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Alpha-Physics and Measurement Requirements for ITER

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Abstract

This paper reviews alpha particle physics issues in ITER and their implications for alpha particle measurements. A comparison is made between alpha heating in ITER and NBI and ICRH heating systems in present tokamaks, and alpha particle issues in ITER are discussed in three physics areas: “single particle” alpha effects, “collective” alpha effects, and RF interactions with alpha particles.

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1. INTRODUCTION

Sustained ignition in ITER requires about 300 MW of alpha particle heating power. Since the alpha particle creation rate will depend strongly on the plasma conditions, this plasma heating will be more difficult to predict and control than existing heating systems such as NBI and ICRH. In addition, alpha particle heating and loss will also depend upon the transport of alphas during their relatively long thermalization time (≈1 sec), during which they may be affected by MHD activity and other non-axisymmetries in the ignited plasma.

This paper reviews alpha particle physics issues in ITER and their implications for alpha particle measurements. First, a comparison is made between alpha heating in ITER and NBI and ICRH heating systems in present tokamaks. Then the alpha particle issues in ITER will be discussed in three physics areas: "single particle" alpha effects, "collective" alpha effects, and RF interactions with alpha particles. Note that this paper will not cover the important subject of alpha particle ash, which is more related to thermal plasma transport.

2. ALPHA HEATING IN ITER vs. PRESENT FAST ION HEATING SYSTEMS

The fast ions used for NBI and ICRH minority heating in present experiments have not been diagnosed in great detail, since they usually heat the plasma without problems[1]. It is interesting to compare the parameters for these fast ion heating systems with those expected for alpha particle parameters in ITER to help identify potential problem areas and appropriate alpha particle measurement requirements. This comparison is shown in Table 1.

The heating power density of alphas in ITER will actually be *lower* than that for present tokamak heating systems, since the plasma energy density will be only slightly larger, but the plasma energy loss rate will be lower. Thus the relative alpha particle density in ITER is typically an order of magnitude lower than the fast ion density in NBI[2] and ICRH[3] heated tokamaks, also in part due to the larger alpha particle energy. The alpha particle beta in ITER is also expected to be *smaller* than the fast ion betas normally obtained with present auxiliary-heated large tokamaks[2,3], but somewhat larger than presently obtained for alphas in the TFTR DT experiment[4].

The similarity of the fast ion orbit parameter ∂/a and the fast ion pressure gradient $R\nabla\beta_f$ between NBI in TFTR and alphas in ITER suggests that the single-particle and collective fast ion physics should also be similar. However, a crucial difference is that the fast ion speed relative to the Alfven speed V_{fo}/V_{Alf} is much larger for alphas in ITER than for NBI in TFTR, leading to the possibility of Alfven instabilities in ITER[5-7]. Although super-Alfvenic fast ions were simulated by ICRH minority heating in JET, these ions were mainly trapped particles and so were potentially different from the nearly isotropic alpha distributions expected in ITER.

If the single-particle and collective alpha physics in ITER were similar to NBI and ICRH ions in existing tokamaks, then the alpha particle *heating* in ITER should be predictable from the DT neutron source profile measurements. However, alpha particle *loss* to the first wall might still be a problem due to ITER's 1000 sec pulse length, which requires that every part of the first wall be actively cooled to avoid impurity influx or wall damage. For example, even a few-percent alpha loss fraction due to TF ripple loss is a concern for ITER[5,8], whereas a similar level of fast ion loss in present experiments is generally undetectable. Hints of this problem were found in the ≤60 sec long pulses in Tore-Supra, in which localized wall heating due to fast ion loss was observed[9].

The conclusion from this comparison is that all the relevant physics parameters are *not* similar between alphas in ITER and fast ions in present experiments, so diagnostics to evaluate the alphaparticleheating and loss must be considered for ITER.

3. “SINGLE PARTICLE” ALPHA INTERACTIONS

Individual alpha particles can be affected by many types of background plasma fluctuations and non-axisymmetries. A list of potential single-particle alpha effects in ITER is shown in Table 2. The timescales of these effects range from steady-state TF ripple loss to sub-millisecond bursts of alpha loss associated with sawtooth crashes or disruptions. *All* of these effects have been observed for fusion products in present tokamaks[1], and all of these have caused some measurable DD or DT fusion product loss in TFTR[10,11].

