THERMONUCLEAR TOKAMAK PLASMAS IN THE PRESENCE OF FUSION ALPHA PARTICLES

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Foreword

Recent progress in the confinement of hot plasmas in tokamak experiments throughout the world has intensified interest and research in the physics of deuterium-tritium burning plasmas, especially in the wide range of unresolved theoretical as well as experimental questions associated with the role of alpha particles in tokamak devices.

Since several years, theoretical research concerning those problems has been carried out at the Institute for Electromagnetic Field Theory and Plasma Physics, Chalmers University of Technology, Göteborg. This effort has developed into a NET contract initiated by Prof. F. Engelmann and Prof. H. Wilhelmsson. The aim of this contract has been to give an overview of the present knowledge on alpha particle effects in a thermonuclear tokamak plasma.

As part of our work a symposium on "The Role of Alpha Particles in Magnetically Confined Fusion Plasmas" was organized by our institute and held at Aspenäsgården near Göteborg, June 24-27, 1986. The full texts of the papers have been published in a special issue of Physica Scripta (Vol. T16, 1987; editors: M. Lisak and H. Wilhelmsson).

The present report completes the contract work by giving an overview of several important aspects of the alpha particle physics and diagnostics in a fusion tokamak plasma.

The authors of this report express their sincere gratitude to Prof. H. Wilhelmsson whose continuing encouragement and advice have been invaluable. It is also a pleasure to acknowledge a fruitful and most enjoyable collaboration with Dr. K. Borrass and Prof. F. Engelmann at the NET Team. Finally, we would like to give our warmest thanks to Mrs. B. Larsson for her patience and her excellent work in typing the manuscript.

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$\mu > 0.5$ the instability is completely suppressed. Assuming that Alfvén waves are primarily damped by plasma electrons, the threshold alpha density above which the instability occurs can be estimated as

$$\frac{n_\alpha^{cr}}{n} \sim 10^{-7} \frac{m_e}{m_i} \frac{k^3 \mu V_{te} V_A^2}{\omega_{cs\alpha}} \tag{27}$$

which for the parameters $n = 5\times 10^{13}$ cm^{-3}, $T = 10$ keV, $B = 3.5$T ($V_{Te} = 4\times 10^9$ cm$\cdot$s^{-1}; $V_A = 5\times 10^8$ cm s^{-1}) becomes $n_\alpha^{cr}/n \sim 10^{-2}$.

In the case of wave excitation by trapped alpha particles the instability growth rate increases with increasing values of μ and it becomes significantly large at $\mu \gtrsim 0.6$. The maximum growth rate occurs at almost longitudinal propagation and is of the order of

$$\gamma_{\alpha,\max} \sim 10^8 \frac{n_\alpha}{n} \tag{28}$$

with the corresponding alpha density threshold

$$\frac{n_\alpha^{cr}}{n} \sim 10^{-8} \frac{m_e}{m_\alpha} \frac{V_{Te}}{V_A} \omega \phi^2 \tag{29}$$

Taking the same parameters as above and $\mu \simeq 0.9$, $\omega = 0.7\times 10^8$ s^{-1}, eq. (29) gives $n_\alpha^{cr}/n \simeq 10^{-4}$.

A quasi-linear theory of the shear Alfvén instability excited by trapped alpha particles, at the wave frequency satisfying $\omega_{ci} \ll \omega = k_\parallel V_A = p\omega_b$, was developed in [19]. The linear evolution of this instability was described in [17]. A self-consistent numerical solution of the system of a quasi-linear equation for the alpha particle distribution, and an equation for the waves together with a particle conservation equation, showed that the quasi-linear evolution of the instability results in an anomalous relaxation of alpha particles. The enhanced electromagnetic perturbations can produce rapid spatial losses of alpha population and energy. Figure 3 shows the time dependence of the alpha particle loss coefficient $R_{NL} = 1 - n_\alpha(t)/(S_\alpha t)$ and the alpha particle energy loss coefficient $R_{EL} = \Delta(n_\alpha E_\alpha)/(E_\alpha S_\alpha t)$, where $S_\alpha = n_D n_T \langle \sigma v \rangle$ and $\Delta(n_\alpha E_\alpha)$ is the total alpha energy lost from the system at time t. The following tokamak parameters were used: $B = 50$ kG, $a/R = 120/400$, $q(a) = 2.5$, $n_e = 5 \times 10^{13}$ cm^{-3}, $T_e = T_i = 15$ keV, $I = 3.6$ MA. It was also assumed that the instability develops on the second bounce harmonics ($p = 2$).

