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ENERGETIC PARTICLE PHYSICS ISSUES FOR ITER

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Abstract

This paper summarizes our present understanding of the following energetic/alpha particle physics issues for the 21 MA, 20 TF coil ITER Interim Design configuration and operational scenarios: (a) toroidal field ripple effects on alpha particle confinement, (b) energetic particle interaction with low frequency MHD modes, (c) energetic particle excitation of toroidal Alfvén eigenmodes, and (d) energetic particle transport due to MHD modes. TF ripple effects on alpha loss in ITER under a number of different operating conditions (L-mode, H-mode, and post-sawtooth) are found to be small with a maximum loss of 1%. With careful plasma control in ITER reversed-shear operation, TF ripple induced alpha loss can be reduced to below the nominal ITER design limit of 5%. Fishbone modes are expected to be unstable for $\beta_\alpha > 1\%$, and sawtooth stabilization is lost if the ideal kink growth rate exceeds 10% of the deeply trapped alpha precessional drift frequency evaluated at the q = 1 surface. However, it is expected that the fishbone modes will lead only to a local flattening of the alpha profile due to small banana size. MHD modes observed during slow decrease of stored energy (as much as 20% in 50-100 msec) after fast partial electron temperature collapse (in about 100 μsec) in JT-60U reversed-shear experiments may be resonant type instabilities; they may have implications on the energetic particle confinement in ITER reversed-shear operation. From the results of various TAE stability code calculations, ITER equilibria appear to lie close to TAE linear stability thresholds. However, the prognosis depends strongly on q profile and profiles of alpha and other high energy particle species. If TAE modes are unstable in ITER, the stochastic diffusion is the main loss mechanism, which scales with $(\delta B_r/B)^2$, because of the relatively small alpha particle banana orbit size. For isolated TAE modes the particle loss is very small, and TAE modes saturate via the resonant wave–particle trapping process at very small amplitude. If a wide range of overlapping medium- to high-*n* TAE modes does prove to be linearly unstable, then a global quasilinear, possibly bursty, flattening of the alpha profile, resulting from an explosive "domino" effect due to enhanced wave energy release, is possible. Finally, theoretical calculations on energetic/alpha particle physics issues have made much progress. Critical energetic/alpha physics experimental input is expected in the near future from JET DT, TFTR DT, and JT-60U negative ion beam experiments.

Introduction

The study of energetic particle transport and effects on MHD modes is important for ITER design and operation. In particular, the behavior of alpha particles produced in DT fusion reactions and that of energetic ions produced by auxiliary ICRF and N-NBI heating planned for ITER should be well understood. Any unanticipated loss of energetic/alpha particle power could result in reduction of plasma beta, serious wall damage, impurity influx, major operational control problems, or even a failure to sustain ignition. NBI and ICRF experiments in large tokamaks have shown that collective MHD modes such as the fishbone and TAE modes can be strongly unstable and cause the loss of up to half of the fast beam ions. Our present understanding of the following critical energetic particle physics issues for the ITER design configuration and operational scenarios are addressed.

1. TF Ripple Effects on Alpha Particle Confinement

Toroidal field ripple breaks the symmetry of any tokamak and can result in the loss of a significant fraction of the fast α heating power. The toroidal field ripple is defined as $\delta \equiv (B_{max} - B_{min})/(B_{max} + B_{min})$, where B_{max} and B_{min} are toroidal magnetic fields calculated at two points having the same radial and vertical coordinates in the meridional cross section but different toroidal coordinates — one under the TF coil and another midway between two neighboring coils. The ITER device has been designed such that the maximum ripple at the plasma separatrix is about 2% and, in the reference ignited operating mode, TF ripple losses of fast α-particles are negligible. However, the situation is less favorable in the high-q (low plasma current) operating modes envisioned for steady-state operation. In high-q operation ripple wells can cover a substantial fraction of the plasma cross-section. Ripple wells occur when $n\,\delta(R,Z) \geq |B_R/B_{\phi 0}|\,(|B|^2/B_\phi^2) - 1/2\,(R/F_0F^2)\,[\partial\psi/\partial Z\,\partial|\nabla\psi|^2/\partial R - \partial\psi/\partial R\,\partial|\nabla\psi|^2/\partial Z]$, where n is the number of toroidal field coils, B_R is the radial component of the magnetic field, $B_{\phi 0}$ is the vacuum toroidal field, B_ϕ is the toroidal field (including equilibrium corrections), $F_0 \equiv RB_{\phi 0}$, $F \equiv RB_\phi$, and ψ is the poloidal flux, and the second term on the right hand side of this inequality is a small correction due to poloidal variations in the poloidal field strength. The leading terms are approximately $\delta(R,Z) \geq \varepsilon/qN$ (where we have used the estimate $B_R/B_\phi \approx \varepsilon/q$, $\varepsilon = r/R$).