The best understood of these alpha interactions is TF ripple loss, which was calculated using Monte Carlo codes specifically for ITER[5]. The conclusion from this study was that the peak alpha heat loads there were in the range ≈0.1-1 MW/m^2, depending on the plasma current and the direction of the toroidal field (for 24 coils). This is comparable to the average heat flux expected on the ITER first wall from plasma radiation (≤0.5 MW/m^2).

The most important measurement of alpha ripple loss in ITER would be a spatially-resolved surface temperature measurement of the first wall, since this information could be used for real-time operational control as well as for physics purposes. A good example of such a measurement is the IRTV image of the JT-60U wall shown in Fig. 1. The localized heating of ≈50ºC between the TF coils is consistent with the expected beam ion ripple loss, as calculated by a Monte Carlo guiding center code[12]. However, the heat deposition pattern is also influenced by a slight misalignment in the tiles, which causes the leading edges to become much hotter than the average wall temperature in the ripple loss region. This type of localized heating is likely to occur in ITER due to the difficulty of aligning the wall tiles and limiters over such a large and complicated vacuum vessel.

Also potentially important for ITER is the effect of sawtooth crashes on the alpha particle heating profile, and also on the alpha loss to the first wall. Evidence for a weak radial redistribution of alpha-like 1 MeV tritons during a sawtooth crash in JET is illustrated in Fig. 2[13]. Sawtooth-induced radial redistribution of H-minority tail ions has also been measured in JET using impurity charge exchange[14], and with alphas in TFTR using the pellet charge exchange (PCX)[15] and alpha-CHERS[16] diagnostics. Direct measurements of alpha particle loss during sawteeth in TFTR show a very fast (≈0.1 msec) but small (<<1% loss) burst of alpha particle loss coincident with a sawtooth crash.

The effect of sawtooth crashes on the confined alpha population in the core of ITER will be difficult to measure directly, since there is no “burnup” of the alpha particles analogous to that for the 1 MeV tritons used for the measurement of Fig. 2, and neutralizing atoms for charge exchange will not normally be present at r/a<0.5. In principle, the sawtooth effects can be measured using charge exchange from neutral beams or pellets in the plasma periphery at r/a≥0.5[15]. Ideally, confined alpha diagnostics could help clarify the physics of the sawtooth-alpha interaction through measurements of the energy and pitch angle dependence of the alpha particle redistribution during a crash. However, even if these measurements were available, the interpretation of the radial alpha transport will also depend on the physics of the sawtooth crash itself, which is not yet understood. Most likely, the effect of sawtooth crashes on confined alphas will be measured indirectly in ITER through the plasma temperature profiles, which will respond slowly to a redistribution of the alpha particle heating. It is reassuring that ITER will probably maintain ignition even if most of the alpha particles were lost from inside the sawtooth inversion radius[8], since the timescale for alpha particle re-creation (≈ 1 sec) is shorter than the energy confinement time (≈ 4 sec).

The effect of sawtooth crashes on alpha particle loss in ITER should be measurable using a wide-angle IRTV camera. For a clearer identification of the loss mechanism, this should by supplemented by discrete IR channels viewing the first wall or limiters with sub-millisecond time resolution, or by low-mass “foil” bolometers such as used at DIII-D[17]. The sawtooth-induced alpha loss might consist of two components; namely, a prompt loss to the wall on the timescale of the sawtooth crash (<1 msec), and a slower diffusive loss of alphas which were redistributed into the TF ripple loss region (≈10-100 msec).

Most of the other single-particle alpha interactions in Table 2 are some form of coherent MHD activity. These modes are usually present in high-powered tokamaks, but normally do not cause a significant redistribution or loss or fast heating ions. However, large MHD levels in TFTR have caused up to a ≈10% fusion product loss, often modulated with this activity over the range 0-20 kHz[10]. Modeling of this type of MHD-induced alpha loss with a Monte Carlo guiding center code predicted that (for a given low-n mode) the alpha loss decreased about an order-of-magnitude as the orbit shift parameter ∂/a decreased from the TFTR value to the ITER value, suggesting that the fractional alpha loss in ITER should be much lower in ITER than in TFTR.

