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FAST ION DRIVEN INSTABILITY GENERATED BY ALPHA PARTICLES IN FUTURE BURNING PLASMA EXPERIMENTS

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Understanding the basic physics of plasmas dominated by strong self-heating is the key goal of ITER, FDF, and other proposed burning plasma experiments and represents a necessary step in the realization of fusion as an attractive energy source. In D-T plasmas, self-heating is provided by the slowing down of 3.5 MeV alphas generated through D-T fusion reactions [1]. With respect to alpha particle physics, there are several outstanding issues; at the forefront is the susceptibility of future next-step devices to fast ion driven instabilities such as Alfvén eigenmodes. These instabilities may impact the success of ITER and other burning plasma experiments since they can resonate with fast ions and be driven unstable, possibly causing enhanced transport of the energetic particles necessary for heating [2,3].

Present tokamak experiments with Alfvénic instabilities show flattening of neutral beam fast ion profiles and loss of injected beam ions during periods of strong Alfvénic activity [3,4] (Fig. 1).

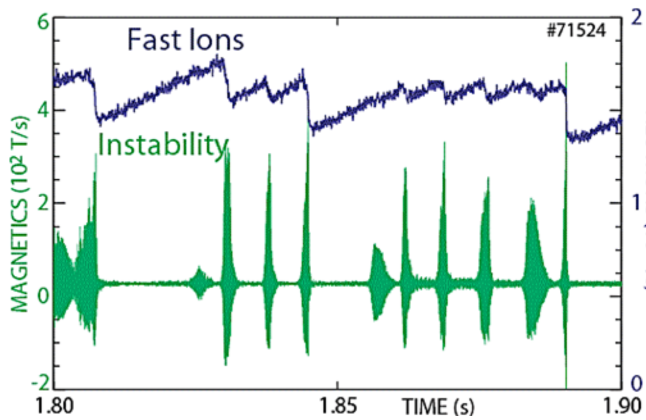

Fig. 1. DIII-D discharge with bursting TAE instability (green) showing drops in neutron emission accompanying each burst (purple). The neutron emission is primarily beam-plasma and serves as a proxy for detection of the fast ion population [4].

This type of redistribution or loss of fusion born alpha particles in a burning plasma experiment could reduce the performance of these devices and potentially damage the first wall. Currently, however, no existing code is able to reproduce the observed levels of fast ion transport in the presence of Alfvenic instabilities [5].

Role of Present Day Devices, ITER, and Possible Gaps to DEMO

There are several key dimensionless parameters relevant to energetic particle physics studies that differentiate ITER and burning plasmas in general from present day tokamaks (PD) and the planned superconducting magnet tokamaks under construction or development. They are the ratio of the fast ion velocity to the Alfvén velocity, which is V_f/V_A~2 in ITER but less than or equal to 1 in most current experiments, much higher plasma minor radius to Larmor radius ratio a/ρ_f ~30-40 in ITER (~10-20 in PD), and the degree of anisotropy of the equilibrium distribution functions; almost isotropic fusion alphas in ITER vs. strongly anisotropic NBI and ICRH ions in PD. These intrinsic differences mean ***only partial tests of fast ion instability and transport models will be possible in present day experiments, and thorough tests will rely on power-plant scale experiments like ITER and the recently proposed Fusion Development Facility (FDF)*** **[6,7].**

Because tests of these models will come from rather few devices, it is important to understand the regimes obtainable in each device, identify any gaps, and maximize the region of parameter space tested for extrapolation to a demonstration reactor. To put the alpha physics of ITER, FDF and an

ARIES [8] type device (ARIES will be used as an approximation to DEMO / a demonstration reactor) in context, Table 1 shows several of the relevant parameters.

Table 1
Main Plasma Parameters of Various Burning Plasma Experiments.
Aries Parameters Obtained from Spreadsheet Analysis [9].

Tokamak	R (m)	a (m)	B_0 (T)	n_{e0} (10^{14} cm^{-3})	T_{i0} (keV)	$\beta_{\alpha 0}$ (%)	β_{DT0} (%)	V_α/V_{A0}	V_{A0} (10^9 cm/s)	$a/\rho_{\alpha 0}$
ITER	6.2	2	5.3	1	19.3	0.7	2.8	1.8	0.72	39.1
FDF	2.49	0.71	4.4-6	2-3	14-20	0.8-1.5	5.8-6.7	3.0-2.7	0.43-0.48	11-15
ARIES-AT	5.2	1.3	5.86	2.7	30	~4	9.5	2.6	0.50	28
ARIES-RS	5.5	1.38	8	2.7	30	1.3	5.1	1.9	0.67	41

In terms of Alfvénic instabilities, there are several noteworthy points from Table 1. Both FDF and ARIES have larger alpha particle (β_α) and thermal ion beta (β_{DT}) than ITER where β is the ratio of plasma pressure to magnetic field pressure. FDF also has the largest ratio of alpha speed to Alfvén speed (V_α/V_{A0}). All of these parameters are fundamental to determining Alfvén eigenmode stability.

