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Microinstabilities of Finite Mirror-Confined Plasmas

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I. Modified Negative Mass Instability (Callen, Horton)

In the original work on the modified negative mass instabilities^{1,2} no satisfactory means was found for stabilizing these modes in finite mirror plasmas. Subsequent work³ which included the effects of finite gyroradius, radial magnetic field variation, a slightly relativistic gyrofrequency and thermal spreading of the velocity distribution (but, still within the regime where the bounce effects are neglected) also failed to yield a suitable means of stabilization. Work by Launois et al⁴ has shown that the inclusion of bounce effects for monochromatic (or delta-function) distributions in both energy and pitch-angle yields, in addition to the basic mode, further negative mass instabilities at bounce satellites of the gyrofrequency.

In the work completed in LPP-2 (see Section IV) it is shown that these potentially quite dangerous modes are stabilized by sufficient thermal spreading in the pitch-angle distribution. Specifically, combining the bounce and thermal spreading effects, we find that all modified negative mass instabilities are completely stabilized if $\eta_{\Delta} \equiv \Delta^2 \Omega_0 / \omega_b > 0.77$, where $\Delta \sim (T_{\perp} / T_{\parallel})^{1/2}$ is the thermal spread (half-width at half-maximum) in the pitch-angle distribution, Ω_0 the minimum gyrofrequency and ω_b the average bounce frequency. Thus, while these modes have plagued some of the early, nearly perpendicular, injection experiments on mirror-confined plasmas, we conclude that they should be completely stabilized in the high density, collisionally equilibrated mirror-confined plasmas of thermonuclear interest.

This work was done in collaboration with Professor C.W. Horton, Jr. of the University of Texas. The collaboration was initiated in the summer of 1969 when both authors were visiting at the Oak Ridge National Laboratory. The work was finally completed, the results analyzed and written up for publication during the project grant period.

- 1) J.F. Clarke and G.G. Kelley, Phys. Rev. Letters 21, 1041 (1968);
J.F. Clarke, G.G. Kelley, J.F. Lyon, and R.F. Stratton, in Plasma Physics and Controlled Nuclear Fusion Research (International Atomic Energy Agency, Vienna, 1969), Vol. II, p. 291.
- 2) B.B. Kadomtsev and O.P. Pogutse, *ibid.*, Vol. II, p. 125.
- 3) J.D. Callen and C.W. Horton, Phys. Fluids 13, 154 (1970).
- 4) D. Launois, G. Laval, R. Pellat and J. Tachon, Plasma Physics 13, 119 (1971).

II. Enhanced Scattering Inherent to "Loss-Cone" Particle Distributions (Callen, Baldwin)

Many theoretical models predict¹ that high density mirror-confined plasmas should be unstable to a number of standing wave (absolute) microinstabilities which have growth rates as large as the ion gyrofrequency. These instabilities, which are driven primarily by the free energy associated with the loss-cone velocity distribution, are expected to attain fairly large non-linear amplitudes and to cause significant and abrupt particle losses out of the confinement region in a hundred or so ion gyroperiods. However in mirror experiments such as 2X² and 2X-II³, under the most favorable conditions, the decaying plasma is apparently quiescent. The typical decay time in those experiments, although about an order of magnitude faster than that expected from classical Coulomb collisions, is about 40,000 ion gyroperiods. Thus, while it is presently incomprehensible from a theoretical viewpoint, it appears that all significant standing wave modes can be eliminated in the 2X series of experiments. Hence, it seems that we must look elsewhere for an explanation of the anomalous loss processes in those experiments.

The place we have looked is in the effect which convective (nonzero group velocity along the magnetic field) microinstabilities might have on the rate of scattering of ions into the loss-cone. Fundamentally, we anticipate that the presence of the convective microinstabilities causes an enhancement of a portion of the stochastic fluctuation level spectrum induced in the plasma by the two-particle scattering process. An enhancement of the fluctuation spectrum should then lead to a related enhancement of the rate of scattering of particles in velocity space. In the work described in LPP-3 (see Section IV) we calculate the particle scattering induced by the most important (shortest growth length) convective microinstability —

the Rosenbluth-Post convective loss-cone instability⁴. We find that the extra, collective contribution to the scattering rate is a factor of $(m_e/m_i)^{1/2} (T_i/T_e)^{3/2} (\ln \Lambda)^{-1}$ x (energy amplification of the convective instability in the finite plasma) times the classical scattering rate. This new, irreversible and irreducible scattering mechanism for ions in a magnetic mirror machine can be more important than the classical Coulomb scattering processes if: 1) the plasma is more than a few convective growth lengths long; and/or 2) the electron temperature T_e is much less than the ion temperature T_i . Our result is of roughly the right order of magnitude to explain the experimentally observed decay in the 2X series of experiments. A more quantitative comparison can be made only after a number of the detailed geometrical effects are taken into consideration. Since this new scattering mechanism is due to a collective (convective microinstability) enhancement of a part of the fluctuation spectrum generated by the classical two-particle process, we refer to it as a "quasi-classical" scattering process.