Measurements of the influence of MHD activity on confined alphas in ITER will be difficult, particularly since this activity is usually not steady or reproducible. If such measurements were available, it would be interesting to correlate the spatial location and mode number of the fluctuations with the radial redistribution of alphas vs. energy and pitch angle. An indirect analysis of the MHD-induced alpha transport effects from the temperature profile measurements will be more problematic than for sawtooth crashes, since the MHD activity will simultaneously affect the thermal plasma transport. Measurements of alpha loss should be made with enough time resolution to see the bursts of alpha loss correlated with ELMs, such as seen during limiter H-modes in TFTR DT discharges[18].

The most serious single-particle alpha losses in TFTR occurred during major disruptions, as illustrated in Fig. 3, when over 10% of the confined alphas were lost within a few milliseconds[11]. This alpha loss was apparently concentrated 90º below the midplane in the ion ∇B drift direction, and so might cause damage at the entrance to the ITER divertor dome. The mechanism of this loss is probably similar to that for coherent MHD modes, but so far there is no modeling to predict its size or location in ITER. It is interesting that any alphas which are not immediately lost during a major disruption will probably be thermalized before the end of the current quench, since the alpha thermalization time will be reduced proportionally to $T_e^{3/2}$ during the thermal quench, i.e. probably to <1 msec.

Measurements of alpha loss during disruptions in ITER will be extremely difficult, since IRTV measurements will be ambiguous due to simultaneous plasma loss and radiation. Energy resolving alpha loss detectors could discriminate alpha loss from thermal plasma loss, but these detectors may not survive the heat loads during an ITER disruption.

4. COLLECTIVE ALPHA PARTICLE INTERACTIONS

A large amount of experimental work has been done on collective fast-ion instabilities[1], and some of the associated theory has been applied to predict alpha particle stability in ITER[5-7]. In general, collective alpha instabilities may have a more serious effect on alpha particle heating and loss than the single-particle effects, but they are less likely occur. Measurements of the *fluctuations* due to these instabilities will be as important as the direct measurements of the alpha particles themselves.

A list of potential collective alpha effects in ITER is shown in Table 3. *All* of these instabilities have been observed on existing tokamaks using fast ions from NBI or ICRH tails. However, so far *none* of these instabilities has been driven by DT alphas, except for the rather benign ICE (ion cyclotron emission) such as seen at JET and TFTR.

The TAE mode (toroidicity-induced Alfven eigenmode) has caused up to an ≈70% loss of injected NBI ions in TFTR and DIII-D, but only when the toroidal field was lowered to make the NBI ions super-Alfvenic. An examples of TAE mode spectrum is shown in Fig. 4, taken during NBI heating in DIII-D[19]. There are multiple TAE modes at a frequency $f=2\pi V_A/2qR$, which are separated by toroidal rotation. In ITER the most unstable alpha-driven TAE modes are so far expected in the range n≈5-50, with multiple m-modes for each n, so there may be very many such TAE mode peaks in ITER (5-7).

Measurement of TAE mode fluctuations in ITER should probably be done using external magnetic loops and internal density fluctuation measurements, as for existing NBI and ICRH experiments. The TAE spectrum in ITER should be localized in the frequency range f≈100 kHz at the radial location of the highest alpha particle pressure gradient near r/a≈0.5. The level of the internal electron density and external magnetic fluctuations would probably be similar to that in present NBI and ICRH TAE simulation experiments, i.e. $\tilde{n}/n \approx 0.1$-1% and $\partial B/B_T \approx 10^{-6}$-$10^{-5}$[20].

Confined alpha particle measurements for TAE studies will be limited by the difficulty of the diagnostic techniques. Present experiments diagnose the fast ion content mainly by changes in the neutron rate (for NBI) or by magnetic measurements of the fast ion stored energy, neither of which would be useful for this purpose in ITER. Ideally, it would be desirable to have a confined alpha diagnostic which could focus on the specific range of alpha particle pitch angles and energies which are expected to interact with TAEs in ITER, e.g. alphas with a parallel speed equal to the Alfven speed. Ideally, such a diagnostic would be able measure the alpha profile changes on the timescale of the individual “bursts” of TAE mode activity, which are typically ≈10 msec apart in present NBI experiments.