Guiding center particle orbit following code calculations have been made to study ripple-induced alpha loss in ITER, under a number of different operating conditions for the 21 MA, 20 TF coil ITER Interim Design [1]: L-mode, H-mode, post-sawtooth, and reversed-shear configurations. In all cases except for reversed-shear operation, alpha loss is below 1% [2]. Alpha loss is substantially higher in a reference 12 MA ITER reversed-shear equilibrium (96015-01) with $q(0) = 5$, $q_{min} = 3.5$, and $q(a) = 6$ at the 95% flux surface, localized near the outer wall. This result is also supported by JT-60U experimental results that the confinement of 1 MeV tritons in reversed-shear plasmas is inferior to that in normal shear plasmas, causing an enhanced heat load on the first wall [3]. The stochastic loss is predicted to be negligible, but the TF ripple asymmetry gives large losses due to ripple well drift. The ripple well domain is quite large. The up-down asymmetry causes it to extend to the edge of the plasma in the upper half plane. Much of the plasma core lies within the ripple well region, and essentially all alpha particles born with banana tips outboard of the magnetic axis will drift to the first wall, while the upper banana tip never leaves the ripple well region. Collisionless losses predicted by ORBIT [2] and GIBRID [4] Monte Carlo orbit simulations and a novel accelerated method [5] are about 15-16%, which may produce unacceptable peak heat loads on the first wall (several MW/m^2).

To mitigate the ripple loss in ITER reversed-shear operations, three operational scenarios are proposed: 1) use of the plasma shape control system to hold the plasma away from the high ripple region, 2) operation with lower values of q at mid plasma radius, and, possibly 3) reduction of the magnitude of the toroidal field ripple. For example, a shorter ITER reversed-shear equilibrium (96015-02) with reduced elongation to make the plasma more nearly centered within the TF coil set, is found to lose less than 3% of alpha particles, below the nominal ITER design limit of 5%. Since it fits the outer wall less snugly, it may present increased problems of vertical control. Hence, it appears that ripple losses of fast α in reversed-shear modes can be held to acceptable values through control of the plasma shape. For a maximum alpha ripple loss of 3% for the 21 MA case we estimate that the heat load gives roughly 0.08 MW/m^2. However, the wall heat load may be increased by MHD and TAE enhanced losses, in addition to toroidal peaking factors.

2. Energetic/Alpha Particle Interaction with Low Frequency MHD Modes

Energetic trapped particles can significantly affect the stability of low frequency MHD modes such as internal kink modes, fishbone modes, and ballooning modes, which in turn can cause energetic particle transport. Recent DT experiments on TFTR have shown a substantial redistribution of partially thermalized alphas by sawtooth crashes [6]. A similar sawtooth-induced alpha redistribution in ITER would cause a change in the alpha heating profile, and possibly an increase in TF ripple loss. Increased alpha particle loss due to the kinetic ballooning mode and various other types of coherent MHD have also been seen on TFTR.

For low frequency MHD modes with frequency below the energetic trapped particle bounce-averaged magnetic drift frequency ω_d, the particle dynamics is no longer governed by the ExB drift, but rather by the magnetic drift. For $\omega << \omega_d$, if the energetic particle diamagnetic drift frequency ω_* has the same sign as ω_d, the MHD modes will be stabilized because the energetic trapped particles precess rapidly and their motion becomes too rigid to release its pressure gradient free energy to the MHD waves. On the other hand, resonant type MHD modes such as fishbone (n = 1 internal kink type) modes and kinetic ballooning modes (KBM) with $\omega = \omega_d$ can resonate with the energetic trapped particles and be destabilized if the hot trapped particle beta β_h is larger than a threshold value. The stability of higher frequency KBM can also be affected by the drift-bounce resonance with energetic particles. Since ω_d is a function of particle velocity, pitch angle, aspect ratio, plasma beta, and plasma shaping, the magnetic drift reversal domain in the pitch angle and minor radius space can be significantly enlarged in ITER. Alpha particles have a uniform velocity pitch angle distribution, and their averaged magnetic drift frequency can be significantly reduced so that the theoretical β_α threshold for the fishbone instability becomes much lower than previously thought.

