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Summary of Alpha Particle Transport

IAEA TCM on Alpha Particles in Fusion Research

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Abstract

This paper summarizes the talks on alpha particle transport which were presented at the 5th IAEA TCM on Alpha Particles in Fusion Research, held at JET in Sept. 1997

1. Introduction:

Experiments and theory on alpha particle transport were important parts of the 5th IAEA TCM on Alpha Particles in Fusion Research. The main question to be answered is this: are the 3.5 MeV alpha particles created by DT 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 this meeting presented successful comparisons between experiment and theory in this area.

The behavior 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 Alfven eigenmodes (TAEs).

There were several invited papers which covered the most recent experimental results and modeling of fast ion transport in large tokamaks and ITER. A description of alpha transport in the TFTR DT experiments was given by **Medley** of PPPL. Classical alpha particle confinement was found during MHD-quiescent discharges, based on measurements of the alpha energy spectrum and radial profiles by the Pellet Charge Exchange

(PCX) diagnostic. The results of fast ion transport in JT-60U were presented by in the invited paper by **Kimura** and the contributed paper by **Tobita** of 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 JET which described the first results from their recent DT experiments. Although measurements of alpha transport in JET are not yet available, these papers described the DT plasma behavior and the extensive alpha diagnostic preparations for the DT 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 Alfven 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 to the contributed papers. The appropriate references can be found in the invited papers, which are published in this issue of Nuclear Fusion.

2. TF ripple-induced transport:

A classical problem in tokamak physics is to determine the effect on fast ion confinement of the toroidal field (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 due to uncompensated vertical drifts near their banana tips. These 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 toroidal field 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 coordinates 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 to 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 modeling 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 onto 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 1/2 - 1/3 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 modeling of 100 keV tritium beam injection into reversed shear deuterium discharges in TFTR were presented by **Ruskov** of PPPL. The DT neutron rate during the ≈70 msec long T beam "blips" was ≈30-50% below that expected from modeling 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 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 directly measure 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 DT 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 centimeters 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 behavior obtained during the course of DT experiments on TFTR using the Pellet Charge Exchange 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 $D_\alpha \leq 0.01$ m^2s^{-1}. 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 modeling indicates that this behavior 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 modeling 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 frequency.

g) **Yavorskij** of the Institute for Nuclear Research at Kiev presented Fokker-Planck modeling which explains the previously-observed "delayed" loss of DD 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 smaller major radius plasmas.

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 with the size of ITER, a radial electric field of 20-50 kV/m, as observed in present H-mode experiments, would significantly affect alphas with energies less than 500 keV. Ripple trapped alpha particle fluxes peak near 3 MeV and 0.5 MeV with a large electric field effect only on the low energy component.

i) Modeling 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 Kurchatov, 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 due 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 increased 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 the both the basic physics and on the modeling of experiments. The implications of this transport mechanism for the high-q(0) steady state scenario of ITER has led to a redesign of the device to reduce the level of ripple using ferromagnetic inserts.

3. Alfven wave-induced transport:

The possibility of increased alpha transport and loss due to Alfven waves created by the alpha particles has generated a large amount of experimental and theoretical work during the past few years. The two conditions necessary for Alfven wave excitation are that the fast ion speed be near the Alfven 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 Alfven waves. There are a wide variety of possible Alfven mode structures depending on the magnetic configuration, and several fast ion species have been experimentally shown to generate Alfven waves in tokamak plasmas.

The summary below concerns only the fast ion transport issues associated with these Alfven 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 nonlinear Alfven instabilities driven by resonant interaction with energetic particles. The Alfven 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) Alfven modes have been driven unstable by energetic particles produced by neutral beam injection 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 search for large amplitude Alfven 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 TAE and IBW modes to move alpha particles to low energy and to the plasma edge. Modes are 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 $\delta B/B \approx 10^{-5}$. A large spectrum of modes is observed, both TAE and EAE modes, with a 1 kHz splitting which is not yet understood. This method promises to provide an excellent test of theoretical analysis of Alfven and kinetic modes.

c) **Borba** of JET described the Alfven 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 alphas reduce the instability drive of the dominant n=4-10 KTAE modes in JET. Non-linear simulations showed that the Alfven 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, similar to TFTR. As of the time of this meeting, no alpha-driven AE have been identified in JET DT discharges.

