetic turbulence. When electromagnetic effects are included, a reduction in transport is predicted without much reduction in fluctuation levels. For strong magnetic fields a damping of the zonal flows is predicted. Y. Nishimura presented a study of shear Alfvén waves using the global gyro-kinetic code GTC. A hybrid model based on a small parameter expansion in the square-root of the mass ratio was employed. Several tests demonstrate that the analytic results of Alfvén wave propagation in toroidal geometry are reproduced by the code. First nonlinear simulations were presented.

Work on edge and scrape off layer (SOL) turbulence was described in two oral contributions. C.S. Chang presented a study of the edge pedestal and plasma rotation physics using the XGC particle simulation code. This particle-in-cell 5D full-f gyro-kinetic code includes many of the effects necessary for the simulation of the plasma edge. The coupling with the M3D nonlinear MHD code to study the evolution of edge localized modes (ELMs) was reported, as well as the evolution of the radial electric field in the edge. The second contribution, presented by P. Tamain, dealt with scale merging in edge and SOL turbulence. Ballistic propagation of self-organized fronts are observed in flux-driven 2D SOL simulations. Furthermore, pedestal and barrier relaxation phenomena are obtained in 3D nonlinear turbulence simulations with ExB shear flows.

Several papers dealt mostly with (quasi-) linear theory aimed at the explanation of observed transport fluxes. T. Fulop discussed the influence of magnetic shear on impurity transport. For negative and large positive shear, a strong reduction of the effective impurity diffusivity is obtained. Furthermore, fluid and gyro-kinetic models give qualitatively similar results for the shear scaling of the impurity transport. The impurity peaking is found to depend on magnetic shear, with more peaked profiles obtained for weak shear. A.G. Peeters presented a paper in which a pinch contribution for the radial toroidal momentum transport was demonstrated to exist. The physics mechanism can be formulated through the effect of the Coriolis drift. Without momentum sources a peaking similar to that of the density profile is predicted. A study of the quasi-linear and neoclassical particle flux in LHD was presented by O. Yamagishi. For the outward-shifted configuration the neoclassical flux is always large and positive so that the quasi-linear flux is constrained to be negative for the steady state, which then leads to hollow profiles. For the inward-shifted configuration the neoclassical flux is negligible. In this case, the anomalous flux itself must be zero for steady state, generating peaked density profiles.

The gyro-kinetic framework was also employed to make progress in a number of other areas. As discussed further in section 3, J. Candy presented results obtained with the nonlinear global gyro-kinetic GYRO code. For trace impurities the flux is found to be a linear combination of a diffusive as well as a pinch contribution. A study of the electron temperature gradient modes revealed that for cyclone base case parameters the ion kinetic effects must be included (i.e. the adiabatic response is insufficient) to obtain a physically meaningful saturated state. Resolving both the ion as well as the electron Larmor radius scales leads to a reduction of the activity at the electron scales compared with simulations in which the ion scales are not resolved. This effect is probably due to an increased velocity shearing connected with the larger scale modes. The spectrum is then isotropic, and the electron heat transport is found to be dominated by the activity on ion Larmor radius scales. P. Xanthopoulos presented nonlinear gyro-kinetic simulations of transport in the W7-X stellarator using the GENE code. Many features are similar to a tokamak (driving gradients, dependence on temperature ratio, strong influence of zonal flows) but the geometry is important leading to a different parallel mode structure, weakly unstable ITG and trapped electron modes as well as the co-existence of different modes.

Finally, F.M. Poli showed that experiments on the basic plasma device, TORPEX, can provide comparisons with linear and nonlinear theories of electrostatic instabilities. On this device the measured dispersion relation is consistent with theory, with curvature being the dominant driving mechanism. Furthermore the development of turbulence is observed to be through three-wave coupling.

