ENERGETIC PARTICLE TRANSPORT AND ALPHA-DRIVEN INSTABILITIES IN ADVANCED CONFINEMENT D-T PLASMAS ON TFTR

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ABSTRACT. This paper reviews the physics of fusion alpha particles and energetic neutral beam ions studied in the final phase of TFTR operation, with an emphasis on observations in Reversed magnetic Shear (RS) and Enhanced Reversed Shear (ERS) D-T plasmas. Energy-resolved measurements of the radial profiles of confined, trapped alphas in RS plasmas exhibit reduced core alpha density with increasing alpha energy, in contrast to plasmas with normal monotonic shear. The measured profiles are consistent with predictions of increased alpha loss due to stochastic ripple diffusion and increased first-orbit loss in RS plasmas. In experiments in which a short tritium beam pulse is injected into a deuterium RS plasma, the measured D-T neutron emission is lower than standard predictions assuming first orbit loss and stochastic ripple diffusion of the beam ions. A microwave reflectometer measured the spatial localization of low-toroidal mode number (n), alpha-driven Toroidal Alfvén Eigenmodes (TAEs) in D-T RS discharges. Although the observed ballooning character of the n=4 mode is consistent with predictions of a kinetic-MHD stability code, the observed anti-ballooning nature of the n=2 mode is not. Furthermore, the modeling does not show the observed strong dependence of mode frequency on n. These alpha-driven TAEs do not cause measurable alpha loss in TFTR. Other Alfvén frequency modes with n=2-4 seen in both D-T and D-D ERS and RS discharges are localized to the weak magnetic shear region near q_{min}. In 10-20% of D-T discharges, normal low-n MHD activity causes alpha loss at levels above the first orbit loss rate.

1. INTRODUCTION

Deuterium-tritium (D-T) operation of the Tokamak Fusion Test Reactor (TFTR) provided a valuable opportunity to study the physics of alpha particles produced by D-T fusion reactions and other energetic particles, such as neutral beam injected ions, in plasma conditions similar to those expected in a tokamak reactor. These experiments were made possible by a unique set of diagnostics for both confined and escaping energetic alphas. The experiments naturally divided into two phases, each addressing different concerns.

The initial experiments were performed in monotonic-shear discharges with values of the central safety factor, q(0), less than one and studied the basic slowing-down and confinement properties of the alphas. The primary conclusions of these experiments were: 1) alpha slowing-down was classical; 2) the alphas were well confined with an upper limit on the anomalous radial diffusivity (in addition to neoclassical transport) of 0.1 m^2/s or less; 3) sawteeth caused strong radial redistribution of confined alphas but little additional alpha loss from the plasma in most cases; 4) alpha heating of the electrons was observed at predicted levels; and 5) transport of alpha ash (thermal helium ions) was similar to that of other thermal ions and was sufficiently rapid that the alpha ash profiles were primarily determined by the alpha source profile and recycling. This work is the subject of several recent reviews [1-3], which contain references to the original papers.

During the time of these initial experiments, interest developed in reactor concepts based on ‘advanced confinement’ tokamak operating regimes, inspired by experiments on TFTR [4] and other tokamaks which demonstrated the superior confinement properties of the Enhanced Reversed Shear (ERS) operating regime. ERS plasmas are characterized by near-neoclassical ion thermal and particle transport in the core region of the plasma, which is believed to be the result of stabilization by sheared plasma flow of turbulence-driven transport. In TFTR ERS plasmas, transitions to enhanced confinement were seen shortly after the start of high power neutral beam injection into a Reversed Shear (RS) plasma. The non-monotonic q(r) profile with q(0)>1 of the RS target plasma was produced by low-power beam injection into the plasma current ramp-up period of the discharge [4]. It was expected that such q(r) profiles could lead to energetic alpha and beam-ion behavior different from that observed in discharges with monotonic q(r) profiles with q(0)<1. In particular, ripple-induced alpha losses could be enhanced in a reactor operating in the ERS regime, possibly leading to reduced alpha heating efficiency and damage to the first wall. Since understanding fast ion behavior in RS and ERS plasmas is important to development of these regimes for a reactor, later TFTR experiments on alpha particle and fast ion physics emphasized studies in these plasmas. This paper reviews these final experiments, including: 1) the effects of stochastic ripple diffusion on alpha confinement in RS plasmas; 2) beam ion confinement in RS discharges; 3) alpha-driven Toroidal Alfvén Eigenmodes (TAEs) in RS plasmas; and 4) MHD-induced alpha loss. Implications for a reactor and directions for future work are discussed in the concluding section.

2. EFFECTS OF STOCHASTIC RIPPLE DIFFUSION ON ALPHA CONFINEMENT

The same conditions that are associated with enhanced thermal and particle ion confinement in ERS plasmas, i. e., high core q and non-monotonic q(r) profiles, are predicted to produce higher levels of stochastic ripple loss of energetic alphas in RS and ERS plasmas than in discharges with monotonic q(r) profiles and q(0)<1. This observation motivated experiments on TFTR to study the effects of stochastic ripple diffusion on energetic alpha confinement.

ORBIT [5, 6], a fast, Hamiltonian-coordinate, guiding-center code, was used to perform D-T simulations of alpha particle loss in deuterium RS plasmas [7]. ORBIT follows an ensemble of alpha particles with an initial energy of 3.5 MeV for one slowing down time in a realistic magnetic geometry. The code includes the non-collisional processes of stochastic ripple diffusion and first orbit loss and the collisional processes of pitch angle scattering and slowing down. This Monte Carlo code makes use of a rapid algorithm for the domain free of stochastic ripple diffusion, allowing simulations with large numbers of alphas to be performed. The ORBIT simulations were compared with measurements in D-T plasmas of the radial profiles of the density of confined trapped alphas as a function of energy.