Calculations for ITER parameters [7], with q = 1 at r = $a/3$, show that fishbone modes can be excited for $\beta_\alpha \geq 1\%$, where β_α is the volume averaged alpha particle beta within the q = 1 surface. Internal kink stabilization is lost if the ideal growth rate exceeds 10% of the deeply trapped alpha precessional drift frequency evaluated at the q = 1 surface. This is mainly because the drift reversal effect reduces the average trapped alpha precessional drift so that low frequency MHD modes can more easily resonate with trapped alphas and release the alpha pressure gradient free energy. The stable window in the β vs. β_α domain for both sawteeth and fishbone modes is further reduced when the core ion diamagnetic drift effect is included. However, it is expected that the fishbone modes (localized mainly within the q =1 surface) will lead only to a local flattening of the alpha profile due to small banana size. To eliminate the possibility of exciting fishbone modes, ITER can be operated with q(0) > 1. However, kinetic ballooning modes may still be excited when the plasma β is below MHD marginal stability.

Recent JT-60U reversed-shear experiments have found very fast (in about 100 μsec) partial collapse of electron temperature in the NBI and ICRF heated plasmas [8]. Following these fast collapse of electron temperature the total stored energy can decrease slowly by as much as 20% in about 50 - 100 msec. Accompanying these slow decrease of the stored energy are MHD activity with frequency in the range of 2 to 7 kHz. The cause of the slow decay of the stored energy has not been clearly identified. Besides the possible cause of the redistribution of the thermal and fast ion pressures and the modification of the current profile after the fast electron temperature collapse, the MHD activity may play some role in the slow stored energy decay. These

MHD modes may be resonant type MHD instabilities because their frequencies are on the order of the beam ion precessional drift frequency. These MHD modes, if excited in ITER reversed-shear operation, may have important effects on energetic particle confinement. The stability calculation of these MHD modes is yet to be performed for both JT-60U and ITER.

3. Energetic Particle Excitation of TAE Modes

The Toroidal Alfvén Eigenmodes (TAE) [9] have been shown to exist with discrete frequencies located inside the shear Alfvén continuum gaps created by toroidal coupling of different poloidal harmonics. The frequency of the TAE mode in the lowest continuum gap is roughly given by $\omega \approx V_A/2qR$ for all toroidal mode numbers. The existence of TAE modes depends on the plasma density and q profiles, plasma β, plasma shaping, aspect ratio, and wall boundary. Energetic particles with velocity near the Alfvén speed can resonate with TAE modes and destabilize them if the expansion free energy associated with the energetic particle pressure gradient can overcome velocity space and collisional damping effects due to all particle species.

Alpha driven TAE modes have recently been observed in TFTR DT plasmas with reduced central shear (< 0.2) out to r/a = 0.6 and elevated central safety factor q(0)=1.5-3.0 [10]. TAE mode are observed within 80-100 msec (D and T beam ion slowing down time) following neutral beam injection. The dominant mode is an $n = 3$ core localized TAE mode with frequency within 10% of the TAE frequency predicted by the NOVA-K code [11]. The threshold fusion power for exciting the $n = 3$ TAE mode is very low (=1.5 MW for q(0)=3.0 and =2.5 MW for q(0)=1.5 corresponding to =300 kW and = 500 kW alpha heating power, respectively). NOVA-K code calculates that the threshold $\beta_\alpha(0)$ is consistent with experiment in the range 0.01-0.02%. The mode amplitude is very weak with $\delta B/B=10^{-8}$ on the Mirnov coils while the reflectometer measurements indicate a mode amplitude $\delta n/n = 10^{-4}$ at $r/a = 0.4$ with no observable density fluctuations at larger radii. No alpha loss due to this TAE mode has been observed.

