ENERGETIC PARTICLES AND RUNAWAY ELECTRONS IN ITER

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Abstract

This paper summarizes results of projections of energetic particles behavior in ITER plasmas. The emphases in this paper are made on new results in the areas of TF ripple loss, TAE instabilities excited by fusion alpha-particles, physics of runaway electrons produced during plasma disruptions, and others.

1. INTRODUCTION

ITER plasmas shall have a variety of energetic particles produced by different sources. Self-sustained ignition of thermonuclear plasma depends on plasma heating by highly energetic alpha particles produced from fusion reactions. The auxiliary plasma heating systems, such as Neutral Beam (NB) injection and Ion Cyclotron Resonance (ICR) heating, generate superthermal ions with particle average energy in MeV range. Energetic runaway electrons can be produced by a high loop voltage developed in the plasma during current quench phase of plasma disruptions. Excessive loss of energetic ions, if it occurs, would reduce the efficiency of plasma heating and would also affect the durability of the plasma facing components such as first wall, divertor targets and limiters. Therefore, it is essential to develop plasma operational scenarios with efficient alpha-particle heating and small energetic particle loss and to develop reliable physics design specifications. This paper summarizes results of projections of energetic particles behavior in ITER plasmas. The emphases in this paper are made on new results in the areas of TF ripple loss, TAE instabilities excited by fusion alpha-particles, physics of runaway electrons produced during plasma disruptions, and others.

2. ENERGETIC PARTICLE RIPPLE LOSS

Toroidal field ripple, or variation of the magnitude of toroidal field due to discreteness of TF coils, should be low to avoid excessive loss of energetic alpha-particles and energetic deuterons produced during NB injection. The loss of ICRH minority ions is expected to be small in ITER, because their source is localized near the magnetic axis where TF ripple is small.

The TF ripple loss of energetic particles in tokamaks is well studied theoretically and experimentally and efficient Monte-Carlo numerical codes which are now available at JAERI, PPPL, and Kurchatov Institute have been validated on experimental results [1]. The codes have been applied to different ITER scenarios for evaluation of the TF ripple loss of alpha-particle and NB ions and associated heat loads on the plasma facing components. Table I summarizes the results of the analysis. It was found earlier [2] that Steady State (SS) operational scenarios based on reversed shear current profiles are significantly more susceptible to the TF ripple loss than the reference H-mode type profiles. To avoid excessive TF ripple loss, the magnitude of the TF ripple has been reduced from original 1.8% to 0.7% by implementation of ferromagnetic inserts in the design of Vacuum Vessel. As can be seen from Table I, the energetic particle ripple loss is small and local heat loads are below the maximum acceptable level of 0.5 MW/m^2 even at low plasma current.

TABLE I. RIPPLE LOSS OF ALPHA-PARTICLES AND NB DEUTERIUM IONS (1 MeV)

Plasma scenario	**Fusion alpha-particles**		**NB ions**	
	Ignited, 21 MA	Steady State, 12 MA	Ignited, 21 MA	Steady State, 12 MA
Total heating by energetic ions (MW)	313	253	40	40
Energy loss fraction (%)	<0.5	0.8–1.5 (2)	0.4 (3)	3.2 (3)
Peak heat load on wall(1) (MW/m^2)	< 0.05	0.1–0.45 (2)	$3.5\ 10^{-3}$ (3)	0.15 (3)

1) The heat load is calculated on the axisymmetric wall. 2) Lower and upper limits correspond to downward (reference) and upward toroidal drift directions, 3) Co injection

Analysis of ripple loss has been carried out also for the diagnostic neutral beam which will be injected almost perpendicularly, through a horizontal port. The TF ripple loss was found to be large but (because of low beam power) does not lead to any significant heat loads in the case of reference field direction (downward toroidal ion drift). However, at the opposite magnetic field direction, almost all particles end up trapped in one ripple well near the beam entrance. Local peak heat load on the wall is as high as 5 MW/m^2. This precludes use of the diagnostic beam at this field direction.

In conclusion, the TF ripple loss of energetic particles in ITER is well quantified and TF ripple was adjusted to eliminate excessive loss and local heat loads.

3. COLLECTIVE INSTABILITIES

The various Alfven modes (TAE and others) still attract the major attention as a most dangerous candidate among alpha-particle induced instabilities in ITER. Impressive progress in theoretical and experimental studies in this area has been reported recently at the last IAEA Technical Committee Meeting on Alpha-particles in Fusion Research [3]. Various modes have been observed on almost all major experimental tokamaks and were identified theoretically with a high degree of details. A comprehensive review of the ITER relevant results can be found in [1]. The modes are well described by the linear theory and so far no significant effects of TAE modes on alpha-particle confinement in DT experiments have been observed in TFTR and JET [4,5]. However, it is well recognized by now that the mode structure in ITER will be different from the present experiments. On the contrary, to the present experiments where a few low mode numbers such as n=1,2,3 are usually observed, one can expect in ITER a large number of high n modes, n>10, if the alpha-particle pressure will exceed a certain critical value. While the experimental study of these regimes shall wait for ITER operation, an evaluation of the expected loss in ITER is a challenge to the nonlinear theory of these instabilities. Progress has been achieved in developing a nonlinear theory for the case of many discrete modes. The theory predicts a pulsation of the loss rather than a quasilinear type diffusion of energetic particles.