Figure 1 shows trapped alpha particle confinement domains predicted by ORBIT for RS and monotonic shear discharges at three alpha energies. The RS and monotonic shear (MS) discharges had similar values of the plasma current (I_p=1.6 MA in the RS case and 1.8 MA in the MS case) toroidal magnetic field (RS: B_T=4.6 T and MS: 4.8 T), and injected beam power (RS: P_b=25 MW and MS: 23 MW). The major radius, R, was 2.60 m in both cases, and the

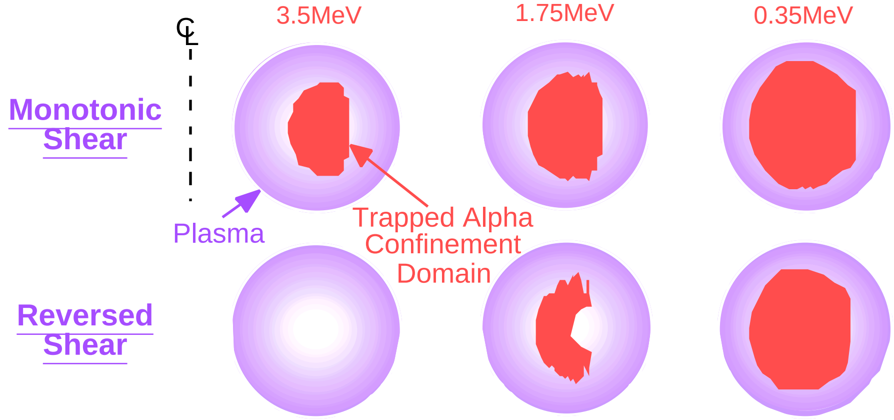

FIG. 1. ORBIT code calculations of trapped alpha particle confinement domains show no confinement of 3.5 MeV trapped alphas in reversed shear discharges.

minor radius, a, was 0.94 m in the RS plasma and 0.96 m in the monotonic shear discharge. In the RS plasma, q was greater than two over the entire radius. The entire plasma was above the threshold for stochastic ripple loss of trapped alphas at the 3.5 MeV birth energy, as shown in Fig. 1. This was not the case in the monotonic shear discharge, which had a significant alpha confinement domain at 3.5 MeV. At an intermediate alpha energy of 1.75 MeV, the confinement domain was smaller in the RS plasma than in the monotonic shear plasma, while the confinement domains at 0.35 MeV were of similar size in both types of discharge.

Approximately 33% of the 3.5 MeV alphas were born on trapped orbits. In the RS case, these alphas were calculated to be promptly lost due to being on unconfined orbits or as a result of stochastic ripple diffusion. Pitch angle scattering of passing alphas repopulated the trapped alpha distribution, resulting in continued loss as the alphas slowed down. These effects are seen in Fig 2, which shows the predicted alpha losses over one alpha slowing down time in the RS and monotonic shear cases. (The slowing down time was ~0.08 s in the

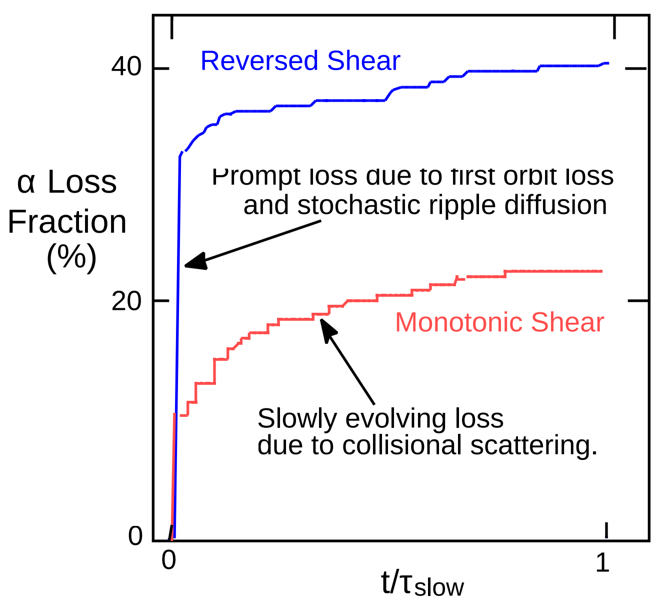

FIG. 2. ORBIT code calculations of alpha loss as a function of time normalized to the alpha slowing down time, τ_{slow}, in reversed shear and monotonic shear plasmas.

RS case.) The predicted cumulative alpha loss in the RS discharge was 40% by the end of one slowing down time, twice that of the monotonic shear plasma.

Radial profiles of the trapped alphas were measured in these RS and monotonic shear discharges by the Pellet Charge Exchange (PCX) diagnostic [8]. The PCX diagnostic measured the energy-resolved radial profile of the confined alphas by mass and energy analysis of alphas neutralized by double charge-exchange with He-like ions in the ablation cloud of an injected lithium or boron pellet. Deeply trapped alphas with pitch $v_{parallel}/v = -0.05$ were observed in a narrow vertical window about the plasma midplane. The measured alpha density profiles in RS and monotonic shear plasmas at alpha energies of 0.6 MeV and 1.35 MeV are shown in Fig. 3. Because the PCX diagnostic could not measure the absolute alpha density, the measurements are normalized to the predicted values at the indicated radial point in each case. The profiles in the RS plasma exhibit reduced alpha density in the core with increasing energy, while the profiles in the monotonic shear case have similar shapes. This observation is consistent with the expected ripple loss of high energy trapped alphas. The ORBIT code simulations shown in Fig. 3 reproduce the PCX diagnostic measurements well, confirming that the ORBIT model includes the essential physics and that stochastic ripple diffusion leads to significant alpha loss in RS plasmas.

Alpha loss from similar RS discharges at I_p=1.6 MA was measured by a scintillator detector located 90° below the plasma midplane [9]. The alpha loss per D-T neutron was approximately three times larger in RS discharges than in similar monotonic shear discharges. This is qualitatively consistent with the increased first-orbit loss at this location caused by higher values of q in the plasma core. As a result of the shadowing effect of the outer limiters in the large minor radius RS and ERS plasmas, the alpha loss could not be measured using the detector 20° below the midplane, which would be expected to see enhanced alpha loss due to stochastic ripple diffusion.