3. Energetic particles

The nine presentations that dealt with energetic particle effects can be subdivided into four groups. There were three talks on MHD stability control via fast ion injection; three talks focused on Alfvén modes and MHD spectroscopy; two talks addressed fast particle diffusion due to background turbulence, and one described rapid nonlinear phenomena associated with phase space structures.

Experiments on sawtooth control by neutral beam injection have motivated I. Chapman to model the asymmetry in the sawtooth period observed on JET and MAST. This analysis employed the MISHKA-F MHD stability code together with an extended version of the HAGIS code to calculate the fast particle contribution to the potential energy of the internal kink mode. In JET, the predominantly passing population of fast ions has been found to produce a destabilizing effect when injected in a direction opposite to the toroidal magnetic field. The main reason for asymmetry in this case is the flow shear that modifies the trapped particle distribution. In MAST, toroidal rotation stabilizes the $n = 1$ kink mode and asymmetry is explained by ion diamagnetic effects.

V. Marchenko presented his recent results on stabilization of the internal kink and quasi-interchange modes by circulating fast ions along with an overview of the earlier work on this topic. In addition to numerical calculation of the fast ion precession in realistic geometry, the author discussed a new kinetic correction to previous theories. Depending on the direction of beam injection, this correction produces a stabilizing or destabilizing effect. In shear-less plasmas, kinetic stabilization of quasi-interchange modes is less significant than the purely fluid mechanism associated with coupling between the $m = 1$ and $m = 2$ poloidal harmonics and the finite orbit width effect, which depends on the direction of beam injection.

W.A. Cooper presented a comparative analysis of fast particle effects on MHD stability in stellarators, based on two phenomenological energy principles: the Kruskal–Oberman principle and the rigid hot particle energy principle by Johnson *etal*. Both models give similar values for the threshold pressure of hot anisotropic ions needed to obtain stability in an ideally unstable heliotron configuration. This study also involved comparison between the on-axis and off-axis hot particle depositions (see section 4) as well as consideration of particle anisotropy effects.

Linear analysis of energetic particle driven modes remains an important part of understanding burning plasma behaviour, which continues to develop. The main challenge here is to incorporate all the essential physics ingredients into computationally efficient codes to allow comprehensive stability assessment in realistic geometry. As a step in this direction, Ph. Lauber presented an extension of the LIGKA code designed to capture the geodesic acoustic and other finite pressure effects on low-frequency Alfvénic modes in gyro-kinetic simulations. LIGKA also provides a relevant treatment of the continuum and radiative damping mechanisms. The code was recently used to reproduce an experimentally observed transition from Alfvén cascades to toroidal Alfvén eigenmodes (TAEs) and to interpret the enhanced damping of TAEs after such a transition. A more detailed comparison with experiment is expected after adding an energetic particle drive to the code.

Observations of Alfvén cascades in tokamaks show that these modes typically exhibit an upward frequency sweeping, which has been attributed to the existence of a radial potential well for the upward sweeping eigenmodes as opposed to a potential hill for the downward sweeping perturbations. However, the lifetime of the transient perturbations at the potential hill may still be sufficiently long to make these perturbations visible in experiments. As discussed by B. Breizman, the underlying reason is that the frequencies of shear Alfvén perturbations are characteristically more robust than the radial structure of the perturbed fields. The transient perturbations at the potential hill can therefore be interpreted as radially propagating quasi-modes rather than standing waves. An interesting feature of these quasi-modes is that their damping rates are quantized, so that their spatial structure still exhibits some rigidity but it is now governed by the quasi-mode damping rate rather than its real frequency.

