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Progress Report
"Theoretical Investigations Relevant to
Controlled Fusion Research"
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1. Introductory Remarks

The main thrust of our research effort for the past year has been directed at two major categories of problems associated with plasma confinement in Mirror machines and Tokamaks. In the latter case the emphasis has been on the effect of "Runaway Electrons" on the overall stability of the system while for the open-ended devices much of the effort went into examining the impact of finite beta and feedback stabilization on loss cone modes as well as some investigations in the reactor aspects of mirror confined plasmas. The highlights of these investigations along with some of the results will be discussed below.

2. The Role of Runaway Electrons in Tokamak Stability

Some of the experimental evidence on runaway dominated discharges in Tokamaks has indicated certain signs of macroscopic instabilities; however, the characteristic features of these instabilities differ significantly from those of MHD modes in the normal Tokamak regime. Typically current dumps are observed; the size of which varies from a few percent up to 20% of the total current as in some of the early ORMAK discharges. In the latter case, the large current steps were thought to have been related to the poor horizontal positioning of the plasma. However, a more recent series of strong runaway discharges on ORMAK⁽²⁾ which were well centered, still showed definite but smaller jumps in current ($< 4\%$). The MHD magnetic probes, which are sensitive to rapid fluctuations in the poloidal field generally exhibit a much quieter level of activity in the strong runaway regime than in the normal Tokamak discharges. This feature has been observed on both the Russian T-6 and ORMAK devices.

While there appears to be evidence of macroscopic instabilities as indicated by fast current dumps there also appears to be enhanced stability as reflected by the level of magnetic field fluctuations in runaway dominated Tokamak discharges. In order to better understand these features and to also examine their implications with respect to fusion applications of toroidal relativistic beams we

embarked on a comprehensive theoretical study of the role of runaway electrons in Tokamak stability. Several mechanisms which are thought to be distinct to runaway-dominated discharges have been incorporated in the analysis. These include: velocity shear in the runaway beam, effects of the longitudinal dynamics of the relativistic electrons, influence of the high transit frequency of the runaways around flux surfaces, and consideration of toroidal drifts.

As a first step we examined the stability of a toroidal relativistic beam with velocity shear against the kink mode $m=n=1$ where m and n are the poloidal and toroidal mode numbers respectively. The model chosen was that of a cylindrical beam consisting of two regions with different constant velocities in each region. With assumptions similar to those of Lee⁽³⁾ (e.g. rigid beam and cold fluid plasma) an MHD stability analysis was carried out and several sufficient conditions for stability were obtained. When evaluated for parameters characteristic of the strong runaway regimes in Tokamaks it was shown⁽⁴⁾ that only a slight change from the usual $q > 1$ is obtained.

In order to assess the role of the other mechanisms referred to earlier a re-examination of the macroscopic stability problem has been initiated. Using the kinetic beam-plasma approach. It is expected that upon completion of the macroscopic analysis a study of microinstabilities associated with runaway electrons in Tokamaks will be conducted.

3. Microinstabilities in Mirror-Confined Plasmas

Since loss cone instabilities continue to be the major obstacle to plasma confinement in Mirror machines our effort for the past year was again directed at examining possible stabilization mechanisms for these instabilities. In the last progress report we indicated that finite beta affects on the convective loss cone modes were not very significant. Since then we have focused our attention on the drift cone instability and have re-examined it for finite beta and

mirror-ratio dependent ion loss cone distribution. We find general agreement with the results of Tang et al⁽⁵⁾ in that higher betas have stabilizing effects. In fact we have shown in the infinite-plasma linear theory that a critical beta exists for which the drift cone mode stabilizes.

Using the local potential perturbation as a control variable we have shown in earlier work⁽⁶⁾ that by using present-day amplification systems the drift cyclotron instability in mirrors can be feedback stabilized as a result of increasing the threshold density by a factor of 100 or more. Since it utilizes constant gain and phase the above analysis was limited in that it can be applied to one mode at a time. In order to make it more applicable to real systems where many modes can exist simultaneously the above mentioned analysis was expanded to include frequency-dependent feedback control of plasma instabilities. It was shown⁽⁷⁾ that unstable modes can be suppressed without driving new instabilities or causing stable modes to become unstable.

We have also extended the above analysis to include nonlinear wave-particle interactions. Using quasilinear analysis we have shown⁽⁸⁾ that feedback stabilization can be used to stabilize weakly turbulent mirror plasmas.

4. Mirror Reactor Studies

As pointed out in the previous progress report analytic expressions for particle and energy confinement times for mirror confined plasmas must be obtained in order to carry out a meaningful study of both the equilibrium and dynamic behavior of mirror fusion reactors.

Several relatively simple formulas^(9,10) for calculating the mirror confinement parameter (the product of density and particle confinement time) are available but they do not agree too well with the Fokker-Planck Calculations⁽¹¹⁾ and provide no information on the average energy carried by the escaping ions.

We have in the past year developed improved formulas which agreed quite clearly with the results of reference.⁽¹¹⁾ Unlike the standard one-dimensional Fokker-Planck Calculation which implicitly assumes an ion injection source broadly distributed over angle, our calculation assumes a source narrowly distributed about the perpendicular to the magnetic field axis. Our results agree quite well with the two dimensional calculations⁽¹¹⁾ utilizing a narrow source. They however, yield a slightly higher value for the average escape energy although this effect is masked by the higher Fokker-Planck ion energies when fusion alphas are present. For alphas our calculations yield too low a value of average escape energy probably because our assumed distribution function is poor for fusion alpha particles.

With formulas for the particle and energy loss rates through the mirror plus formulas which could be used to calculate the plasma potential we should be able to write the (spatially independent) particle and energy balance equations for a mirror reactor and examine in detail its equilibrium operating conditions as well as its stability against thermal fluctuations.

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