The calculated total alpha-particle loss in a TFTR RS discharge of ~40%, twice the level in a similar monotonic shear discharge, implies strong constraints on the acceptable level of ripple in a reactor operating in the RS regime. Ripple loss in ITER RS plasmas has been reduced to acceptable levels by the use of ferritic shims [10]. Global ripple losses should not significantly reduce the efficiency of alpha heating in a reactor, but concern remains that locally peaked alpha losses could cause damage to the wall.

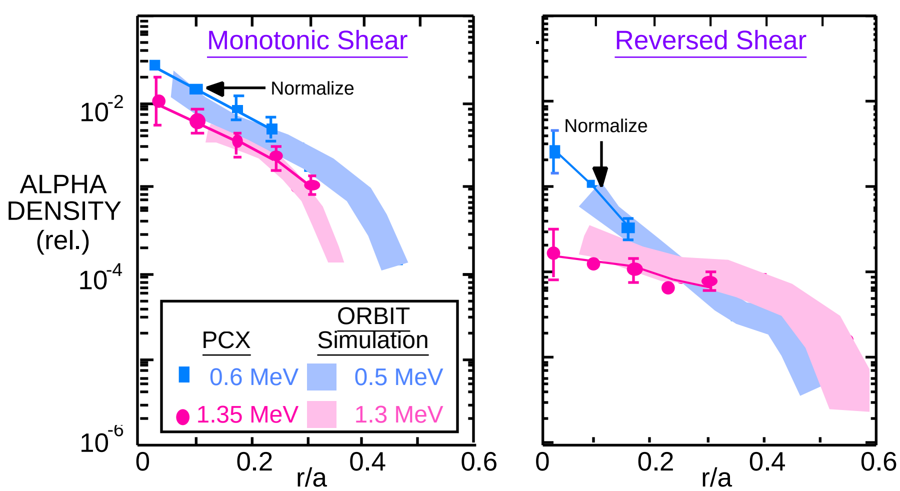

FIG. 3. PCX diagnostic measurements and ORBIT code calculations of trapped alpha densities in reversed shear and monotonic shear discharges show reduced alpha core alpha density with increasing alpha energy in the reversed shear case.

3. BEAM ION CONFINEMENT IN REVERSED SHEAR DISCHARGES

The conclusion that alpha particle loss is larger in RS plasmas than in those with monotonic shear motivates study of the confinement of other types of energetic ions in RS discharges. Experiments to study beam ion confinement in RS plasmas on TFTR were performed by injecting short tritium beam pulses into deuterium plasmas heated by deuterium beam injection. These 'beam-blip' experiments took advantage of the large difference in the cross sections for D-T and D-D fusion reactions which allowed the confinement of the deuterium and tritium beam ions to be individually deduced. The plasma stored energy depended only on the deuterium beam ion confinement because the tritium beam pulse did not significantly perturb the background plasma. The tritium beam pulse was short compared to the beam ion slowing down time so the peak value of the 14 MeV neutron emission, S_{DT}, during the beam blip depended only on tritium beam ion confinement, while the subsequent decay rate was indicative of tritium beam ion transport.

Experiments were performed in RS discharges with 9 MW of steady deuterium beam power and a pair of 5 MW tritium beam blips of 50 ms duration, as shown in Fig. 4. Both co- and counter-injected tritium beam blips had similar effects on S_{DT}; we focus here on a discharge with a counter-injected tritium beam blip. The RS background plasma was typical for TFTR RS and ERS experiments and had the following parameters: I_p=1.6 MA, B_T=4.3 T, R=2.60 m, and a=0.94 m. The Shafranov shift calculated by TRANSP was 0.14 m. The q-profiles were obtained from Motional Stark Effect diagnostic measurements and were characterized by q(0)~5, q_{min}~3, and q(a)~ 6. No significant MHD activity or locked modes were present.

Fig. 4 also shows the time evolution of the measured S_{DT} and a prediction from the TRANSP time-dependent transport code. The TRANSP simulation used measured ion temperature and Z_{eff} profiles as inputs and assumed both first-orbit loss and stochastic ripple diffusion. TRANSP utilizes a stochastic ripple diffusion model based on the Goldston-White-Boozer criterion [11] scaled by a multiplier obtained from comparisons with ORBIT code results [12]. As seen in Fig. 4, the TRANSP model over-estimates the measured peak S_{DT} during the beam blip by 25%, compared to the D-T neutron measurement error of ±8%. The calculated neutron emission falls within the error bars on the measurement well after the

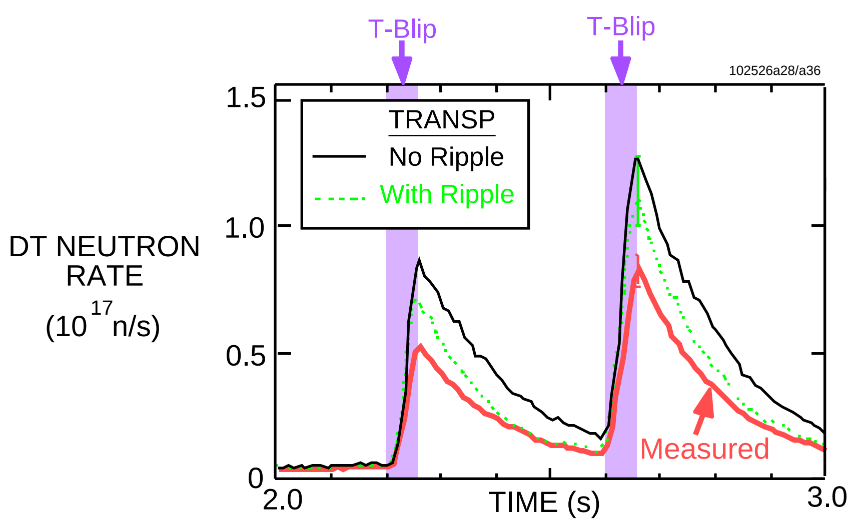

Fig. 4. Measured D-T neutron emission for a tritium beam blip injected into a deuterium reversed shear discharge. TRANSP code predictions with and without the effects of stochastic ripple diffusion are also shown. TRANSP overestimates the peak neutron emission by ~25%.

blip, probably as a result of pitch angle scattering conversion of passing beam ions to trapped ions, which are then lost. It is important to note that similar TRANSP modeling, including first orbit loss and stochastic ripple diffusion, generally showed satisfactory agreement with the measured neutron emission and stored energy in monotonic shear discharges. A TRANSP model which does not include the effects of stochastic ripple diffusion is also shown in Fig. 4 and indicates the magnitude of the effect of ripple on the neutron emission. The error bar on the TRANSP calculation in Fig. 4 is an estimate based on a group of TRANSP runs in which input parameters were varied. Note that the effect of vacuum magnetic fields on the beam ion orbits is not significant for these large major radius plasmas which closely fit the limiter aperture.