This work was begun independently by the two authors. At the recent Annual Sherwood Theoretical Meeting (Los Alamos, March 23-24, 1972) D.E. Baldwin of Lawrence Radiation Laboratory presented a talk on it. Discussions there between the two authors revealed that they both had essentially the same results at that time and so it was decided to make it a joint paper. The work of J.D. Callen on this project was accomplished during the present contract period.

- 1) See for example: H.L. Berk, L.D. Pearlstein and J.G. Cordey, Phys. Fluids 15, 891 (1972) and references cited therein.
- 2) F.H. Coensgen, W.F. Cummins, Jr., V.A. Finlayson, W.E. Nexsen, Jr., and T.C. Simonen, in Plasma Physics and Controlled Nuclear Fusion Research

(International Atomic Energy Agency, Vienna, 1972), Vol. II, p. 721.

- 3) F.H. Coensgen, W.F. Cummins, Jr., W.E. Nexsen, Jr., T.C. Simonen,
Lawrence Livermore Report UCRL-51208, March 10, 1972.
- 4) M.N. Rosenbluth and R.F. Post, Phys. Fluids 8, 547 (1965).

III. Radial Eigenvalue Problem for Drift-Cone Modes (McCroory, McCune, Callen)

Electrostatic "drift-cone" modes^{1,2}, which in a mirror device can combine the expansion free energy of a confined plasma with the free energy of a loss-cone type distribution to lead to a potentially destructive instability, have usually been analyzed in a one-dimensional "slab model", the variation across the slab being intended to represent the radial (cross-field) inhomogeneity of the medium. A relatively simple dispersion relation is obtained in that model if one assumes the modes to be well localized spatially, at some typical "radius" or on a flux surface. Under the present contract we have developed a formalism which enables us to study this problem in axisymmetric cylindrical geometry and to consider radial eigenmodes which are not necessarily localized in space. Starting from the integro-differential equation derived from the Vlasov-Poisson equations³, the method utilizes a Fourier-Bessel transform technique to obtain an integral equation for the Hankel transform of the radial eigenfunction. The kernel of the transformed equation is "localized", i.e. it is such that the integral equation for plasma parameters of practical interest can be reduced to a differential equation in the transform variable. A WKB solution in the transform variable can be constructed and used to determine the conditions for the existence of an eigenmode. The method has been tried out to date for the low frequency regime, $\omega < \omega_{ci}$, i.e. for "drift-universal" instabilities. It is possible in that case to obtain a dispersion relation for non-localized drift modes, leading to the conclusion that such modes can indeed exist in plasmas of sufficient length. For mirror devices, however, study of the drift cone mode, with $\omega \approx n\omega_{ci}$, $n = 1, 2, \dots$, remains the more important application. Available theory^{4,5} indicates that such modes are not stabilized by finite length

effects (along the mirror axis), yet they have apparently not been observed in experiments where they "should" have been expected. The present theory provides a method of reevaluating the radial eigenmode problem in a manner not restricted to the local approximation or the slab model, and may offer new information on the structure and conditions for existence of drift-cone instabilities.

1. A.B. Mikhailovskii, Nucl. Fusion 5, 125 (1965) (in Russian); and Sov. Phys. - Doklady 11, 603 (1967).
2. R.F. Post and M.N. Rosenbluth, Phys. Fluids 9, 730 (1966).
3. Y. Shima and T.K. Fowler, Phys. Fluids 8, 2245 (1965).
4. D.E. Baldwin, C.O. Beasley, H.L. Berk, W.M. Farr, R.C. Harding, J.E. McCune, L.D. Pearlstein and A. Sen, Proceedings, 4th Conference on Plasma Physics and Controlled Nuclear Fusion Research June 17-23, 1971, Madison, Wisc.
5. H.L. Berk, L.D. Pearlstein and J.G. Cordey, Phys. Fluids 15, 891 (1972).

IV. Papers Completed

1. J.D. Callen and C.W. Horton, Jr., "Stabilization of the Modified Negative Mass Instability", AEC Report #C00-2168-1 (MIT Report LPP-2), February, 1972 (submitted for publication in the Physics of Fluids).
2. D.E. Baldwin and J.D. Callen, "Enhanced Scattering Inherent to 'Loss-cone' Particle Distributions," AEC Report #C00-2168-2 (MIT Report LPP-3). Originated as Lawrence Radiation Laboratory Report UCRL-73929, May 4, 1972 (submitted for publication in Physical Review Letters).

V. Conferences Attended

1. Annual Meeting of the Division of Plasma Physics of the American Physical Society, Nov. 15-18, 1971, at Madison, Wisconsin (J.D. Callen).
2. Annual Sherwood Theoretical Meeting, March 23-24, 1972, at Los Alamos, New Mexico (J.D. