SUMMARY OF ALPHA PARTICLE TRANSPORT

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ABSTRACT. This paper summarizes the contents of the 5th IAEA Technical Committee Meeting on Alpha Particles in Fusion Research regarding alpha particle transport, and the confinement of alpha particles.

1. INTRODUCTION

Experiments and theory on alpha particle transport were important parts of the 5th IAEA Technical Committee Meeting on Alpha Particles in Fusion Research. The main question to be answered is this: are the 3.5 MeV alpha particles created by D–T fusion reactions confined long enough to transfer their energy to the main plasma? If the answer is 'no', the requirements for ignition are increased and special provisions need to be made to handle the alpha energy loss to the first wall. Besides this practical significance, the study of alpha particle transport has some intrinsic interest as a relatively simple test bed for the physics of fast ion transport. Indeed, several papers at the meeting presented successful comparisons between experiment and theory in this area.

The behaviour of fast ions in tokamaks has been reviewed fairly recently [1]. The general conclusion both from this meeting and from previous work is that fast ions and alpha particles are confined 'classically' unless there is large 'MHD activity' in the plasma. Here 'classical' confinement refers to the combined influence of the externally imposed magnetic fields and classical Coulomb collisions on fast particle transport, including the effects of the toroidal field ripple. The main exceptions to this good confinement occur during 'MHD activity', which refers to any large scale global magnetic perturbation generated by either the background plasma or the fast ion population itself, e.g. tearing modes or toroidal Alfvén eigenmodes (TAEs).

There were several invited papers which covered the most recent experimental results and modelling of fast ion transport in large tokamaks and ITER. A description of alpha transport in the TFTR D–T experiments was given by Medley of the Princeton Plasma Physics Laboratory (PPPL). Classical alpha particle confinement was found during MHD quiescent discharges, based on measurements of the alpha energy spectrum and radial profiles using the pellet charge exchange (PCX) diagnostic. The results of fast ion transport in JT-60U were presented in the invited paper by Kimura and the contributed paper by Tobita of the Japan Atomic Energy Research Institute (JAERI). Of special interest in JT-60U were the observations of increased TF ripple loss in the reversed magnetic shear regime, and the preliminary results showing good confinement of 350 keV negative ion neutral beams (N-NBI).

Among the most exciting talks were those by Jacquinot and Kerner of the JET Joint Undertaking, which described the first results from their recent D–T experiments. Although measurements of alpha transport in JET are not yet available, these papers described the D–T plasma behaviour and the extensive alpha diagnostic preparations for the D–T campaign. The physics of alpha particles in ITER was summarized by Putvinski of ITER. The crucial issues were the alpha transport due to TF ripple loss in the reversed shear regime and the potential effects of low frequency MHD and Alfvén modes on alpha transport. Criteria for acceptable levels of fast alpha particle loss were defined, e.g. a maximum of 5% fast alpha power loss to the wall during steady state operation.

The short summaries below are organized according to the various potential alpha particle transport mechanisms, with special emphasis given to the contributed papers. The appropriate references can be found in the invited papers, which are published in this issue.

2. TF RIPPLE INDUCED TRANSPORT

A classical problem in tokamak physics is to determine the effect on fast ion confinement of the TF ripple due to the finite number of TF coils. There are two standard regimes of interest: the ripple trapping regime, in which ions are mirror trapped between adjacent TF coils; and the stochastic diffusion regime, in which normal trapped ion orbits become randomized owing to uncompensated vertical drifts near their banana tips. There were several new developments in both experiment and theory in this area.

(a) White of PPPL described calculations for the threshold of stochastic transport of high energy trapped ions due to TF ripple. The calculation was done by explicit construction of primary resonances and a numerical examination of the route to chaos, and the critical field ripple amplitude for loss was determined [2]. The expression is given in magnetic co-ordinates and makes no assumptions regarding shape or up–down symmetry. An algorithm was developed which included the effects of prompt axisymmetric orbit loss, ripple trapping, convective banana flow and stochastic ripple loss, and gives accurate ripple loss predictions for representative TFTR and ITER equilibria. The algorithm was extended to include the effects of collisions and drag, allowing rapid estimation of alpha particle loss in tokamaks. Results for ITER indicated that losses of fusion alpha particles are unacceptably large (5–10%) in reversed shear scenarios with the plasma near the outboard wall. This situation can be corrected with the introduction of ferromagnetic shims to reduce field ripple.

(b) Experimental results and modelling of fast particle ripple loss in reversed shear operation of JT-60U and ITER were presented by Tobita of JAERI. The confinement of 350 keV negative ions from the new N-NBI injector is as good in reversed shear as in normal shear, since most of the ions are injected into passing orbits. Confinement of ICRF tail ions (<300 keV) is as good in reversed shear as in normal shear, except in the plasma core. Triton burnup in reversed shear is about half to a third that in normal shear discharges, indicating a significant loss of higher energy ions, which is expected from the theory of fast ion ripple loss at high q. Calculations done for the ITER reversed shear scenario show that alpha confinement can be significantly degraded by ripple loss at high $q(0)$.

(c) Experimental results and modelling of 100 keV tritium beam injection into reversed shear deuterium discharges in TFTR were presented by Ruskov of PPPL. The D–T neutron rate during the ∼70 ms long T beam 'blips' was ∼30–50% below that expected from modelling by TRANSP, which included only the first orbit loss and collisional slowing down. This discrepancy was somewhat larger for beams injected in the counter-direction than in the co-direction, and larger for reversed shear compared to normal magnetic shear. Calculations of the collisional ripple loss of these beam ions using the Monte Carlo ORBIT code have not yet been able to account for the full magnitude of this discrepancy.

(d) An attempt to measure directly the effect of $q(r)$ on alpha particle ripple loss was described by Zweben of PPPL. Measurements were made of the alpha particle flux to a movable scintillator detector located just below the outer limiter, where the stochastic ripple loss was expected. The alpha loss per D–T neutron varied by a factor of ∼4 with differing $q(r)$ profiles at a fixed detector position, but also decreased by a factor of ∼10 when the detector was moved outward by a few centimetres near the shadow of the outer limiter. Calculations of global ripple loss did not scale with these local measurements, and it was concluded that the limiter shadowing effects dominated the interpretation of these alpha loss signals.

(e) Measurements of the confined trapped alpha behaviour obtained during the course of D–T experiments on TFTR using the PCX diagnostic were reported by Medley of PPPL. In the core of MHD quiescent D–T supershot discharges, measurements of the spectra up to the birth energy and the centrally peaked radial distribution for both alpha particles and tritons are consistent with these fusion products being well confined and slowing down classically. These results set an upper limit on possible anomalous radial diffusion for trapped alphas of $D_\alpha < 0.01\,\mathrm{m^2/s}$. In sawtooth-free discharge scenarios with reversed shear operation, the radial profile shapes are energy dependent and exhibit a particle depletion in the core and profile broadening with increasing alpha energy. ORBIT code modelling indicates that this behaviour is caused by stochastic ripple loss effects resulting from the elevated central q factor in such discharges.

(f) Basiuk of Tore Supra described measurements and modelling of the ripple loss of ICRH minority tail ions on Tore Supra. The energy spectrum and flux of the escaping fast ions were diagnosed using charge collection and thermal detectors in a vertical port. A change in the major radial distribution of the ripple loss was observed during the operation of the ergodic magnetic divertor, and attributed to a large (∼10 keV/m) radial electric field created in the plasma edge. Also, a significant change in the TF ripple loss was observed with a change in the wave–particle resonance location obtained by changing the applied ICRF.

(g) Yavorskij of the Institute for Nuclear Research at Kiev presented Fokker–Planck modelling which explains the previously observed 'delayed' loss of D–D charged fusion products in TFTR. The key element was a calculation of the collisional ripple diffusion of 1 MeV tritons, along with a careful treatment of the vacuum magnetic field between the plasma and the detectors. The calculated collisional ripple loss was consistent with several features of the data from the detector at the bottom of TFTR, e.g. the pitch angle and energy of the delayed loss, and its increase with plasma current and plasmas of smaller major radius.