It was not possible to directly measure the beam ion loss in these experiments. However, significant beam ion loss in JT-60U RS discharges was deduced from triton burn-up measurements [13]. The JT-60U measurements were explained by ripple loss of the beam ions. However, there are several differences between the two experiments: the toroidal field ripple on JT-60U is significantly larger than on TFTR, the ratio of pitch angle scattering time to slowing down time is an order of magnitude larger for 1 MeV tritons than for 100 keV beam ions, the orbit size relative to the plasma size is four times larger for 1 MeV tritons, and the birth velocity distribution functions are quite different.

The explanation for the discrepancy between the calculated and measured values of the D-T neutron emission in these discharges remains unclear. The fact that the discrepancy is greatest at the peak neutron emission indicates that prompt loss of beam ions is responsible, as opposed to anomalous diffusion of the beam ions. Stochastic ripple diffusion remains the likely candidate. The stochastic ripple diffusion calculation is sensitive to the details of the q(r) profile, in particular, the values of q(0) and the q_{min} radius, and it is also sensitive to radial variations in the beam deposition. Further modeling work will evaluate whether or not varying these quantities within their uncertainties can bring the predictions to within the error bars on the measurements. It is important to resolve this discrepancy, given the likely importance of stochastic ripple diffusion in determining the confinement of energetic ions generated by auxiliary heating in a reactor operating in the RS regime.

4. ALPHA-DRIVEN TOROIDAL ALFVÉN EIGENMODES

The pressure profile of alpha particles created by D-T fusion reactions is highly peaked in the plasma core. The free energy available in the strong alpha pressure gradient can drive various collective instabilities, and a particular mode is destabilized when its growth rate exceeds its damping rate. Early theoretical work predicted that toroidal Alfvén eigenmodes (TAEs) could be destabilized by super-Alfvénic alpha particles via parallel wave-particle resonances [14]. These modes occur within toroidicity-induced gaps in the shear Alfvén spectrum. Alpha-driven TAEs are a concern for reactors because they could cause significant alpha loss. Thus, experiments to study alpha-driven TAEs were performed in TFTR D-T plasmas.

Although TAEs driven by neutral beam ions and energetic minority ions created by ion cyclotron heating were observed in deuterium plasmas on a variety of devices [15] early attempts to observe alpha-driven TAEs during high-power beam heating in TFTR D-T plasmas were unsuccessful because the modes were stabilized by various damping mechanisms, including Landau damping on unthermalized beam ions, electron Landau damping, and radiative damping on kinetic Alfvén waves [16]. Because the alpha slowing-down time is long compared to that of beam ions, $\beta_\alpha(0)$ remains high compared to the total plasma β(0) for several hundred milliseconds following the termination of beam injection. The damping terms, which increase with β(0), decrease faster than the alpha drive term, reducing the stability of the TAEs. The optimum time to look for TAEs is therefore 0.1-0.2 s after the end of beam injection. However, alpha-driven TAEs were not observed following beam injection in high fusion power D-T plasmas with q(0)<1 and values of $\beta_\alpha(0)$ up to ~0.3%.

Further theoretical work revealed that reducing the core magnetic shear and raising q(0) to values greater than one might allow alpha-driven TAEs to be observed following beam injection in TFTR. This is because radiative damping decreases with increasing mode width and decreasing shear, while the condition q(0)>1 aligns the low-n gaps in the shear Alfvén spectrum with the peak of the β_α gradient and reduces radiative damping. Thus, the first observations of alpha-driven TAEs were made in weak-shear TFTR D-T discharges with q(0)>1 [17]. These discharges were similar to RS plasmas in that q(0)>1 was obtained by neutral beam injection into the current ramp-up phase of the discharge, but differ because there was no shear reversal in the core region. TAEs were seen in plasmas with q(0) greater than ~1.5.

Figure 5 shows the beam timing and time evolution of $\beta_\alpha(0)$ and β(0) calculated by TRANSP for a discharge in which alpha-driven TAEs were observed. The slow decay of $\beta_\alpha(0)$ compared to β(0) following beam injection is clearly seen, and TAEs were observed starting ~0.1 s into this period when $\beta_\alpha(0)$~0.06%. Mirnov coil measurements of edge poloidal magnetic field fluctuations relative to the average field, $\tilde{B}_\theta/B_T$, show the appearance of TAEs with toroidal mode numbers n= 2-5. (Modes with n=1 and n=6 were also sometimes seen.) $\tilde{B}_\theta/B_T$ is small, less than 6×10^{-9}, at the wall. The mode frequencies are in the range 150-250 kHz and increase with increasing toroidal mode number. The