S.E. Sharapov presented an overview of recent fast particle studies on JET and MAST using a wide range of new diagnostics in both conventional and shear-reversed regimes. The renewed X-mode reflectometry on JET now provides information on the radial location of Alfvén cascades, which is also the location of the shear reversal point where the safety factor $q = q_{\mathrm{min}}$ is a minimum. Therefore, both the location and the time dependence of q_{min} can be inferred from the Alfvén cascade measurements, giving more control over the creation of internal transport barriers. The so-called tornado modes in JET have now been identified as core localized TAE modes rather than energetic particle modes. Their frequency changes in time due to evolution of the safety factor profile. JET data indicate that multiple tornado modes can be responsible for gradual depletion of the fast ion population inside the $q = 1$ magnetic surface. The TAE-induced transport of fast ions eventually results in a monster sawtooth crash when the fast ion pressure inside the $q = 1$ surface falls below the sawtooth stabilization threshold. This scenario appears to be a very interesting candidate for integrated modelling that would involve an interplay between the ion cyclotron production of fast ions, the high-frequency Alfvénic activity, the fast particle transport, and the sawtooth dynamics. On MAST, a successful effort was made to identify Alfvén cascades experimentally. These modes were not seen previously in MAST because of the strong modification of the modes by the injected beams. With lower beam power, the modes are now observed unambiguously, which demonstrates that they are in fact common to conventional and spherical tokamaks.

A relatively new topic in the fast particle area is the investigation of fast particle diffusion due to background short-wavelength turbulence. These studies partially reflect the emerging trend to develop a unified description of fast particle and bulk plasma transport. At a qualitative level, the short-scale perturbations are commonly believed to be of secondary importance for the energetic particle transport because their effect tends to be suppressed by gyro-averaging. The talks by J. Candy and T. Hauff dealt with an accurate quantitative evaluation of the effect. J. Candy presented calculations performed with the GYRO code for ITER-relevant parameters. The calculated diffusion rate for the alpha particles is found to be benign for the fastest alphas, so that the short-wavelength turbulence does not degrade their confinement. These calculations also reveal that the diffusion rate increases as the alpha-particles slow down, which may help remove helium ash. T. Hauff has performed direct numerical simulations of test-particle diffusion in the presence of two-dimensional electrostatic turbulence. A distinctive feature of this work is systematic characterization of fast particle diffusivity with regard to particle Larmor radius and Kubo number. In particular, it is found that large Kubo numbers tend to prevent the FLR-reduction of the diffusivity. An effort is under way to extend these simulations to more realistic turbulence in tokamaks.

Nonlinear evolution of energetic particle instabilities often involves rapid frequency sweeping events that are associated with convective transport of spontaneously arising phase space structures. A simple one-dimensional numerical model for frequency sweeping presented by R. Vann exhibits a pattern that is suggestively similar to that observed on MAST and several other machines. This similarity apparently calls for more realistic modelling of the phase space structures in tokamaks in order to assess their effect on energetic particle confinement as well as on direct heating of plasma ions. It is also noteworthy that, together with related analytical calculations for the model nonperturbative problem of two-stream instability, the simulations performed by R. Vann suggest that the recurrent frequency sweeping events tend to maintain a marginally stable time-averaged distribution function of the energetic particles.

4. MHD instabilities

There were two sessions on MHD instabilities in addition to an overview by T. Hender, asking how well does MHD theory explain observed tokamak stability? We structure this section around a summary of Hender's overview, incorporating the other presentations into this.

The overview presented the issues in the context of ITER. Some, such as sawteeth, fishbones and neoclassical tearing modes (NTMs) are relevant to the $Q = 10$ operational scenario; others, such as infernal modes and resistive wall modes are more relevant for the steady state, $Q = 5$ scenario, while issues such as (ELMs) and disruptions are a concern for both modes of operation.

Disruptions get increasingly severe as one goes to larger tokamaks and, for this reason, they are a main driver for the engineering design of ITER. It is felt that we now have a good quantitative understanding of the role that ideal MHD instabilities have to play in triggering disruptions, although this does not cover all classes. In particular, our understanding of the cause of density limit disruptions remains at a more qualitative level. Our understanding of the consequence of disruptions is improving and we are now making quantitative predictions for a range of related phenomena such as halo current peaking, runaway electron production and mitigation by massive gas injection. A complete integrated model, incorporating the wide range of timescales and challenging phenomena associated with the plasma wall-interaction is still some way off.

