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SOME OBSERVATIONS CONCERNING ALPHA INSTABILITIES
AND DRIVEN TOKAMAK REACTORS

T. Kenneth Fowler
Consultant to Lawrence Livermore National Laboratory

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SOME OBSERVATIONS CONCERNING ALPHA INSTABILITIES
AND DRIVEN TOKAMAK REACTORS*

T. K. Fowler†

Lawrence Livermore National Laboratory
University of California, Livermore, California 94551

ABSTRACT

While much research is needed to assess the reality and consequences of alpha-induced instabilities, crude transport estimates for the TAE mode indicate that as little as 10 percent of the alpha energy would be deposited in steady-state. Even so, CIT and the ITER technology phase would meet their minimal goals of $Q = 5$ if only the alphas themselves are ejected and not the fuel itself.

Higher gain up to $Q \sim 20$ may be possible in driven reactors of a different design, depending on the effects of aspect ratio and other geometric features on confinement. Very high gain still requires alpha testing.

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†Consultant to the Lawrence Livermore National Laboratory, Livermore, CA

1. TAE Transport Rates

As a crude estimate, we take an alpha diffusion coefficient $D_\alpha = \gamma_\alpha / k_\perp^2$ where γ_α is the TAE growth rate given by Fu and Van Dam¹,

$$\gamma_\alpha = \frac{9}{4} k_\parallel V_A \left\{ \beta_\alpha \left(\frac{\omega^* \alpha}{k_\parallel V_A} - \frac{1}{2} \right) F - \beta_e \frac{V_A}{V_e} \right\} . \quad (1)$$

Here

$$\omega^* \alpha = \frac{k_\perp T_\alpha}{Z_\alpha e \beta a_\alpha} \quad (2)$$

$$F(x) = x (1 + 2x^2 + 2x^4) e^{-x^2}$$

where $x = V_A / V_\alpha$, a_α is the alpha scale length and we let $k_\perp = m/a$. To get instability for a mode with poloidal wave number m and toroidal wave number n requires

$$q = \frac{2m+1}{2n} . \quad (3)$$

This is the condition that $k_\parallel = -k_\parallel$ in the so-called "gap" in the toroidal Alfvén dispersion diagram. Evaluating $k_\parallel$ in the gap using Eq. (3) gives

$$k_\parallel = \left(n - \frac{m}{q} \right) \frac{1}{R} \approx \frac{1}{2qR} . \quad (4)$$

Note that this gap value of $k_\parallel$ is independent of n . Then we get $\gamma_\alpha > 0$, indicating instability, for some $k_\perp$ over a wide range of parameters. The maximum growth rate, from Eq. (1), is

$$(\gamma_\alpha)_{\max} \approx \frac{9}{4} \beta_\alpha \omega^* \alpha F . \quad (5)$$

Here we estimate the steady-state n_α consistent with

$$n_\alpha = \frac{1}{4} n^2 \sigma v \tau_\alpha \quad (6)$$

$$\tau_{\alpha} = \frac{a^2}{D_{\alpha}} = \frac{k_{\perp}^2 a^2}{\gamma_{\alpha}} . \quad (7)$$

As an example, we have carried out the calculation for ITER parameters, corresponding to $V_{\alpha} \approx 10^7 \text{ ms}^{-1}$, $V_A \approx 7.3 \times 10^6 \text{ ms}^{-1} = V_i/\sqrt{\beta_i}$, $k_{\parallel} V_A \approx 2.04 \times 10^5 \text{ s}^{-1}$, $\beta_{\alpha} \approx 3.76 \times 10^{-20}$, n_{α} , $T_{\alpha} = \frac{2}{3} 3.5 = 2.33 \text{ MeV}$, $\beta_e \approx 0.025$, $T = 15 \text{ Kev}$, $n \approx 10^{20} \text{ m}^{-3}$, $\sigma v = 2.65 \times 10^{-22} \text{ m}^3 \text{ s}^{-1}$. Then,

$$\gamma_{\alpha} \approx \frac{9}{4} \times 2.04 \times 10^5 \times \left[\beta_{\alpha} \left(k_{\alpha} \alpha - \frac{1}{2} \right) F - \frac{\sqrt{\beta_e}}{60} \right] \quad (8)$$

and

$$n_{\alpha} \approx \frac{1}{4} n^2 \sigma v \frac{k_{\perp}^2 a^2}{\beta_{\alpha} \left(k_{\alpha} \alpha - \frac{1}{2} \right) F - \frac{\sqrt{\beta_e}}{60}} \quad (9)$$

where

$$\alpha = \frac{\omega_{* \alpha}}{k_{\parallel} V_A k_{\alpha}} .$$

Extremizing Eq. (9) on k_{α} gives the maximum n_{α}/n and minimum τ_{α} . We find

$$k_{\alpha} = \frac{1}{\alpha} \left[1 + \frac{2\sqrt{\beta_e}}{60\beta_{\alpha} F} \right] . \quad (10)$$

Combining Eqs. (9) and (10) and solving for n_{α}/n gives:

$$\begin{aligned} \frac{n_{\alpha}}{n} &= 3 \times 10^{-4} \\ k_{\alpha} &= 7 \\ \tau_{\alpha} &= .03 \text{ s} \\ \tau_s &= \frac{10^{18} T^{3/2}}{n} = 0.6 \text{ s (slowing downtime)} \\ \beta_{\alpha} &= 1.1 \times 10^{-3} \end{aligned}$$

Since $\tau_\alpha \ll \tau_s$, the alphas would escape before losing their energy (consistent with our assumption $T_\alpha = 2.33$ Mev in the calculations).