(h) Heikkinen of VTT (Finland) described the effect of a radial electric field on ripple trapped particles using Monte Carlo simulations and solutions of the drift kinetic equations. The electric field was found to modify the location of the maximum heat load on the first wall, and to change the neutral particle fluxes from the slowing down ions blocked in local magnetic ripples. In a reactor the size of ITER, a radial electric field of 20–50 kV/m, as observed in current H mode experiments, would significantly affect alpha particles with energies less than 500 keV. Ripple trapped alpha particle fluxes peak near 3 and 0.5 MeV with a large electric field effect only on the low energy component.

(i) Modelling of the expected alpha ripple loss in ITER was summarized by Putvinski of the ITER JCT. The calculations were done by orbit following Monte Carlo codes at the I.V. Kurchatov Institute, JAERI and PPPL. Alpha particle loss in the standard 21 MA reference configuration was small (1–2%), but for operation in the steady state, reversed shear configuration it was too large to satisfy the desired wall heat loads (>5%). Surprisingly, the N-NBI ripple loss fraction was larger than the alpha ripple loss in both configurations owing to the relatively shallow beam penetration. It was shown that these losses can be much reduced by the installation of ferromagnetic inserts between the TF coils to reduce the ripple strength.

In summary, the experimental work at this meeting confirmed the potential importance of TF ripple induced fast ion transport in tokamak experiments, and provided the first evidence for the theoretically predicted increase in fast ion loss at high-$q(0)$ reversed field discharges. Although the theory of ripple induced fast ion transport is fairly well understood, new developments were reported on both the basic physics and the modelling of experiments. The implications of this transport mechanism for the high-$q(0)$ steady state scenario of ITER have led to a redesign of the device to reduce the level of ripple using ferromagnetic inserts.

3. ALFVÉN WAVE INDUCED TRANSPORT

The possibility of increased alpha transport and loss due to alpha driven Alfvén waves has generated a large amount of experimental and theoretical work during the past few years. The two conditions necessary for Alfvén wave excitation are that the fast ion speed be near the Alfvén speed and that the instability drive due to the fast particle pressure gradient be larger than the various wave damping mechanisms, e.g. thermal ion Landau damping and coupling to kinetic Alfvén waves. There is a wide variety of possible Alfvén mode structures depending on the magnetic configuration, and several fast ion species have been experimentally shown to generate Alfvén waves in tokamak plasmas.

The summary below concerns only the fast ion transport issues associated with these Alfvén waves, whereas the instability physics itself is summarized by Romanelli in a separate summary paper in this issue.

(a) Kerner of JET gave an overview of the JET team's results on linear and non-linear Alfvén instabilities driven by resonant interaction with energetic particles. The Alfvén mode excitation capabilities on JET using saddle coils give an excellent opportunity to compare experiment and theory. The theoretical analysis was performed with a hybrid MHD–gyrokinetic code using techniques which are rapidly becoming more refined for this type of simulation. The wave saturation amplitude is found to be proportional to the square of the growth rate, with typical values of $\delta B/B < 10^{-4}$ on JET, which is too low to induce stochastic loss of alpha particles. Both global toroidicity modes, which extend across the plasma and experience continuum damping, and core localized modes with very small damping are found. In all large tokamaks (ASDEX-U, DIII-D, JET, JT-60U and TFTR), Alfvén modes have been driven unstable by energetic particles produced by NBI and RF heating. These experiments give an important test of both MHD and kinetic theory, and are essential for the design of successful reactors.

(b) Heeter of JET and PPPL reported on the search for large amplitude Alfvén eigenmodes driven by ICRH beat waves and RF tail ions in JET. The motivation was the possible alpha particle loss induced by such modes, which could have deleterious effects on ignition and wall loading. An additional motivation is the possible deliberate use of a combination of TAEs and ion Bernstein wave (IBW) modes to move alpha particles to low energy and to the plasma edge. Modes were driven with saddle coils tuned so that the frequencies are near the TAE frequency, with about 3 kW of power with a peak amplitude of $\delta B/B \sim 10^{-5}$. A large spectrum of modes was observed, both TAEs and elongation induced Alfvén eigenmodes (EAEs), with a 1 kHz splitting which is not yet understood. This method promises to provide an excellent test of theoretical analyses of Alfvén and kinetic modes.