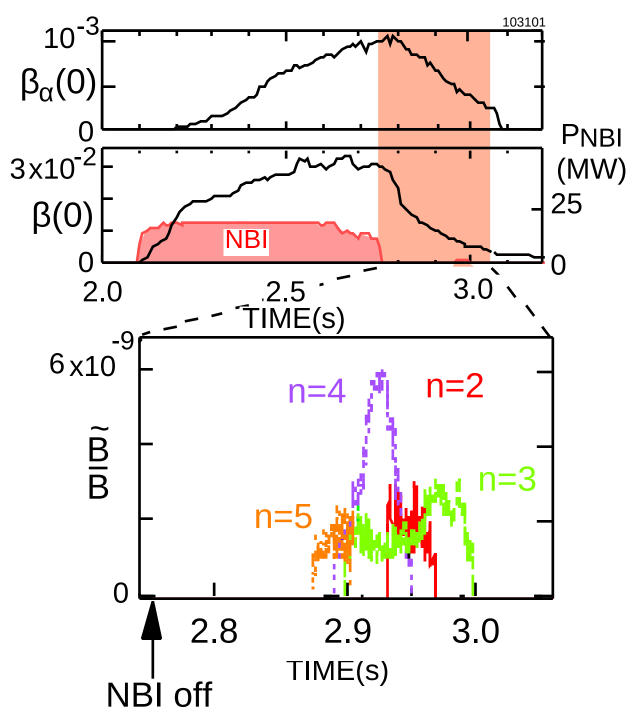

Fig. 5. Time evolution of β_α (0) and β(0) and Mirnov coil data showing TAE signatures.

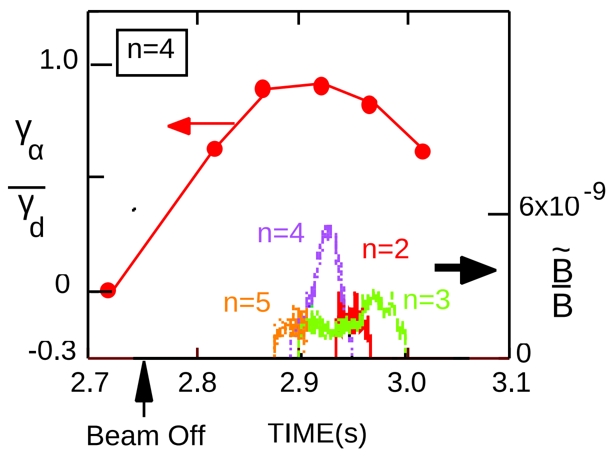

Fig. 6. Observed TAEs appear when γ_α/γ_d *calculated by NOVA-K code peaks.*

frequency of each mode increases with time because the Alfvén velocity increases as the density falls following termination of beam injection.

The TAE drive term, γ_α, and the total damping term, γ_d, were calculated perturbatively with the NOVA-K kinetic-MHD stability code [18]. The time evolution of the ratio γ_α/γ_d for the n=4 mode is shown overlaid on the Mirnov data in Fig. 6. The n=4 mode appears at the maximum of γ_α/γ_d. Radiative damping is the dominant damping mechanism during the time that TAEs are seen.

The calculated and observed mode frequencies at the time of peak amplitude of the n=4 mode, 2.92 s, are shown in Fig. 7 for modes with n=2-5. The measured frequencies exhibit a strong dependence on n while the calculated frequencies do not. The predicted frequencies of the modes with n=3-5 are close to the measured values, while the calculated n=2 mode frequency is significantly lower than the measurement. The cause of these discrepancies is unclear as frequency corrections due to kinetic effects or plasma rotation are much smaller than the difference.

The radial locations of the TAEs were measured using an X-mode reflectometer, which measured the phase fluctuations on microwave probe beams reflected from their cutoff layers. This was a local measurement because the phase fluctuations were primarily due to

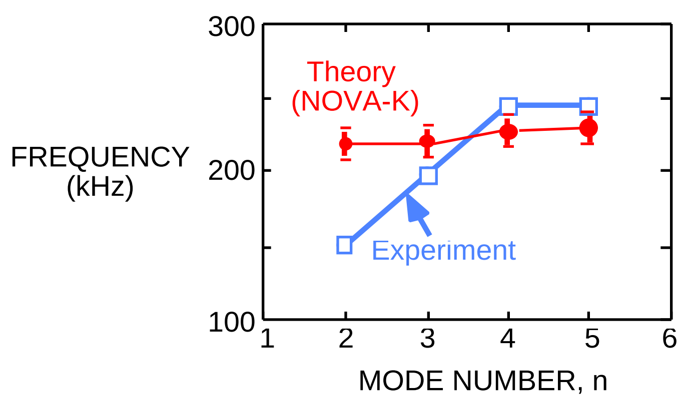

FIG. 7. Measured TAE frequencies show stronger dependence on mode number than predicted by NOVA-K code.

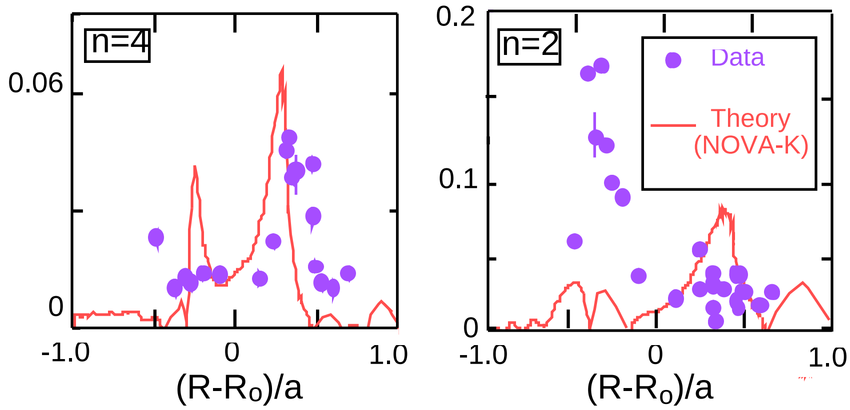

FIG. 8. Reflectometer measurements of TAE mode locations. The NOVA-K code predicts the ballooning character of the n=4 mode but not the anti-ballooning character of the n=2 mode.

density fluctuations at the location of each X-mode cutoff layer. The reflectometer had three fixed frequencies and could therefore make measurements at three radial locations for a given value of the toroidal field. The radial position of the cutoff layer is sensitive to the toroidal field, so radially-resolved measurements could be made by making 10% variations in the toroidal field while holding q(a) constant. Figure 8 shows such a measurement of the radial structure of the phase fluctuation level for the n=4 and n=2 modes, obtained by combining data from a number of discharges with reproducible mode activity as seen on the Mirnov coils. Both modes were localized in the core at r/a~0.3. The n=4 mode had a ballooning radial structure, i. e., localized on the low field side of the magnetic axis, while the n=2 mode was anti-ballooning (localized on the high field side). Fig. 8 also shows the phase fluctuation level calculated from the NOVA-K modeling of the density perturbations due to these modes. The calculations are in agreement with the measured ballooning structure of the n=4 mode, but predict that the n=2 mode should also have a ballooning structure, in contrast to the measurements. This indicates that the n=4 mode is a TAE but that the n=2 mode may not be a TAE [18].