Note that $ka \sim 7$ minimizes τ_α for the chosen parameters, and hence would be the most dangerous mode. To maintain $1 < q < 2$ in Eq. (3), the corresponding n-mode value is $4 < n < 7$. However, $k_\parallel$ itself (the projection along B) is always $(2qR)^{-1}$, by Eq. (4). Since $kp_\alpha = 0.3$, finite Larmor radius corrections may alter the result.

2. Discussion

The foregoing calculation is meant to be illustrative only. Further work on the TAE and other alpha-induced instabilities may modify growth rates, or lead to different estimates of the transport. Or, perhaps these modes may turn out to be stable after all, though it does appear to be true that energetic ions excite magnetic fluctuations in some experiments. A review of alpha instabilities is given in Ref. 2.

Taking these modes seriously, what might be the consequences?

First, according to Eq. (1), there is no threshold if one allows a free range in $k_\perp$. On the other hand, there is a threshold at a given $k_\perp$, and $D_\alpha \propto k_\perp^{-1}$. Thus, as the alphas build up, one might first expect excitation of high $k_\perp$ modes with little transport (less than normal drift wave heat transport at the rate $\chi \sim \rho^2 \omega_e$). But as the alphas build to high density, smaller $k_\perp$ values yielding larger values of D_α begin to grow until saturation occurs as calculated in Eq. (9).

Second, since these modes are in some sense resonant with the high-speed alpha particles, it may be that the transport rate for fuel particles is weak. If so, one could still contemplate a driven tokamak reactor even in an operating regime in which alpha instabilities eject the alphas.

The minimum goals of CIT (as recently revised) and the steady-state ITER technology phase are consistent with a purely driven regime. The ITER Terms of Reference calls for a minimum of $Q = 5$ in the technology phase, $Q \equiv 10$ being the nominal design value. Similarly recent discussions of CIT have emphasized a minimum expectation of $Q = 5$, with $Q = 25$ as the nominal value. In either case, an nte yielding $Q = 10$ with the

aid of alpha heating (consistent with both designs) would yield $Q = 5$ without the aid of the alphas so long as alpha instabilities do not also eject the fuel. Thus, for both CIT and ITER the most crucial question regarding performance (if the testing role of ITER is emphasized) would not be whether alpha instabilities occur, but rather their effect on confinement of the DT fuel.

Now let us extend this discussion to higher Q -values. As a model, consider gyro-scaling³, whereby the gain Q_0 without alpha heating is given by (omitting irrelevant factors):

$$Q_0 = \frac{n\tau_E\sigma v}{T} = \frac{\beta a^3 B^4}{T} \sigma v \cdot f \quad (11)$$

where f depends on β , q , κ , ϵ and other dimensionless variables. The fusion power and wall load are:

$$P = \frac{1}{\epsilon} n^2 a^3 \sigma v = \frac{\beta^2}{\epsilon} \frac{a^3 B^4}{T^2} \sigma v = \frac{Q_0 \beta}{f \epsilon T} \quad (12)$$

$$\Gamma = \frac{P \epsilon}{a^2} \quad (13)$$

According to Eq. (11) at a given β and fixed f (ϵ , q , ...) the maximum Q_0 occurs at $T_i \simeq 25$ KeV, in the range of present steady-state reactor designs. Thus, increasing Q_0 requires either a larger a , larger B or larger β . To maintain a power P in the present range (under 1 GWe, probably the largest acceptable), the only parameter we can change is βf , to increase Q_0 , compensated by a larger ϵ to maintain constant power (but increasing wall load). Unless the not-well-understood largely-geometric factor f holds pleasant surprises, this would argue that driven tokamak designs utilize the high- β , low aspect ratio regime studied by Peng⁴. Even so, the limiting Q_0 is probably 20 or less. Higher gain still requires significant alpha heating.

In addition, attention must be given to avoiding instabilities by auxiliary heating. For example, neutral beam injection parallel to field lines at beam energies adequate to penetrate the plasma (~ 1 MeV) gives parameters and predictions similar to alpha heating at T_e high enough for high Q . Perpendicular injection may be preferable to avoid large $V_{||}$. Energetic ions injected perpendicular to B do not acquire parallel velocity in slowing down on electrons, but too large velocity anisotropy could cause other problems. Similar remarks apply to ICH. Recent experiments in JET with minority-species ICH heating of He_3 to about 1 MeV and substantial density are reassuring⁵. On the other hand, current drive by energetic particle velocity parallel to B requires further investigation.

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