Measurements of TAE-induced alpha loss should attempt to distinguishing three different processes: radial diffusion of passing alphas to the outer or inner midplane regions of the first wall, loss across the passing-trapped boundary over a wider range of poloidal angles in the ion-∇B drift direction, and TF ripple trapping and loss of alphas between the TF coils. The last of these was responsible for making a hole in the TFTR vacuum vessel during ICRH hydrogen minority tail-driven TAE modes[21]. Wall and limiter temperature measurements using a wide-angle IRTV would be useful for operational purposes, and ≈10 msec time response would be useful to correlate these temperature rises with TAE fluctuation measurements.

Measurement requirements for the alpha-driven KBM (kinetic ballooning mode), BAE/EAE (beta- and ellipiticity-induced Alfven eigenmodes) and the alpha-driven fishbone modes are generally similar to those for TAE modes. The fluctuation diagnostics should be designed to cover the whole range up to ≈300 kHz (the toroidal transit frequency of 3.5 MeV alphas). Since alpha particle diagnostics will probably not respond on the timescale of the mode frequency, the specific diagnostic requirements for various modes would differ only in their focus in pitch angle, energy, and r/a, and first-wall location. Theoretical predictions of these characteristics have not yet been made for alphas in ITER.

The collective alpha effect on sawteeth is unique in having a stabilizing influence. However, it may be difficult to identify this effect in ITER, since there will be no alpha-free comparison discharges. The AFM (Alfven frequency mode) was recently identified at TFTR as a magnetic fluctuation at the edge Alfven frequency occurring with or without DT alpha particles[22]. A measurement of the edge electron density would be useful in ITER to help distinguish the AFM mode from a TAE mode. ICE is apparently due an unstable distribution function of fast ions near the outer midplane, but will probably be benign for alphas in ITER. Ion cyclotron absorption (ICA) measurements may be useful as an alpha particle diagnostic in ITER [23].

5. RF INTERACTIONS WITH ALPHA PARTICLES

There have been several recent proposals for the use of various RF waves to *control* alpha particles in order to improve the performance of a tokamak reactor. If these schemes are to be tested in ITER, then measurements need to be made to monitor this control.

One idea is to “channel” the alpha particle’s energy directly into the fuel ions, rather than using the collisional ion heating from the electrons. In principle, this can be done using an externally launched IBW (ion Bernstein wave) resonant with the alphas on a spatial scale of the alpha gyroradius and a timescale of the alpha gyroperiod[24]. This interaction could be studied in ITER with a spatially-resolved IBW wave detector capable of measuring density fluctuations of $\tilde{n}/n \approx 1\%$ on these time and space scales, and by confined alpha diagnostics with good spatial and energy resolution. Evidence for such an interaction has come from IBW experiments in TFTR, in which an increase in the fast ion loss and energy was measured by the lost alpha scintillator detectors[25].

Another idea is to launch low frequency waves which can resonate with the transit frequency of the alphas in order to remove epithermal alpha ash or control the burn. Calculations have been done which demonstrate that alphas can be selectively and efficiently transported using swept-frequency waves of a few hundred kilohertz[26,27], but no experimental evidence for this interaction exists at present. If this idea is to be tested in ITER, measurements of the wave fields and energy-dependent radial profiles of the confined alphas would be useful to monitor this interaction.

Even if these novel alpha control schemes are not tested in ITER, there will be many possible interactions between alphas and the normal RF heating and/or current drive systems. For example, it is well known that some fraction of ICRF minority heating power will be absorbed by the fast alphas, and it has been demonstrated in TFTR that alphas are lost during ICRH through RF-induced transport across the passing-trapped boundary[28]. Spatially asymmetrical ICRH can also be used to cause radial transport of fast or epithermal alphas[29], and alphas can also resonate strongly with lower hybrid waves. Therefore measurements of confined and lost alphas should be done during any RF heating of ITER to insure that the alphas stay well confined.