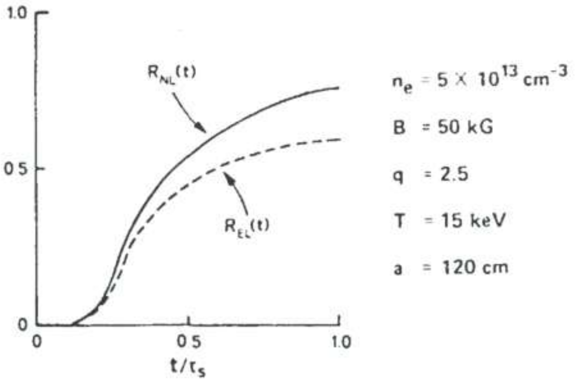

Fig. 3. Alpha particle and energy loss rate coefficients versus time. R_{NL} and R_{EL} are defined in the text, [19].

Figures 4, 5 and 6 show the scaling of R_{NL} with increasing of B, n_e and T, respectively.

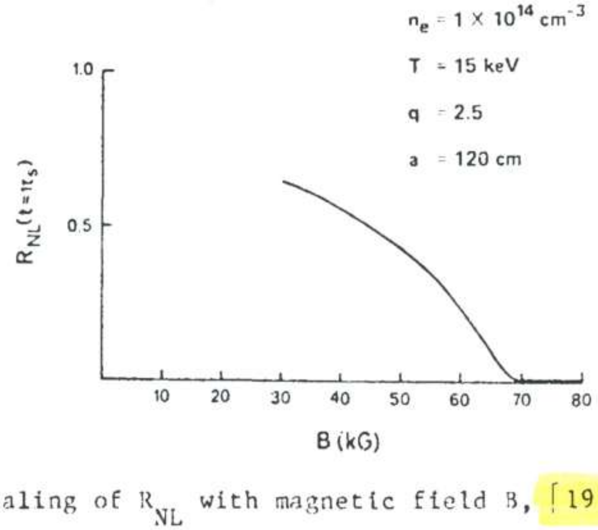

Fig. 4. Scaling of R_{NL} with magnetic field B, [19].

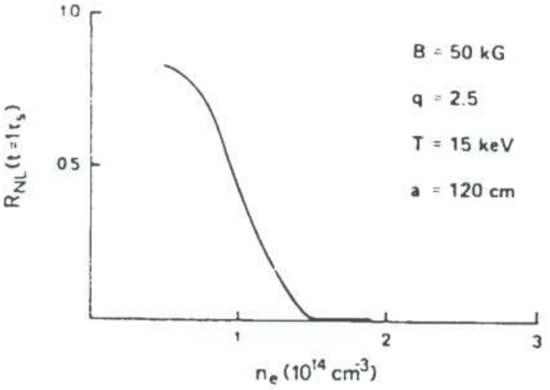

Fig. 5. Scaling of R_{NL} with electron density, n_e, [19].

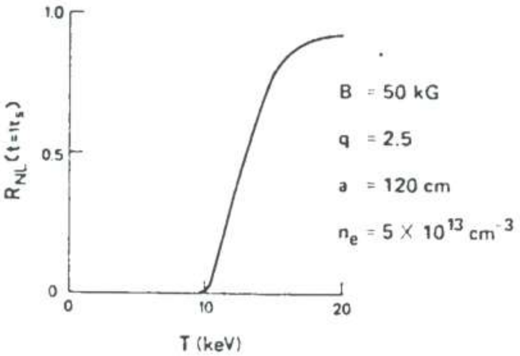

Fig. 6. Scaling of R_{NL} with plasma temperature T, [19].

Overall, Figs. 4 - 6 indicate that the anomalous alpha losses can be reduced by working at large values of magnetic field, high density, and low temperature. All of these conditions are favoured in a very high- current, high-magnetic-field, high density Ohmic tokamak without blanket, but may be very difficult to achieve in a practical fusion reactor. In a finite system, the alpha particle losses prevent the alpha velocity distribution from attaining a stable collisional equilibrium, thus maintaining a steady-state turbulence level.