To answer the question whether the TAE instabilities can cause loss or only redistribution of alpha-particles in ITER, the TAE stability analysis has been carried out for a range of alpha-particle pressure profiles described by the formula $p_a(r) = fp_{a,\ original}(r) + (1-f)(1 - r^2)$. Parameter f=1 corresponds to the reference peaked profile, and f=0 corresponds to quasilinearly smoothened parabolic profile. The results presented in Fig. 1 were obtained by means of the numerical code based on the gyrofluid model which includes continuum/radiative damping, and ion/electron Landau damping. The stability analysis was carried out for two representative mode numbers, n=20 and n=30. A range of alpha pressure profiles are considered, starting with that determined by transport modeling and gradually broadening this out to a parabolic profile: $p_a(r)$ µ $1 - (r/a)^2$. It was found that for these two mode numbers, the broader profiles are more stable (i.e., have higher TAE thresholds). These results suggest that alpha-particle redistribution may be a viable quasilinear saturation mechanism and the effect of the TAE will be redistribution of the heating profile but not a significant loss.

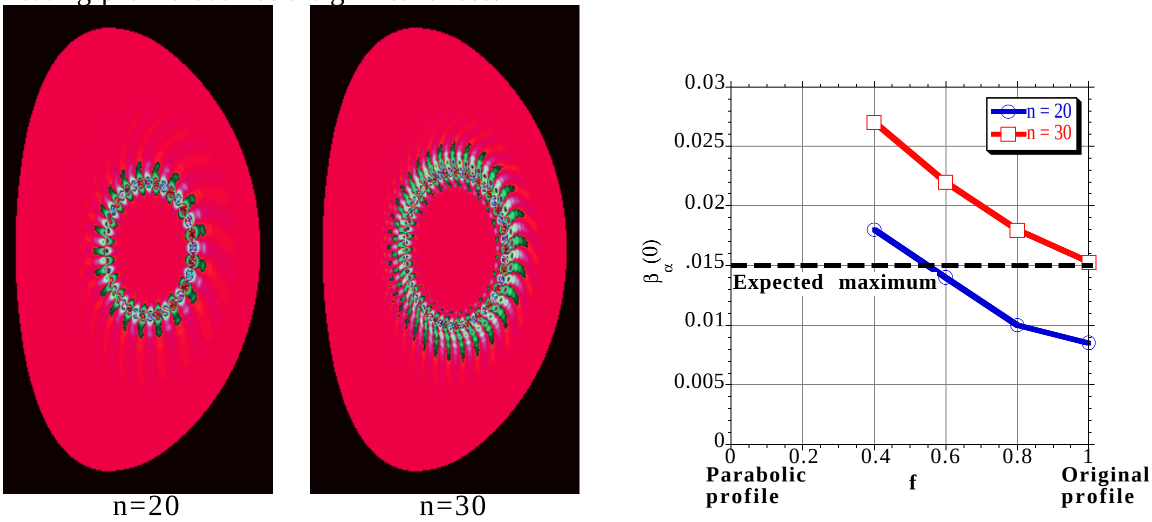


FIG. 1. 2D mode structures and threshold value of central alpha-particle beta as a function of the alpha-particle profile steepness, $p_a(r) = fp_{a,\,original}(r) + (1\text{-}f)(1 - r^2)$.

The above results of the linear analysis are in agreement with large-scale numerical simulation of energetic-particle-driven instabilities that have been carried out for both TAE modes and fishbone oscillations in ITER-like plasmas. A perturbative nonlinear simulation of the alpha transport due to 10 core-localized TAE modes showed only a small amount of anomalous diffusion, with no alpha losses. The small alpha orbit width, combined with the core-localized nature of the modes, ensures that consequences of the instability are benign.

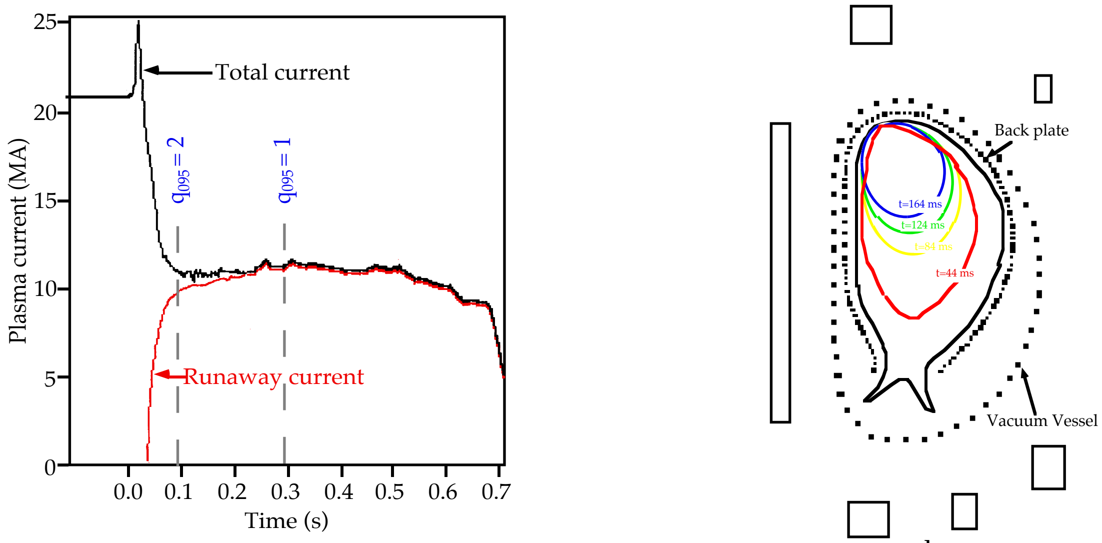
We can conclude that significant progress in understanding and quantifying the alpha-particle driven Alfven instabilities in ITER has been achieved since the previous IAEA conference. The first attempts to simulate effect of these instabilities on alpha-particle confinement in ITER indicate that one can expect a benign effect rather than a violent loss of the alpha-particles.