TAE modes have also been observed in JT-60U experiments [8] with high power ICRF and NBI. TAE modes with n=1, 2 are observed in low positive shear (q(0)=1.6) plasmas, but not in reversed-shear plasmas with strong ITB (internal thermal barrier) formation. However, weak TAE modes with n=5-8 have been observed in reversed-shear plasmas (q(0) = 3-4, q_{min} = 2 (at r/a =0.7), and q(a)=3.5) after partial collapse of the stored energy (weak ITB plasmas). The results have also been confirmed by the NOVA-K code calculation. Due to different radial wave structure, TAE modes do not access as much hot ion drive in strong ITB cases than in weak ITB cases. These JT-60U results indicate that TAE modes will probably be unstable in ITER weak normal shear or reversed-shear plasmas

For ITER the increased size shifts the spectrum of unstable TAE modes towards medium- to high-n modes. Linear TAE stability in ITER has been examined for ITER reference (PRETOR 1) pressure and q profiles which have very flat regions in the center (r/a < 0.7) due to assumed rapid sawtoothing and sharp gradients outside the q = 1 surface. Code calculation results from NOVA-K [11] and TAE/FL [12] codes show that TAE modes are stable up to at least n = 50. However, using relatively more realistic peaked pressure profiles for TAE stability calculation we find that TAE modes can be more easily destabilized in ITER than in the TFTR D-T experiments. One reason is because ITER has lower q(a) ($\approx$ 3.5) and its plasma beta is below the Troyon limit so that TAE modes can exist with more global radial structure. Another reason is that the expected $\langle\beta_\alpha\rangle$ is about one order of magnitude larger than in TFTR D-T experiments. The existence of core-localized TAE modes [13,14] has been predicted in the low-shear region, where the population of destabilizing fusion alpha particles is peaked for normal ITER operation. In reversed-shear operations the low-shear region is moved outward but these modes can still be unstable due to their enlarged mode width. For more peaked pressure profiles in ITER, core localized TAE modes are expected to be unstable. In the following we summarize the present status of TAE stability in ITER as predicted by various codes.

(a) NOVA-K Code Results

To study the medium-n TAE stability for ITER experiments using the NOVA-K code [11] we consider a series of equilibria with varying plasma beta. The fixed parameters of the ITER equilibrium are taken to be the major radius R = 8.1 m, the minor radius $a = 2.8$ m, the ellipticity $\kappa = 1.6$, the triangularity $\delta = 0.25$, the toroidal field B = 5.7 T. The pressure profile is chosen as $P = P(0)\,(1-\psi)^{1.2}$, where ψ is the normalized poloidal flux. The q-profile is chosen with q(0) = 1.0, q(1) = 3.78, q'(0) = 0.5, q'(1) = 13. The plasma is assumed to consist of thermal electron, thermal D-T ions and alpha particles. The electron density profile is given by $n_e = n_e(0)\,(1-0.8\,\psi^2)$. The thermal ions are assumed to consist of an equal mixture of D and T with equal temperature. We assume $n_i = n_e$ and $T_i = T_e$. The alpha pressure profile is chosen to be proportional to $P(r)^{3.5}$. The TAE stability is studied in the $n_e(0)$-$T_e(0)$ space with self-consistent equilibria and alpha pressure profiles for $n \leq 30$. Both global TAE and core localized TAE are considered. The main damping mechanisms are the ion Landau damping, which increases rapidly with $\langle\beta_i\rangle$, and the radiative damping. But, the alpha drive also increases with $\langle\beta_i\rangle$. The global TAEs tend to have large amplitude near the plasma edge and are found to be stable up to $n = 10$. On the other hand high-n (n = 15 - 30) core localized TAEs tend to be unstable due to large alpha drive. Without the radiative damping, the core localized mode is unstable below a critical density; the $n = 25$ core localized TAE mode is stabilized for $n_e(0) > 2\times10^{14}$ cm^{-3} by the ion Landau damping. Higher n TAE modes will have higher density threshold. However, the radiative damping stabilizes TAE modes in the low density domain. Based on an analytical radiation damping formula the $n = 25$ core localized TAE mode is stabilized for $n_e(0) < 7\times10^{13}$ cm^{-3}. Nonetheless, the radiative damping is sensitive to plasma profiles, especially the q profile, and thus, the exact stability boundary depends on details of the profiles. Because ITER is expected to operate in the range $2\times10^{14}\ cm^{-3} \geq n_e(0) \geq 5\times10^{13}\ cm^{-3}$ and 30 keV $\geq T_e(0) \geq$ 10 keV, TAE modes may be destabilized in ITER experiments. Operations at lower temperature and higher density would put ITER below TAE instability thresholds.