In terms of the potential impact these instabilities may have, FDF has the lowest ratio of minor radius to alpha particle gyroradius ($a/\rho_{\alpha 0}$) for the proposed burning plasma experiments inTable 1. Present experiments show that as $a/\rho_{\alpha 0}$ is decreased, the effects of Alfvénic instabilities tend to move from a regime of fast ion redistribution to fast ion loss [4,10], thus making this an important dependence to investigate fully in a plasma with large alpha particle pressure, particularly since AT based DEMO type devices may have smaller $a/\rho_{\alpha 0}$ than ITER [9]. As mentioned, many present day devices are able to access this large Larmor radius regime, however, not for isotropic fast ion populations in the anticipated resonance regime.

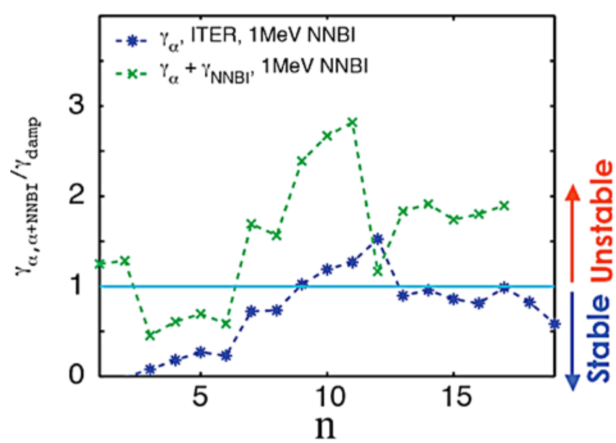

Fig. 2. NOVA-K calculated TAE stability in ITER (from Ref. [11]).

ITER will rely on 1 MeV super Alfvénic negative ion beams that analysis (Fig. 2), indicates will contribute net drive to Alfvén eigenmode instabilities [11]. FDF, on the other hand, is designed to achieve high fusion gain with 20-30 MW of shallowly penetrating (r/a > 0.7) low energy sub-Alfvénic neutral beam injection (NBI). Historically, TFTR and JET-DT experiments were in a regime with centrally peaked, sub-Alfvénic NBI populations in the core that provided a large net damping to AE instability [12]. It was only transiently after these populations decayed that alpha driven instabilities appeared. It is likely such a regime may be obtainable in ITER at reduced Q by turning off the NNBI, however, FDF baseline plasmas will be unique in that they will allow routine testing of AE stability in the presence of fast ion populations that are truly dominated by fusion generated alphas, i.e. no other central energetic ion sources. Such fast ion populations will be typical of plasmas with primarily EC auxiliary heating, which is an attractive option for a DEMO type device, and as such should be included in a comprehensive fast ion instability studies program.

Thrust

A key focus of the US fusion program must be the development of a set of generally applicable validated models that are capable of predicting fast ion driven instabilities as well as their nonlinear consequences in a burning plasma. To proceed with a demonstration reactor, these codes must be able to reliably predict the growth and saturation of alpha driven instabilities as well as what their overall impact will be on plasma performance. If instabilities occur, will an innocuous (possibly beneficial) level of redistribution result, or will violent bursting instability followed by rapid loss of fast ions happen? To accommodate modes from the lower Alfvenic gap such as the BAE [13] and the recently discovered BAAE [14] and CAE [15], the codes or suite of codes should include both shear and compressional polarization eigenmodes and function from acoustic to ion cyclotron range of frequencies. Despite the crucial importance of this goal no existing code is able to self-consistently predict the observed levels of fast ion transport seen in the presence of Alfvenic activity [5].

Further, integral to this effort, is the simultaneous development of diagnostics to observe both the instabilities and the impact they have on the fast ion population. While measurements of AE frequency and structure as well as fast ions are becoming increasingly common, extrapolation of these techniques to future devices is not always clear, particularly in the case of confined fast ions. Not only for model validation, but also for safety concerns, techniques to monitor these instabilities in burning plasma experiments must be developed and made routine.

Finally, to ensure the success of a demonstration reactor project, these tools must be developed and tested over a wide range plasma parameters including that dominated by alpha particle heating. While it is envisaged that ITER and present day tokamaks will be the primary source of alpha physics studies for model/diagnostic validation before a demonstration reactor is built, another device such as FDF would provide an excellent complement and help significantly for extrapolation to DEMO. FDF could provide much needed data on alpha driven instability in the large Larmor radius limit where the effects are expected to be most deleterious as well as in alpha dominated fast ion regimes characteristic of burning plasmas with primarily EC auxiliary heating. Further, should alpha driven instabilities prove to be a serious problem in reactor relevant conditions, more than one burning plasma device for developing, testing, and validating mitigation and measurement techniques over a wide range of parameter space will be essential.

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