There was no measurable alpha loss associated with any of the alpha-driven TAEs observed on TFTR. This is not surprising because the modes were very weak. However, TAE-driven alpha transport may be an issue for a reactor. In ITER, TAEs are predicted to have higher values of n than in present devices due to the lower ρ_α/a [10]. Some modes with n=10-30 are predicted to be unstable and could therefore drive alpha transport. Although considerable progress has been made in developing the theory of alpha-driven TAEs, further experimental and theoretical work is needed to ensure that reliable predictions can be made for a reactor.

In addition to alpha-driven-TAEs, low-n modes (n=2-4) in the Alfvén range of frequencies (90-160 kHz) were observed in RS and ERS discharges heated by ~100 keV beam ions [19]. These modes were seen in the high-power and reduced-power beam heating phases of both deuterium and D-T plasmas. Reflectometer measurements showed them to be radially localized to the weak magnetic shear region around q_{min}. These modes have not been definitively identified, but may be TAEs driven by beam ions or kinetic ballooning modes. Enhanced alpha loss was not associated with these modes, consistent with the observation that the modes were weak.

5. MHD-INDUCED ALPHA LOSS

It is well known that MHD activity causes time-dependent internal magnetic field perturbations which can degrade fast-ion confinement. This phenomenon has been studied for D-D fusion products and other fast ions in deuterium experiments on TFTR and elsewhere [20]. MHD-induced alpha loss is a potentially serious issue for reactors: even when the MHD activity is not strong enough to cause significant global alpha losses and thus loss of alpha heating power, wall damage could result from localized alpha losses.

MHD-induced alpha loss in TFTR D-T plasmas was studied using a group of lost alpha detectors located at one toroidal location and four different poloidal angles below the midplane: 20°, 45°, 60°, and 90° [9]. The 20° detector could be moved radially and the other three were fixed at positions just outside the radius of the outer poloidal limiters. These scintillator detectors could measure the alpha loss flux as a function of time with a frequency response up to 100 kHz. Both monotonic shear and RS discharges were studied.

MHD activity was found to cause measurable alpha loss at levels above the first orbit loss background level in 10-20% of the D-T discharges studied [21]. Normal coherent low frequency modes, higher frequency coherent modes (e. g., kinetic ballooning modes [22]), and stationary magnetic perturbations, caused local alpha loss rates up to twice first-orbit loss levels. Reconnection events, such as sawtooth crashes and major and minor disruptions, caused larger bursts of local loss for periods less than 1 ms. Sawteeth have also been observed to cause radial redistribution of confined alphas in TFTR [8, 23].

Two examples of MHD-induced alpha loss are shown in figures 9 and 10. Fig. 9 shows the signals seen by the 60° detector and the Mirnov coils during a mode with a frequency of ~300 Hz. This mode was identified to be a combination of a 2/1 (m=2, n=1) tearing mode and a 1/1 kink mode. The alpha loss is strongly modulated in phase with the Mirnov coil signals. This MHD mode caused the local alpha loss to increase by up to a factor of two over the background first-orbit loss level at this detector, but the corresponding increase of global alpha loss was estimated to be much smaller. Figure 10 shows alpha loss during a sawtooth crash. The first of two short bursts of alpha loss seen in the 90° detector is well correlated with the measured drop in the core electron temperature. Significant poloidal variation of

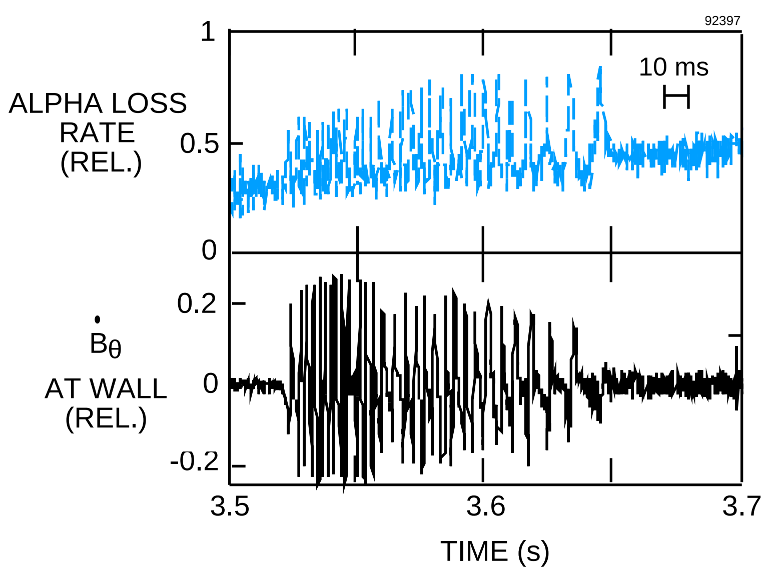

FIG. 9. Alpha loss and poloidal magnetic field fluctuations for a mode identified to be a combination of a 2/1 tearing mode and a 1/1 kink mode.