d) Observations of purely alpha-particle-driven TAEs with toroidal mode numbers n=1-6 in DT plasmas on the TFTR were described by **Nazikian**. The appearance of mode activity following termination of DT neutral beam injection 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~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 TAE modes were centrally hollowed and radially broadened, as observed by the Pellet Charge Exchange diagnostic and reported by **Petrov** of the A. F. Ioffe Institute. Analysis shows that the energy (E > 2 MeV) and radial position (r/a = 0.1 - 0.4) of detected trapped alphas are consistent with the observed TAE modes. 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 TAE modes were generated by ICRH hydrogen minority tail ions and N-NBI ions. A significant decrease in the $\geq$ 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 $^{11}B(p,n)^{11}C$ 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 UC Irvine described some new analysis of a "classic" TAE shot in DIII-D in which the TAE modes were generated by NBI ions at reduced toroidal field and relatively high plasma beta. The modes come in bursts in which each burst expels ≈7% of the beam ions, as measured by the DD neutron rate. Calculations of beam ion orbits with various assumed TAE mode 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 IPP Garching described the effects of global Alfven eigenmodes on the injected fast ions in the Wendelstein 7-AS stellarator. The GAE modes appear in regimes of flat q profiles, but a transition to TAE modes was observed with the addition of ohmic current, as expected from theory. In some cases a correlation between high frequency bursting GAE modes and reductions in the DD 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 IFS (Texas) described the theory of nonlinear 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 behavior 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 BGK mode with a large nonlinear 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. They concentrated on the destabilization of Alfven eigenmodes in JET during neutral beam injection of 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 Frascati presented an analytic analysis of high and low frequency Alfven modes excited by energetic particles. There is a wide range of possible frequencies, from the toroidal gap in the shear Alfven 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 Alfven eigenmode BAE, which is strongly related to the kinetic ballooning modes KBM. At intermediate frequencies energetic particle modes (EPM) smoothly connect the higher frequencies of the toroidal branch to the lower diamagnetic frequencies. The plasma dynamics and the energetic particle dynamics is 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 Alfven modes can cause significant fast ion loss in present 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 due 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 due to the complexity and irreproducibility of these MHD phenomena. The clearest results are from experiments and modeling of the "sawtooth" instability in tokamaks, in which a magnetic reconnection occurring near the center when $q(0)<1$.

a) **Medley** from TFTR showed that significant redistribution of the alpha radial profile was observed in the presence of strong sawtooth activity, wherein alphas are depleted in the core and redistributed to well beyond the $q = 1$ radius. Modeling of the sawtooth redistribution of trapped alphas was developed in which the helical electric field produced during the sawtooth crash plays an essential role. Redistribution of trapped alphas 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** from the Institute for Nuclear Research (Kiev) described in great detail a theoretical model for 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 the these particles within the sawtooth mixing region.

c) The first observation of TAE modes in the heliotron/torsatron type device CHS was described by **Isobe** of NIFS. In NBI heated plasmas in CHS, the magnetic fluctuations contain two types of coherent components: 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 mode with a toroidal mode number of $n = 2$, as determined from a magnetic probe array. At low NBI power ($P_{NBI} < 0.6$ MW), the frequency band of the TAE mode is fairly narrow: i.e. $f/\Delta f \sim 100$ where Δf is the FWHM of the spectrum. When the NBI power is increased up 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 mode.

d) Modes in the frequency range of 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 ($P_{NBI} \sim 0.5$ 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 two 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 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 has been observed in a variety of tokamaks and stellarators, and such transport is expected theoretically due 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 possible effect of externally imposed RF waves on alpha transport has been of recent interest due to experimental observations of increased fast ion loss during RF, and particularly due to the theoretical potential for favorably affecting a fusion reactor using RF-induced "alpha channeling". The most important interaction in this area is usually with waves which resonate with the cyclotron frequency of the alphas.

a) Measurement of impurity-induced neutralization of MeV energy, ICRF-driven helium-3 ions in JET plasmas was described by **Korotkov** of the A. F. Ioffe Institute. Analogously, neutralization of alpha particles in DT is predicted due to double charge exchange reactions with two-electron species of the main intrinsic plasma impurities He^{o}, C^{4+} and Be^{2+}. A density of these donor ions sufficient to enable NPA measurements of alphas with an integration time of $t > 0.5$ s during the JET tritium experiments was predicted.

b) **Darrow** of PPPL described measurements and modeling of the loss of fast ions during mode-converted ion Bernstein wave 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. Modeling 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 analyzer, 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 keV vs. 300 keV). The fast ion pressure profile is broader in the negative shear case due to larger banana widths and enhanced banana-drift diffusion in the core, but the total loss fraction of the absorbed RF power was the similar in both cases ($\approx$50-70%).

d) **C.S. Chang** from NYU described how the ion cyclotron resonance with fast waves can induce radial transport of energetic ions. Such radial transport can be non-ambipolar, hence can generate 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 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 channeling in TFTR demonstrated a strong wave-particle interaction with D beam ions, but did 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, modeled by the Hasegawa-Mima equation. The nonlinear 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, due 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 transport can shed additional light on the fluctuations.

b) **Thyagaraja** of UKAEA Culham reported simulations of the saturation of alpha particle driven Alfven modes in JET and ITER conditions using a large eddy simulation code CUTIE. The code involves a strong coupling of the shear Alfven and drift branches. Simulations suggest the possibility of saturation by nonlinear mode-mode coupling at very low levels of turbulence, $dB/B \approx 10^{-5}$. 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 normally 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 a engineering solution was proposed for ITER to reduce the TF ripple.

There was 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 Alfven wave instabilities on fast ion confinement are being actively studied on several devices. Significant progress in modeling the effects of sawteeth and Alfven waves on alpha transport was reported by various groups.

The influence of applied RF waves and intrinsic plasma turbulence on fast ion transport are 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 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 DT plasmas concerns the possible effects of alpha-driven Alfven modes on alpha particle confinement. This may be a generic issue, since the Alfven 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 these modes could have on alpha particle heating and loss to the first wall. Although there is a good understanding of the present 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 modeling of alpha 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 ($n \approx 20$-40) which are not easily accessible to simulations using present experiments.

This meeting showed that great progress has been made in measuring alphas and other fast ions, and in understanding the physics of their confinement. However, further diagnostic development 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 measurements in reactor-grade plasma devices such as ITER. The rapid development of theory and modeling, along with further experiments in DD devices, should greatly clarify the issues which need to be addresses in the next-step burning plasma device.

References

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