(b) TAE/FL Code Results

The α-particle effect on the stability of TAE modes has been studied for ITER by using the TAE/FL gyro-fluid simulation code [12] for an equilibrium with peaked profiles, which occurs just before a sawtooth event. The equilibrium is obtained from the TRANSP analysis code with q(0) = 0.9, q(a) = 3.7, $n_e(0) = 1.67\times10^{14}$ cm^{-3}, $T_e(0)$ = 22 keV, $T_i(0)$ = 20 keV. The alpha pressure gradient is finite over a significant domain of the plasma radius ($0 < r/a < 0.6$). At $\langle V_\alpha\rangle/V_A(0) = 1$, two core localized TAE modes (n = 2 and 5) are found to be unstable for the TRANSP calculated value of $\beta_\alpha(0) = 0.95\%$. At higher $\beta_\alpha(0) = 1.2\%$ (above that predicted by TRANSP) four core localized TAE modes (n = 2, 3, 5, and 6) are unstable. At higher $\beta_\alpha(0)$ (say at 2%) a range of high-n (n = 20 - 30) global TAE modes are unstable.

(c) CASTOR-K Code Results

The α-particle effect on the stability of kinetic toroidal Alfvén eigenmodes (KTAE) has also been studied for ITER by using the CASTOR-K code [15]. The frequencies of KTAE modes are near the upper Alfvén continuum gap boundary. The α drive is usually smaller for KTAE modes than for TAE modes due to higher frequency and narrower radial wave structure. However, the thermal plasma damping effects on KTAE modes can be smaller than on TAE modes. We consider the α pressure profile $P_\alpha = P_\alpha(0)\,(1-\psi)^s$, where $s > 1$, and the plasma pressure profile is chosen as $P = P(0)\,(1-\psi)$. The fixed parameters of the ITER equilibrium are taken to be the major radius $R = 8$ m, the minor radius $a = 2.6$ m, the ellipticity $\kappa = 1.6$, the triangularity $\delta = 0.25$, the toroidal field $B = 6$ T. The central electron density is set at $n_e(0) = 10^{14}$ cm^{-3}. The CASTOR-K code results show that for $s < 4$, KTAE modes are stable for $n < 10$. For $s > 2$, high-n KTAE modes can be unstable and with $s = 4$, $n > 10$ KTAE modes are unstable with $\gamma/\omega \approx \langle\beta_\alpha\rangle$.

(d) High-*n* TAE Modes

All global TAE eigenvalue stability codes are based on a perturbative approach and due to limitation of computing power are quite inefficient to calculate high-n TAE stability. For high-n TAE modes, the core ion FLR effects are as important as other damping mechanisms in determining the TAE stability. Therefore, 2D high-n TAE stability codes based on 2D WKB-ballooning formalism, such as the HINT code [16] and a semi-analytical 2D WKB code developed at Frascati [17], have been developed to take into account full core ion FLR effects as well as wave-particle resonance on a nonperturbative basis. Results for the peaked alpha profiles show that resonant TAE modes (also called Energetic Particle Modes) can be destabilized. The calculation assumes all deeply trapped alpha particles and is based on a large aspect ratio s-α equilibrium with circular shifted circular flux surfaces. For example unstable modes (n = 5-20) are found near the peak gradient at $r/a = 0.4$. The most unstable mode has $n = 10$, $\omega_r/\omega_A \approx 0.32$, and $\gamma/\omega_A \approx 3.5 \times 10^{-3}$. However, using a more realistic uniform pitch angle alpha distribution but an analytical local (1D) dispersion relation the Frascati semi-analytical 2D calculation indicates that the $n = 10$ mode is stable for expected β_α values in ITER [17].

To summarize from the above TAE stability calculations, ITER equilibria appear to lie close to TAE linear stability thresholds. The prognosis is not yet clear due to the complexity of mode structures and damping mechanisms, the strong dependence on alpha profiles, and additional free energy sources due to other high energy particle species such as ICRH minority tail ions and high energy NBI and N-NBI beam ions, which can contribute additional TAE instability drive and lower the instability threshold. On the other hand, $q(r)$ and $n_e(r)$ profiles can be controlled so that the radial gap structure does not line up across the minor radius, and the TAE mode will experience continuum damping and can be stabilized. Another way is to increase plasma β. As the plasma β exceeds the ballooning mode β limit or the magnetic shear decreases to zero, the TAE frequency will move downward into the lower continuum and suffer continuum and radiation damping to provide continuum damping and stabilize the TAE modes. In addition, plasma rotation can have a strong stabilizing effect on the TAE stability as shown in the JT-60U ICRF experiments. Therefore, TAE stability in ITER needs to be investigated further by considering more realistic plasma profiles and more particle species.