(c) Borba of JET described the Alfvén eigenmode stability and fast particle transport in JET, based on a hybrid MHD–gyrokinetic model. It was found that finite orbit effects of very energetic alpha particles reduce the instability drive of the dominant $n = 4$–10 kinetic TAEs (KTAEs) in JET. Non-linear simulations showed that the Alfvén waves saturate at $\delta B/B < 10^{-4}$, which is expected to be too small to cause significant alpha particle redistribution. The analysis of the time evolution of the drive and damping indicates that the most unstable condition is after the NBI is switched off and the beam damping disappears, similarly to TFTR. As of the time of this meeting, no alpha driven AEs have been identified in JET D–T discharges.

(d) Observations of purely alpha particle driven TAEs with toroidal mode numbers $n = 1$–6 in D–T plasmas on TFTR were described by Nazikian. The appearance of mode activity following termination of D–T NBI in plasmas with $q(0) > 1$ is generally consistent with theoretical predictions of TAE stability. Internal reflectometer measurements of TAE activity were compared with theoretical calculations of the radial mode structure. Core localization of the modes to the region of reduced magnetic shear was confirmed; however, the mode structure can deviate significantly from theoretical estimates. The peak measured TAE amplitude of $\delta n/n \sim 10^{-4}$ at $r/a \sim 0.3$–0.4 corresponds to $\delta B/B \sim 10^{-5}$, while $\delta B/B \sim 10^{-8}$ is measured at the plasma edge, confirming the core localization of the mode activity. Enhanced alpha particle loss associated with TAE activity has not been observed.

(e) TFTR alpha profiles in the presence of these alpha driven TAEs were centrally hollowed and radially broadened, as observed by the PCX diagnostic and reported by Petrov of the A.F. Ioffe Physical–Technical Institute. Analysis shows that the energy ($E > 2$ MeV) and radial position ($r/a = 0.1$–0.4) of detected trapped alpha particles are consistent with the observed TAEs. A preliminary model to describe these observations based on synergistic effects involving stochastic ripple, orbit perturbation due to the α–TAE resonance and pitch angle scattering was presented.

(f) The invited paper by Kimura of JAERI described an extensive set of experiments on JT-60U in which TAEs were generated by ICRH hydrogen minority tail ions and N-NBI ions. A significant decrease in the >3 MeV hydrogen tail population during high-n multiple mode TAE activity was observed in low-q discharges by monitoring the neutron emission from the $^{11}\mathrm{B(p,n)}^{11}\mathrm{C}$ reaction. This decrease occurred only in low-q discharges in which the TAE activity had higher n numbers, and was located inside the $q = 1$ surface.

(g) Heidbrink of the University of California at Irvine, described some new analyses of a 'classic' TAE shot in DIII-D in which the TAEs were generated by NBI ions at reduced TF and relatively high plasma beta. The modes come in bursts in which each burst expels ~7% of the beam ions, as measured by the D–D neutron rate. Calculations of beam ion orbits with various assumed TAE structures were made with the PPPL ORBIT code. The calculated beam ion loss fraction varied strongly with the assumed magnetic fluctuation level of the mode, and seemed to fit the PENN mode structure better than that derived from the NOVA code.

(h) Weller of the Max-Planck-Institut für Plasmaphysik, Garching, described the effects of global AEs (GAEs) on the injected fast ions in the Wendelstein 7-AS stellarator. The GAEs appear in regimes of flat q profiles, but a transition to TAEs was observed with the addition of ohmic current, as expected from theory. In some cases a correlation between high frequency bursting GAEs and reductions in the D–D neutron rate have been observed. However, it is not yet clear if this is due to fast ion loss due to GAEs, or to decreased heating efficiency induced by charge exchange losses.

(i) Breizman of the Institute for Fusion Studies (University of Texas at Austin) described the theory of non-linear evolution of a single mode driven by resonant particles in cases with strong damping, so that the mode growth rate can be much smaller than the kinetic instability drive. With no background damping the mode grows to a saturated value determined by the particle wave trapping frequency, leading to a wave saturation amplitude proportional to the square of the growth rate. Weak background damping produces a subsequent decay to small amplitude. However, the evolution very near threshold (large damping) produces strongly oscillatory behaviour rather than simple saturation. The subsequent evolution is given by an evolving frequency spectrum corresponding to the propagation of phase space holes and clumps in the distribution function. This can be viewed as a Bernstein–Greene–Kruskal (BGK) mode with a large non-linear frequency shift. An analytic treatment of this evolution shows that the frequency shift is proportional to the square root of the time, and that the mode lasts much longer than the inverse damping rate, since the changing frequency extracts energy from different parts of the particle distribution. Comparisons were made with experiments on PDX and JET.