6. SUMMARY OF ALPHA PARTICLE MEASUREMENT REQUIREMENTS

These alpha physics issues suggest the measurement requirements summarized in Table 4. These are prioritized in terms of their operational value rather than their intrinsic physics interest. For example, the most serious alpha particle problem in ITER is the potential impurity influx or damage due to overheating of the first wall by alpha particle loss. Therefore the highest diagnostic priority is for measurements of the first wall temperature, which could alert the operators to an impending problem. The next highest priority would be measurements of the internal plasma fluctuations which might become a source of this problem. Perhaps of a greater physics interest would be direct measurements of the confined and lost alpha particle populations, e.g. their spatial, energy, and pitch angle distributions.

Fortunately, the highest priorities on this list generally have the lowest diagnostic difficulties. Surface temperature measurement such as shown in Fig. 1 could be made with imaging mirrors and conventional IRTV detectors. High frequency fluctuation diagnostics can be made rugged and radiation resistant, and will be useful for other areas of ITER physics. The confined and escaping alpha particle diagnostics may be quite difficult to implement on ITER, but they are certainly worth pursuing for the sake their unique contributions to the understanding of burning plasmas.

Finally, it is important to recognize that these measurements in themselves will not guarantee satisfactory control over the ≈300 MW of alpha particle heating in ITER. Practical and reliable methods must be developed to use this information in feedback control schemes, for example, to abate an alpha-induced hot spot on the wall by moving it to another place, or to quench the ignition of a plasma which is becoming strongly unstable to TAE modes. In this regard, any potential alpha particle control scheme may have substantial value for ITER.

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Table 1: Fast Ion Parameters for Various Heating Systems

Parameter	NBI*	ICRH‡	Alphas* (TFTR)	Alphas (ITER)
$P_f(0)$ [MW/m^3]	3	1-3	0.3	0.3
∂/a (orbit shift)#	0.05	0.3	0.3	0.05
$n_f(0)/n_e(0)$ %	13	1-10	0.3	0.3
$\int_f(0)$ %	0.9	1-3	0.26	0.7
$<\int_f>$ %	0.4	0.5	0.03	0.2
$R\nabla\beta_f$	0.04	≈0.1	0.02	0.06
$V_{fo}/V_{Alf}(0)$	0.35	≈1-2	1.6	1.9

* TFTR with 40 MW of 100 keV NBI in a 5 T. DT plasma (#76770)[2]
‡ JET with ≈15 MW ICRH He^3 minority heating with $<E_f>\approx 1$ MeV[3]
\# ∂ (orbit shift from magnetic flux surface) ≈ $q(R/r)^{1/2}\,\rho_{tor} \approx 5\,\rho_{tor}$ @ q≈2

Table 2 - Potential “Single-Particle” Alpha Interactions in ITER

Interaction	Frequency (kHz)	Toroidal mode #	Loss in TFTR
TF ripple	0	20	10%
locked modes	0	1 (?)	1%
tearing modes	0.1	1-3	1-10%
ELMs	1	1-3	1%
fishbones	10	1	1%
sawtooth crash	10^2	1 (?)	<<1%
disruptions	10	1 (?)	>10%

Table 3 - Potential “Collective” Alpha Particle Effects in ITER

Instability	Freq.(kHz)	n-mode #	Location (r/a)	Some Observations
sawtooth	0	1	≈0.5	JET, TFTR, JT-60
fishbones	10	1	≈0.5	PDX, JET
KBM	50 (?)	10-20	≈0.5	TFTR
BAE/EAE	50 (?)	10-50	≈0.5	DIII-D, JET
TAE mode	100	10-50	≈0.5	TFTR, DIII-D, JT-60U
AFM	100	0	≈1	TFTR
ICE	105	-	≈1	JET, TFTR, DIII-D

Table 4 - Summary of Alpha Physics Measurements Needed in ITER

Physics area	Spatial resolution	Time resolution	Possible Techniques
Alpha heat loss	≈3-30 cm	≈10-100 msec	IRTV, thermocouples
Alpha instabilities	î(r/a) ≈ 0.1	≤300 kHz	B loops, reflectometer
Confined alphas	î(r/a) ≈ 0.1	≈0.1 Hz	CX, EM wave scattering
Lost alphas	a few points	≈100 kHz	Faraday cups, foils