4. Energetic Particle Transport due to TAE Modes

TAE modes can lead to energetic particle transport as high as 80%, as has been found both experimentally and theoretically in present tokamaks. Two main MHD mode induced transport mechanisms have been identified [18]: (1) near-boundary transient loss, which affects mainly particles near the prompt loss boundary, and (2) stochastic diffusion loss across the prompt loss boundary in the phase space of particle energy, pitch angle, and toroidal angular momentum, which arises from overlapping of particle drift orbit islands. For particles trapped inside a well-defined resonant drift orbit island intersecting with the prompt loss boundary, their loss rate scales as $(\delta B_r/B)^{1/2}$. If the particle loss is due to distorted orbits close to the resonant drift orbit island, the transient loss rate scales as $(\delta B_r/B)$. The stochastic diffusion loss will last longer and it arises from the overlap of particle drift orbit islands. The stochastic diffusion loss rate scales as $(\delta B_r/B)^2$, and the loss rate can be drastically increased in case of multiple modes. The stochastic threshold is $(\delta B_r/B) \approx 10^{-3}$ for a single global TAE mode which can produce multiple drift orbit islands. When multiple global TAE modes are present, the orbit stochasticity threshold can be substantially reduced to $(\delta B_r/B) \approx 10^{-4}$.

In tokamak experiments, the loss rate scaling with the TAE mode amplitude will be a mixture of these three scalings and will strongly depend on the plasma equilibrium, the TAE mode structure, and the duration of TAE activity. For bursting TAE activity, it is more likely that the total energetic particle loss scales linearly with the wave amplitude, as observed experimentally. However, it is expected that the diffusive loss mechanism can be more important for saturated large amplitude TAE modes with amplitudes exceeding the stochastic threshold for a longer duration. Because of the relatively small banana orbit size in ITER only the stochastic diffusion loss mechanism is expected to be important, in contrast with many present experiments.

Nonlinear simulations of the TAE mode saturation mechanisms and related fast ion transport have been carried out with the use of hybrid kinetic-MHD models. Without a strong and steady energetic/alpha particle source, quasi-linear profile modification is found to be the most efficient means of achieving TAE mode saturation. Resonant particles trapped in the wave produce flattening of the local pressure gradient. Also, the particle energy gradient becomes steeper because high energy particles lose energy whereas low energy particles do not interact with the mode, so the mode further loses drive due to increased velocity space Landau damping and eventually saturates. As in previous studies of TAE mode induced particle loss, the dominant loss process is that of barely counter-passing particles losing energy to the wave, transferring into fat banana orbits, and then hitting the outside wall in the co-moving direction. The losses are very effective for particles with large banana width. For ITER the particle loss is very small due to small banana width, and the alpha particles remain in the device and contribute to mode damping so that TAE modes saturate at very small amplitude. The time scale for the profile modification is orders of magnitude shorter than the time scale for alpha replenishment, so the additional new alpha particles would not modify this result. The nonlinear response may be a superposition of single mode responses when there is no resonance overlap. If a wide range of overlapping medium- to high-*n* TAE modes does prove to be linearly unstable, then a global quasilinear, possibly bursty, flattening of the alpha profile, resulting from an explosive, avalanche-like "domino" effect due to enhanced wave energy release, is possible [19]. For multiple-*n* TAE modes, resonance overlap among different modes is expected for linearly unstable profiles. On the other hand, a flattened alpha pressure profile such as might evolve quasilinearly could be stable to TAE modes even without actual loss of alphas.

5. Conclusion

Alpha/energetic particle loss due to MHD modes and TF ripple is an important issue for ITER. MHD modes are expected to be destabilized by alpha/energetic particles in ITER. However, the prognosis depends strongly on q(r) profile and profiles of alpha and other high energy particles. Finally, alpha/energetic particle loss can be reduced to a manageable level by controlling plasma profiles to reduce MHD activity and by careful control of plasma shape to reduce TF ripple well.

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