(j) Appel of JET reported on a self-consistent study of the effect of several MHD modes on energetic particle distributions. The study concentrated on the destabilization of AEs in JET during NBI with deuterons, using the numerical code HAGIS for energetic particle motion and CASTOR for the linearized MHD mode structures. For few modes and small amplitudes the distributions are flattened locally at resonant islands, and above a critical amplitude there can be stochastic transport with rapid radial diffusion.

(k) Zonca of the Centro Ricerche Frascati presented an analytic analysis of high and low frequency Alfvén modes excited by energetic particles. There is a wide range of possible frequencies, from the toroidal gap in the shear Alfvén spectrum at $\omega_A/2$ down to the low frequency ion diamagnetic gap in the range of the ion diamagnetic frequency. At high frequencies the spectrum is dominated by the TAE and the KTAE. The lowest frequencies are characterized by the beta induced AE (BAE), which is strongly related to the kinetic ballooning modes (KBMs). At intermediate frequencies, energetic particle modes (EPMs) smoothly connect the higher frequencies of the toroidal branch to the lower diamagnetic frequencies. The plasma dynamics and the energetic particle dynamics are strongly dependent on which of these modes are unstable, which is determined by the equilibrium profiles.

In summary, it is clear from the experimental data that large amplitude, low-n Alfvén modes can cause significant fast ion loss in current devices, but it is not yet clear how to extrapolate these results to alpha particles in reactor relevant regimes. This is due to the difficulty of calculating the linear stability of these modes, and particularly to the non-linear problem of the saturation of the mode amplitude due to alpha particle transport. A reliable solution to this problem for future machines such as ITER is not yet available, although many interesting discoveries are being made.

4. MHD INDUCED TRANSPORT

Low frequency plasma driven MHD modes are common in tokamaks and other fusion devices, and these modes can cause non-classical alpha particle transport and loss. There are many experimental examples of this phenomenon but relatively few quantitative studies, owing to the complexity and irreproducibility of these MHD phenomena. The clearest results are from experiments and modelling of the ‘sawtooth’ instability in tokamaks, in which a magnetic reconnection occurs near the centre when $q(0) < 1$.

(a) Medley of TFTR showed that significant redistribution of the alpha radial profile was observed in the presence of strong sawtooth activity, wherein alpha particles are depleted in the core and redistributed to well beyond the $q = 1$ radius. Modelling of the sawtooth redistribution of trapped alpha particles was developed in which the helical electric field produced during the sawtooth crash plays an essential role. Redistribution of trapped alpha particles was also observed in the presence of core localized TAE activity with elevated central safety factor, $q(0) \sim 2$. Stochastic ripple loss effects were studied, and the results agreed with the energy and q scaling of the Goldston–White–Boozer theory.

(b) Kolesnichenko of the Institute for Nuclear Research (Kiev) described in great detail a theoretical model of how the sawtooth mode can redistribute fast ions through resonant effects, which is particularly important for particles with large orbit width. He discovered that particles with energy large enough to precess significantly during the sawtooth crash time are not significantly affected, since the precession averages out the effect of the modes. Resonances thus play the dominant role in the transport of ions of large energy. These resonances can overlap, leading to a redistribution of these particles within the sawtooth mixing region.

(c) The first observation of TAEs in the heliotron/torsatron type device CHS was described by Isobe of the National Institute for Fusion Science, Nagoya, Japan. In NBI heated plasmas in

CHS, the magnetic fluctuations contain two types of coherent component: one in the low frequency region ($f < 30$ kHz), which is thought to be a resistive/ideal interchange mode, and the other at higher frequency ($50 < f < 200$ kHz), which is identified as a hydrogen beam ion driven, core localized TAE with a toroidal mode number $n = 2$, as determined from a magnetic probe array. At low NBI power ($P_{\rm NBI} < 0.6$ MW), the frequency band of the TAE is fairly narrow, i.e. $f/\Delta f \sim 100$, where Δf is the FWHM of the spectrum. When the NBI power is increased to 0.8 MW, $f/\Delta f$ decreases to about 5. In this case, the amplitude is modulated in a manner similar to fishbone bursting, and frequency chirping occurs during each burst of the TAE.