4. RUNAWAY ELECTRONS

In ITER, the high electric fields produced in either disruptions or the proposed use of impurity pellet injection to effect a fast fusion power and current shutdown are predicted to produce substantial conversion of plasma current to runaway electron current. The dominant mechanism for runaway production in large multi-MA reactor tokamaks is expected to be avalanching of runaway electrons owing to large-angle (knock-on) Coulomb collisions that produce secondary electrons which also run away [1]. This phenomena can result in conversion of a major fraction (up to about 75%) of the decaying plasma current to runaway current.

To assess the total energy transformed to the runaway electrons and to identify a most probable energy deposition pattern on the first wall, we have carried out numerical simulation of plasma disruption in ITER. 1.5D transport code DINA has been modified to include in the transport equations the analytical model for runaway electrons [6]. Recent and a more detailed Monte-Carlo analysis of runaway electron kinetic has proven the validity of the above model in a wide range of the plasma parameters. The code allows following 2D evolution of plasma equilibrium within ITER conducting structures and, therefore, evaluate plasma wall contact position during vertical plasma displacement event (VDE) which follows thermal quench of plasma disruptions in ITER. The calculations include the model for halo current which was tested and validated in experiments on DIII-D [7].

A typical time trace of the plasma current is shown in Fig. 2. The initial spike in the plasma current is related to the plasma current profile flattening at the end of the thermal quench which was included in the model. Owing to impurity radiation, a low plasma temperature forces plasma current to decay and hence generates a high loop Voltage which in turn produces runaway electrons. Simultaneously, plasma moves vertically and forms a limiter configuration with a plasma wall contact point near the upper left corner of the vessel. As soon as all plasma current is overtaken by the runaway electrons, the current quench and VDE slows down significantly, but the plasma continues to move toward the wall until all runaway electrons are scrapped off and lost at the wall.



a b

FIG 2. a) Typical plasma current time trace predicted for ITER disruption. Dashed lines mark the times when q at the edge passes 2 and 1 values. b) Sequence of plasma equilibriums during VDE.

Modeling has been done for a variety of post disruption plasma parameters and different pre disruption plasma currents and has allowed us to draw the following conclusions:

1) VDE with fast current quench and hence runaway formation has predominantly the upward direction in ITER and the deposition of runaway is localized near “11 o’clock” position on the first wall;

2) The total energy transformed to the runaway electrons is as high as 150-200 MJ but most of the energy is transformed when the plasma cross section shrinks sufficiently and safety factor at the edge, q, drops below 1 and when violent plasma instabilities and fast loss of high energy electrons are expected. At q=1, the energy which was transformed to the electrons is much smaller than the maximum calculated values.

The simulations have allowed us to reduce specification for the total energy deposited on the wall in the form of runaways from 300 MJ (as was expected earlier) to 50-100 MJ. Even at the reduced total energy, the runaway electrons remain the serious threat to the durability of the first wall and mitigation techniques are being considered in ITER. The runaway electrons can be avoided by an increase of the plasma density. Schemes based on deuterium injection, as in the form of multiple pellets and as in the form of cryogenic jets, have been analyzed [8].

References

[1] ITER Physics Basis Document, Section 5, 1998, Submitted to Nucl. Fusion.
[2] CHENG, C.Z., et. al., “Fusion Energy” 1996 (16th Conference Proc.), IAEA, Vienna, V2, p.953.
[3] Contributed Papers, Fifth IAEA Technical Committee Meeting “Alpha-particles in Fusion Research”, JET, 1997.
[4] TAYLOR, G., et.al., Phys. Rev. Letters, 76 (1996) 2722.
[5] THOMAS, P.R., et.al., Phys. Rev. Letters, 80 (1998) 5548.
[6] ROSENBLUTH, M.N., PUTVINSKI, S., Nuclear Fusion, **37** (1997) 1355-1361.
[7] DINA validation on DIII-D.
[8] ROSENBLUTH, M.N., PUTVINSKI, S., PARKS, P.B., Nuclear Fusion **37** (1997) 955-965.