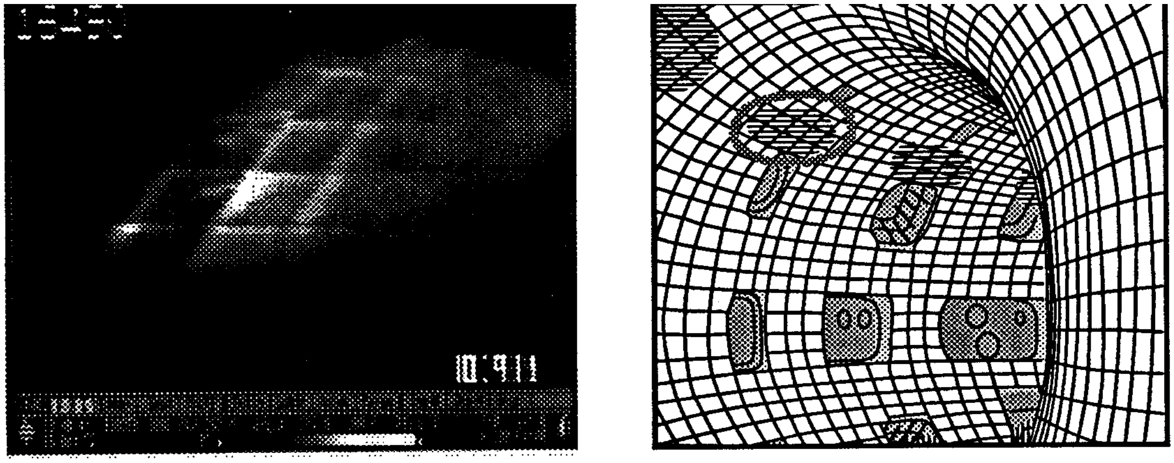

Fig. 1 - At the left is an IRTV image of the surface temperature of the JT-60U wall showing TF ripple loss of beam ions during perpendicular NBI. These hot spots occur just above the outer midplane between the TF coils (right). The heat flux in this case is ≈1 MW/m^2, similar to that expected for alpha ripple loss in ITER.

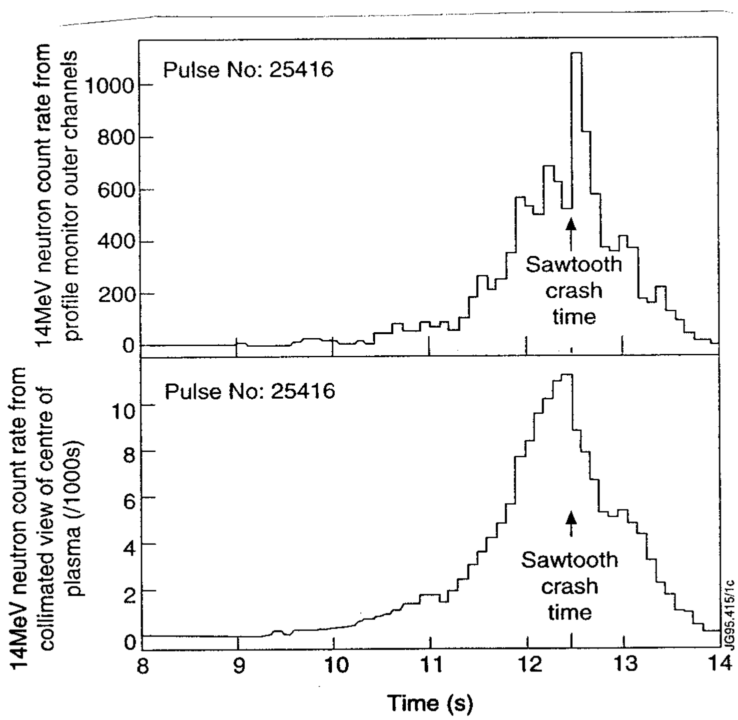

Fig. 2 - Measurements of triton burnup in JET showing a weak redistribution of confined tritons during a sawtooth crash. The top trace shows an increase in tritons near the plasma edge, and the bottom trace shows an decrease in tritons nearer the plasma center.