Moving to ELMs, there is a good quantitative understanding of the trigger for large type I ELMs in terms of the peeling–ballooning model. This is of crucial importance for ITER, where large ELMs cannot be tolerated. S. Saarelma described the modelling that he has been doing for MAST which shows that the peeling–ballooning stability boundary is approached just before the ELM. He highlighted challenges to the theory, however, such as the role of the separatrix, which appears to have a stabilizing effect on the peeling component. Interestingly, he finds that high poloidal beta also has a stabilizing effect (with constant pedestal parameters), which perhaps might help to explain at least some of the regimes that have small ELMs. Saarelma also postulates the importance of flow shear in the ELM cycle on MAST. The physics of the ELM crash remains incomplete, and we do not yet have a predictive model. However, the filamentary structures have been predicted both in analytic theory and large scale computational simulations. The implications of these structures for the losses during ELMs remains unclear, but progress is nevertheless being made in integrated modelling of the ELM cycle using transport codes coupled to an ideal MHD code for the trigger, combined with a prescribed model for the enhanced losses due to the ELM. Such a model was described by N. Hayashi, who integrates these ingredients with a model for the SOL. He finds that the experimentally observed collisionality dependence of the ELM size could be interpreted either through the influence of the bootstrap current and its effect on the magnetic shear, or through the SOL transport processes (which influence the edge gradients).

The effective β-limit is often determined by the NTM. Of relevance for ITER, R. Buttery showed experimental data demonstrating that the threshold for onset of NTMs depends on the plasma rotation induced by neutral beams on DIII-D, with a lower threshold at lower rotation. This highlights the need for a quantitative predictive model for NTM onset. There are two pieces of uncertain physics here: how NTMs are seeded (e.g. by other MHD instabilities) and what is the threshold physics? The seeding remains poorly understood, but there is increasing understanding of the threshold physics. Papers by M. James and F. Waelbroeck addressed the fundamental physics of the polarization current: one of the mechanisms thought to play a role in the threshold physics. The interaction between islands and turbulence is emerging as an important area of research. In particular, Waelbroeck demonstrated that turbulence can affect the rotation frequency of tearing modes which, in turn, would affect the polarization current.

In advanced scenarios, the resistive wall mode is an important instability to control. T. Hender highlighted the importance that rotation has to play in damping resistive wall modes. This is observed experimentally and predicted theoretically, but the theory is not yet in quantitative agreement with experiment. A new piece of physics was presented by F. Waelbroeck on behalf of R. Fitzpatrick. He showed that MHD instabilities can induce a current density in the SOL. Furthermore, such a current can influence resistive wall modes and may be an important ingredient of a complete model.

A new theory for error field penetration that includes the effect of neoclassical toroidal viscosity was presented by C. Hegna. This theory predicts that the critical error field for penetration increases with density, which is in qualitative agreement with experiment. Nonresonant error field components play an important role, tending to maintain a plasma rotation through a toroidal neoclassical viscous torque, and making the plasma less susceptible to error field penetration.

Much of the above work has focused on the tokamak. As discussed in section 3, W.A. Cooper presented a study of the impact of an anisotropic energetic particle species on the MHD stability of stellarator plasmas. One important result is that a stellarator plasma with off-axis energetic particle deposition is more unstable to both global and local modes than one with on-axis deposition.

5. Summary

This meeting demonstrated that great progress is being made in our theoretical understanding of plasma instabilities in fusion devices. Nevertheless, there remain a number of key questions relating to confinement, stability and exhaust that do not yet have complete answers. These are issues of vital importance to the success of ITER, and it is therefore important that progress continues to be made in all areas of plasma instabilities to take full advantage of ITER when it begins operation.