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CONTENTS

plasma. The majority of experiments on larger tokamaks show a rather uniform Z_{eff} distribution over the plasma cross-section. Impurities injected at the edge of the plasma were found in all cases to have inward velocities on the order of 1 cm/ms. Impurity particle confinement times appear to be of the same order as those of the primary plasma ions.

4. Suprathermal Ion Confinement. If suprathermal ions formed by ionization (or charge exchange) of high-energy neutral atoms injected into the plasma are born such that their "banana orbit" intersects the wall or limiter, they are lost immediately. While this was a problem in some of the smaller tokamaks in which early neutral beam injection experiments were performed, the fraction of injected particles so lost is small in present (PLT, T-10) tokamaks and will be negligible in future, larger tokamaks.

However, the loss of suprathermal ions during the slowing down process due to toroidal field ripple enhancement of radial transport is a more serious concern. The most stringent requirement for low ripple will arise from the need to confine ions produced by nearly perpendicular ($v_{\parallel} \simeq 0$) neutral beam injection, which is required for beam penetration with low beam energies. These fast ions are formed in the region of velocity space most susceptible to ripple loss, and for shallow penetration, into the spatial region with the highest ripple.

5. Suprathermal Alpha Particle Confinement. In future D-T tokamak plasmas, 3.5 Mev alpha particles will be created by fusion, preferentially near the center of the plasma with an isotropic velocity distribution. Neglecting field ripple effects, alpha confinement depends only upon the plasma current, aspect ratio and the radial fusion rate distribution. For plasma currents of 4 or 5 MA or more, only a few percent or more of the fast alpha particles will be lost because their orbit intercepts the limiter or wall. The toroidal field ripple effect should be relatively unimportant for alpha particles because most will have thermalized before they are scattered into the $v_{\parallel} \simeq 0$ region where they can be trapped.

Several mechanisms have been suggested for the loss of alpha particles due to microscopic fluctuations before they have deposited their energy in the plasma. The potentially most dangerous of these seems to involve $\vec{E} \times \vec{B}$ transport in the fluctuating electric fields arising from unstable shear

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Alfven waves that are excited by the alpha particles (*16*). However, the magnitude of the effect decreases markedly with plasma density above about $10^{20}/\mathrm{m}^3$, and there are a number of approximations in the theory that tend to overestimate the magnitude of the effect.

C. Stability and Control

1. MHD Stability. The possible MHD instabilities in a tokamak plasma may be categorized according to whether they involve internal or surface perturbations. Internal helical perturbations (with a fixed plasma boundary) with high toroidal mode number (n) are known as "ballooning modes" with internal helical perturbations with low toroidal mode number are known as "low-n internal modes". Surface helical perturbations with low toroidal mode number are known as "kink" modes. The rigid body vertical displacement ($n = 0$) is known as the axisymmetric instability. The physical characteristics of these instabilities are discussed in a recent review (*17*). The practical consequences of these MHD instabilities is to set an upper limit on the allowable value of $\beta \equiv$ plasma pressure/magnetic pressure, produce microscopic turbulence that enhances outward energy transport, and place certain requirements on the control coil system.

Theoretically, stability of high-n internal (ballooning) modes at high β in the presence of large pressure gradients requires low shear (change in pitch of the helical magnetic field surfaces) and the presence of a magnetic well. Stability is enhanced by plasma elongation and triangularity (D-shape). For the INTOR plasma (aspect ratio = 4, plasma shape = D, plasma elongation = 1.6), which has been extensively studied and which is typical of the plasmas that are envisioned for tokamak reactors, requiring the shear parameter $rq / q' < 0.5$ leads to upper limits of the volume averaged $\langle\beta\rangle_{max} \simeq 5\text{-}6\%$ (*18*). However, preliminary calculations indicate that inclusion of a separatrix in the computational model may lead to lower beta limits (*19*) (a separatrix separates those magnetic field lines that remain entirely within the closed volume of the plasma chamber from those that do not, and usually is associated with the presence of a diverter for impurity control). On the other hand, substantially higher limits have been found in other studies (*20*).

It is not clear that ballooning modes actually limit

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