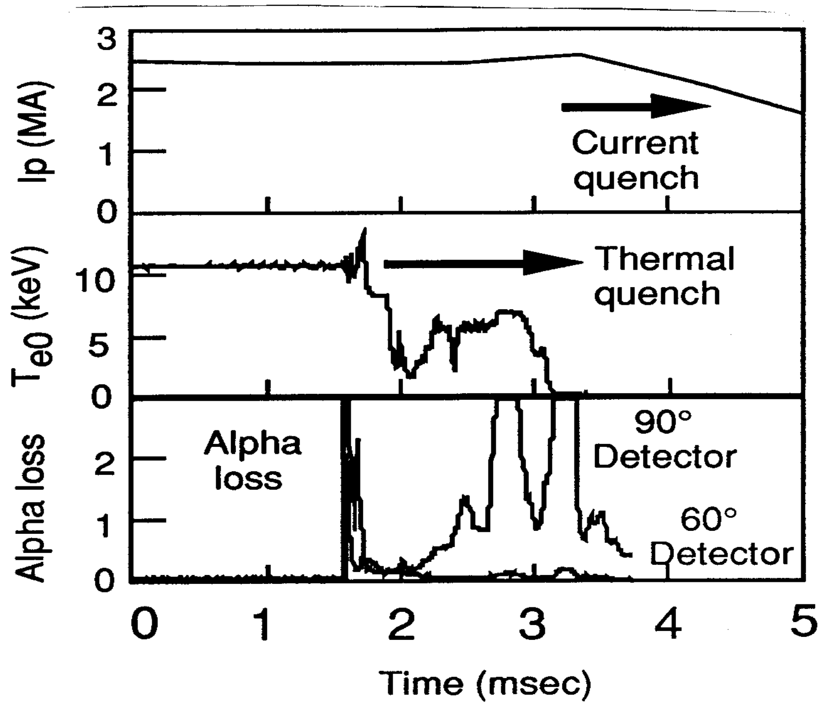

Fig. 3 - **Measurement of DT alpha particle loss during a major disruption in TFTR. The disruption at 1.5 msec causes a rapid loss of ≥10% of the confined alphas before the current quench, mostly to the 90º detector. The loss at ≤1.5 msec is the normal first-orbit loss level.**

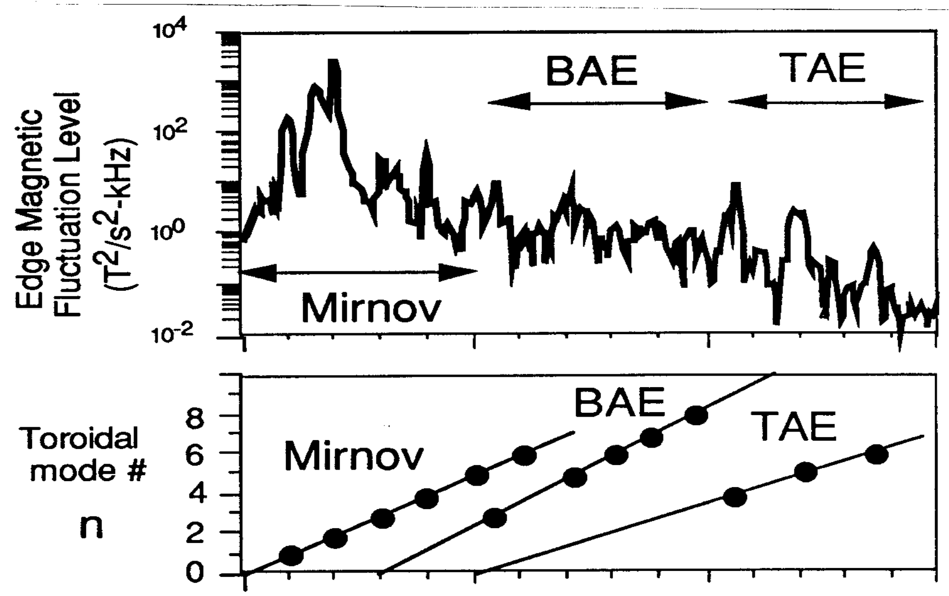

Fig. 4 - **Edge magnetic fluctuation spectrum showing TAE modes driven by NBI in DIII-D. The TAE (and BAE) have mode numbers in the range n≈3-8. The TAE modes in ITER are expected to be unstable over the range n=5-50, implying a more complex frequency spectrum in ITER (figure courtesy of W. Heidbrink).**