(d) Modes in the frequency range 50–130 kHz having a TAE-like spectrum were observed in START discharges over a range of conditions at moderate NBI power, as described by McClements of UKAEA (Culham). At relatively high NBI power ($P_{\rm NBI} \sim 0.5$ MW), a 'chirping' mode is often seen preceding the onset of sawteeth, which appears as high frequency ($f \sim 100$ kHz) bursts on the Mirnov coils and soft X ray signals, and 'whistles' down in frequency by a factor of 2 during a single 0.1–0.3 ms burst. Measurements of the spatial distribution and spectrum of this whistling mode suggest that its location is linked to the beam position rather than the flux surfaces, which led to tentatively identifying this as an energetic particle mode driven by fast beam particles.

In summary, fast ion transport and loss due to large scale MHD activity have been observed in a variety of tokamaks and stellarators, and such transport is expected theoretically owing to the breaking of symmetry and/or the reconnection of magnetic field lines. The experimental results are quite variable, depending on the MHD amplitude and mode structure, but substantial progress has been made in understanding the underlying physics of this MHD fast ion interaction.

5. RF WAVE INDUCED TRANSPORT

The effect of externally imposed RF waves on alpha transport has been of recent interest, owing to experimental observations of increased fast ion loss during RF heating, and particularly to the theoretical potential for favourably affecting a fusion reactor using RF induced 'alpha channelling'. The most important interaction in this area is usually with waves which resonate with the cyclotron frequency of the alpha particles.

(a) Measurement of impurity induced neutralization of megaelectronvolt energy, ICRF driven ^{3}He ions in JET plasmas was described by Korotkov of the A.F. Ioffe Physical–Technical Institute. Analogously, neutralization of alpha particles in D–T is predicted owing to double charge exchange reactions with two-electron species of the main intrinsic plasma impurities He^0, C^{4+} and Be^{2+}. A density of these donor ions sufficient to permit neutral particle analyser (NPA) measurements of alpha particles with an integration time of $t > 0.5$ s during the JET tritium experiments was predicted.

(b) Darrow of PPPL described measurements and modelling of the loss of fast ions during mode converted IBW heating in TFTR. The strongest effect was a loss of counter-injected 100 keV deuterium neutral beam ions in D–^{3}He discharges associated with their acceleration to above 1 MeV. This loss peaks when the mode conversion layer is on-axis, and the ions are lost at the pitch angle of the passing–trapped boundary. A diffusion model describing the change in r/a and μ of the ion passing through the IBW resonant layer can reproduce the beam ion loss energy and time history. Modelling of the observed loss implies that the collisionless diffusion limit would be reached for RF power around 10 MW in TFTR, as described in a related contribution from Heeter.

(c) Kimura of JAERI described experiments of proton minority heating in JT-60U in negative central shear discharges. Energetic neutral particle fluxes were measured with a charge exchange neutral analyser, and the expected confinement was evaluated with the OFMC code. The tail ion stored energy was comparable in the negative and positive shear discharges at the same RF power, but the tail temperature was 60–80% that in the positive shear discharge (200 versus 300 keV). The fast ion pressure profile is broader in the negative shear case owing to larger banana widths and enhanced banana drift diffusion in the core, but the total loss fraction of the absorbed RF power was similar in both cases (∼50–70%).

(d) C.S. Chang of New York University described how the ion cyclotron resonance with fast waves can induce radial transport of energetic ions. Such radial transport can be non-ambipolar, and hence can generate a strong radial electric field. Theoretical study, with some experimental evidence from TFTR, DIII-D and ALCATOR C-Mod, shows that toroidal rotation generated by ICRH resonance with minority ions can be of the same order as ion thermal speed in the plasma core. Enhancement of plasma confinement and/or stabilization of the MHD mode by this mechanism may be possible in a toroidal fusion reactor device.