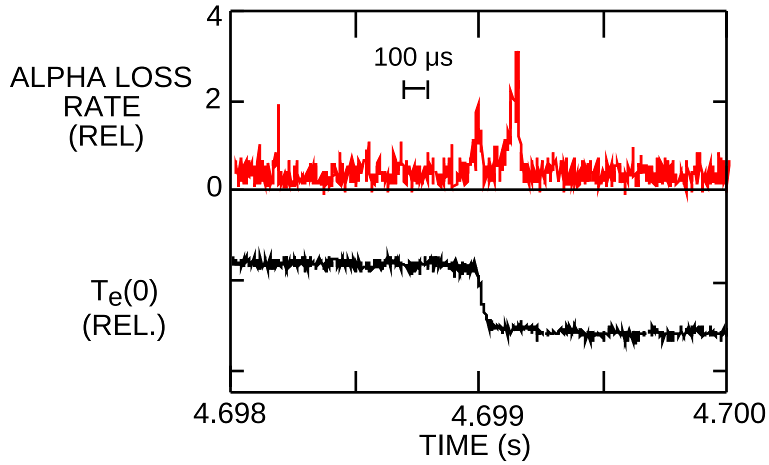

Fig. 10. Alpha loss and drop in core electron temperature due to a sawtooth crash.

alpha loss was often seen: alpha loss due to low-n coherent MHD activity usually peaked at 45-60° below the midplane, while alpha loss caused by disruptions and sawtooth crashes usually peaked at the 90° detector and the 20° detector. The theory of alpha transport due to sawteeth developed by Kolesnichenko *et al.* [24] predicts significant losses at 90° below the midplane.

Coherent low-frequency MHD is theoretically predicted to cause alpha loss by two mechanisms [25]: 1) radial transport due to internal field perturbations can move both passing and trapped alphas to the wall, and 2) counter-passing alphas in the plasma core can become converted to trapped alphas which are lost promptly. Figure 11 shows a plot of an ORBIT code prediction of global alpha loss normalized to total loss (first-orbit loss and ripple-induced loss) versus assumed magnetic island width for the same 2/1 mode shown in Fig. 9. The calculated alpha loss increases with increasing island width, and significantly exceeds the first orbit loss level for large island widths. The measured local alpha loss in this case is shown in Fig. 11. The global alpha loss calculated with both the measured 2/1 island

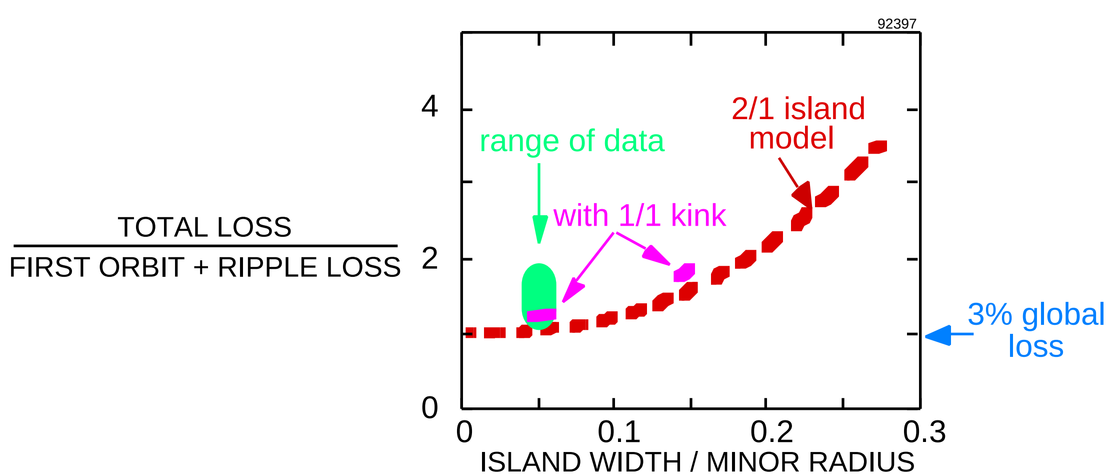

FIG. 11. ORBIT code predictions of global MHD-induced alpha loss due to an assumed 2/1 island similar to the mode shown in Fig. 9. The calculated effect of an additional 1/1 internal kink mode is also plotted. The range of observed increases in alpha loss (normalized to the pre-MHD induced loss) is shown. The model is in qualitative agreement with the data.

width and 1/1 kink flux surface displacement is also shown in Fig. 11. The global alpha loss including MHD-induced alpha loss is 4%, i. e., about ~25% above the global loss calculated assuming no MHD modes. This is in qualitative agreement with the range of the observed MHD-induced alpha loss, which was up to a factor of two for the 60° detector, but was much less for the 45° and 90° detectors.

Alpha loss due to coherent MHD activity increases with increasing alpha gyroradius relative to the plasma minor radius, ρ_α/a, for constant island size relative to minor radius. Thus, while alpha loss due to coherent MHD activity can be significant for TFTR, it is expected to be negligible for ITER because ρ_α/a is much smaller. However, alpha loss due to reconnection events such as sawteeth and disruptions may still be significant in reactor-scale plasmas because the alpha motion in these events is not explicitly dependent on ρ_α/a. To evaluate the local wall heat load due to alphas in future D-T devices, it will be important to consider the effect of the vacuum fields on the escaping alpha orbits. This has been shown to be significant in modeling the poloidal dependence of alpha loss due to sawteeth [24] and toroidal field ripple in TFTR [26].

6. CONCLUSION

We have given an overview of the physics of alpha particles and neutral beam ions studied in the final phase of TFTR operation, with an emphasis on observations in Reversed Shear (RS) and Enhanced Reversed Shear (ERS) D-T plasmas. The primary conclusions regarding the implications of our results for a reactor are:

1. Energy-resolved measurements of the radial profiles of confined, trapped alphas in RS plasmas exhibit reduced core alpha density with increasing alpha energy, in contrast to the monotonic shear case. The measured profiles are consistent with guiding-center code predictions of increased alpha loss due to stochastic ripple diffusion and first orbit loss in RS plasmas. These results imply that toroidal field ripple must be minimized in a reactor operating in the RS regime.