In summary, the transport effects of ICRH waves on fast ions in tokamaks have been measured, but normally do not strongly affect the heating efficiency of the fast ions. Preliminary experiments to explore the alpha channelling in TFTR demonstrated a strong wave–particle interaction with D beam ions, but have not yet showed a direct effect on alpha particle thermalization or transport. However, there is a great potential for using controlled RF–alpha particle interactions to modify the fast ion and thermal transport in tokamaks, and more experiments are needed.

6. TURBULENCE INDUCED TRANSPORT

(a) Dendy of UKAEA Culham reported analytical and numerical studies of the transport of energetic alpha particles by strong electrostatic drift turbulence, modelled by the Hasegawa–Mima equation. The non-linear coupling significantly reduces the level of transport compared to the linear regime. In addition, large Larmor radius effects also reduce the diffusion rate of energetic alpha particles compared to thermal ions, owing to spatial averaging of the fluctuations. The scaling of the diffusion coefficient with Larmor radius derived from closure theory is broadly consistent with the simulations. Since the response of large orbit alpha particles to the turbulence is quite different from background thermal ions, the observation of alpha particle transport can shed additional light on the fluctuations.

(b) Thyagaraja of UKAEA Culham reported simulations of the saturation of alpha particle driven Alfvén modes in JET and ITER conditions using a large eddy simulation code called CUTIE. The code involves a strong coupling of the shear Alfvén and drift branches. Simulations suggest the possibility of saturation by non-linear mode–mode coupling at very low levels of turbulence, $\delta B/B \sim 10^{-5}$. Whether this strong coupling is correct must be the subject of future work. The coupling is the result of a fluid model relevant to turbulence over a very large range of scales.

7. CONCLUSIONS

There is usually good agreement between experiment and theory in the area of fast ion transport in MHD quiescent beam heated tokamaks, as shown by experiments on TFTR, JT-60U, JET and Tore Supra. The major issue in these MHD-free discharges is the predicted increase of TF ripple induced loss in high $q(0)$ and reversed magnetic shear regimes, which was calculated to be a potentially serious alpha particle loss mechanism for ITER. Experiments on JT-60U and TFTR at least qualitatively confirmed this effect, and an engineering solution was proposed for ITER to reduce the TF ripple.

There were less data and a less complete understanding of the effects of MHD activity on the confinement of fast ions in tokamaks and other magnetic fusion devices. This can be attributed to the complexity and irreproducibility of the MHD activity, and to the difficulty of making time resolved measurements of the confined fast ion distributions. However, it was shown on TFTR that the sawtooth instability can internally redistribute alpha particles, and the effects of Alfvén wave instabilities on fast ion confinement are being actively studied on several devices. Significant progress in modelling the effects of sawteeth and Alfvén waves on alpha particle transport was reported by various groups.

The influence of applied RF waves and intrinsic plasma turbulence on fast ion transport is the least explored of the major interaction mechanisms. Although these effects seem to be relatively small in present devices, there are strong incentives to continue their study. For example, an RF technique which could transfer the alpha particle energy to fuel ions could increase the fusion reactivity of a plasma at a given beta, and a quantitative understanding of the reduced turbulent transport for high energy particles could potentially lead to techniques for improving thermal confinement.

The largest area of uncertainty and the most crucial area for D–T plasmas concerns the possible effects of alpha driven Alfvén modes on alpha particle confinement. This may be a generic issue, since the Alfvén speed and alpha particle speed are fairly independent of the device geometry. A focus of concern at this meeting was the high-n TAE stability of ITER, and the effect that such modes could have on alpha particle heating and loss to the first wall. Although there is a good understanding of the current experimental results based on the linear stability theory, far less is understood about the non-linear mode saturation and fast ion transport. These latter areas need to be understood before any reliable predictive modelling of alpha particle transport in ITER can be done. Even then, the larger size scale of ITER or other reactor grade plasmas will most likely result in high-n TAEs ($n \sim 20$–40) which are not easily accessible to simulations using current experiments.

This meeting showed that great progress has been made in measuring alpha particles and other fast ions, and in understanding the physics of their confinement. However, further diagnostic developments are needed to complete the study of alpha particle transport in devices such as JT-60U and JET, and new innovations are needed to make alpha particle measurements in reactor grade plasma devices such as ITER. The rapid development of theory and modelling, along with further experiments in D–D devices, should greatly clarify the issues which need to be addressed in the next step burning plasma device.

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