2. Experiments to study beam ion confinement in RS plasmas on TFTR were performed by injecting short tritium beam pulses into deuterium plasmas. TRANSP calculations including stochastic ripple diffusion overestimate the measured peak D-T neutron emission by ~25%. In contrast, similar TRANSP modeling of monotonic shear discharges generally showed satisfactory agreement with the measured neutron emission and stored energy. Beam-ion loss on a time scale faster than the beam ion slowing down time is the cause of this discrepancy in RS plasmas. The stochastic ripple diffusion models are sensitive to small changes in the beam deposition and to uncertainties in the q(r) profile. Since these observations may have implications for a reactor operating in the RS regime, further work is needed to understand this phenomenon.

3. Alpha-driven, low-n Toroidal Alfvén Eigenmodes (TAEs) were observed in D-T discharges with weak magnetic shear. The appearance of these modes following the termination of beam injection is predicted by the NOVA-K MHD stability code. The TAEs were sufficiently weak that they did not cause loss of alphas from the plasma. A microwave reflectometer measured the spatial localization of the modes. The NOVA-K modeling reproduces the observed ballooning radial character of the n=4 mode, but not the observed anti-ballooning character of the n=2 mode. In addition, the modeling does not show the

observed strong dependence of mode frequency on n. Thus, some, but not all, features of the observed alpha-driven TAEs are explained by the NOVA-K modeling. Further development of the theory is required to fully explain the observations and to benchmark the models so that they can be reliably used to predict TAE behavior in a reactor. Modes in the Alfvén range of frequencies with n=2-4 are seen in both deuterium and D-T ERS and RS discharges. Reflectometer measurements indicate that they are localized to the weak magnetic shear region near q_{min}. These modes occurred in both the high- and reduced-power phases of ERS plasmas and did not cause measurable alpha loss. The identity of these modes is not clear.

4. MHD activity caused increased alpha loss at levels above first orbit loss in 10-20% of D-T discharges produced on TFTR, and most types of MHD activity caused alpha loss: coherent low-frequency modes, higher-frequency modes such as kinetic ballooning modes, stationary magnetic perturbations, sawtooth crashes, and major and minor disruptions. Significant poloidal variation of the alpha loss was often seen. Global alpha loss due to low-frequency coherent MHD activity is likely to be negligible in a reactor due to the lower ρ_α/a, but damage due to localized loss remains a possibility. Further theoretical work is needed to determine whether or not alpha loss due to reconnection events such as sawteeth or disruptions will be significant in a reactor.

Finally, it is worthwhile to put these conclusions into the context of the requirements for a reactor operating in a modified magnetic shear regime. In such a reactor plasma, the plasma pressure and q profiles must simultaneously be consistent with: 1) enhanced thermal confinement; 2) alpha heating; 3) MHD stability; and 4) a self-consistent bootstrap current. At present, it is not known whether these requirements can be met simultaneously. In addition, fast particle confinement must be good, for both the alphas and for fast ions produced by auxiliary heating, to ensure efficient plasma heating and to avoid localized losses which could damage the first wall. The results presented here show that achieving good fast ion confinement in a modified magnetic shear reactor may impose different design and operational requirements than those for a reactor operating in a monotonic shear regime.

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REFERENCES

[1] Hawryluk, R. J., Rev. Mod. Phys. **70** (1998) 537.
[2] Hawryluk, R. J., et al., Phys. Plasmas **5** (1998) 1577.
[3] Zweben, S. J., et al., “Alpha Particle Physics Experiments in TFTR”, submitted to Nuclear Fusion (Oct. 1998).
[4] Levinton, F. M., et al., Phys. Rev. Lett. **75** (1995) 4417.
[5] White, R. B., and Chance, M. S., Phys. Fluids **27** (1984) 2455.
[6] White, R. B., et al., Phys. Plasmas **3** (1996) 3043.
[7] Redi, M. H., et al., Phys. Plasmas **4** (1997) 4001.

[8] Medley, S. S., et al., Nucl. Fusion **38** (1998) 1283.
[9] Darrow, D. S., et al., Rev. Sci. Inst. **66** (1995) 476.
[10] Putvinski, S., et al., IAEA-CN-69/ITERP1/10, these Proceedings.
[11] Goldston, R. J., White, R. B., and Boozer, A. H., Phys. Rev. Lett. **47** (1981) 647.
[12] Redi, M. H., et al., Nucl. Fusion **35** (1995) 1509.
[13] Tobita, K., et al., Nucl. Fusion **37** (1997) 1583.
[14] Fu, G. Y., et al., Phys. Fluids B **1** (1989) 1949.
[15] Wong, K. L., Phys. Rev. Lett. **66** (1991) 1874.
[16] Nazikian, R., et al., Phys. Plasmas **5** (1998) 1703.
[17] Nazikian, R., et al., Phys. Rev. Lett. **78** (1997) 2976.
[18] Fu, G. Y., et al., ”Alpha Particle-Driven Toroidal Alfvén Eigenmodes in Tokamak Fusion Test Reactor Deuterium-Tritium Plasmas: Theory and Experiments”, Princeton Plasma Physic Laboratory Report No. PPPL-3279 (Sept. 1998). Accepted for publication in Physics of Plasmas.
[19] Nazikian, R., et al., “Coherent Alfvén Frequency Modes in Reverse Magnetic Shear Plasmas on TFTR”, in Proceedings of 25th European Physical Society Conference on Controlled Fusion and Plasma Physics, Prague, Czech Republic (29 June- 3 July, 1998).
[20] Heidbrink, W. W., and Sadler, G., Nucl. Fusion **34** (1994) 535.
[21] Zweben, S. J., et al., Bull. Am. Phys. Soc. **42** (1997) 1971.
[22] Chang. Z., et al., Phys. Rev. Lett. **76** (1996) 1071.
[23] Stratton, B. C., et al., Nucl. Fusion **36** (1996) 1586.
[24] Kolesnichenko, Ya I., et al., IAEA-CN-69/THP2/25, these Proceedings.
[25] Sigmar, D. J., et al., Phys. Fluids B **4** (1992) 1506.
[26] Yavorskij, V., et al., IAEA-CN-69/THP2/27, these Proceedings.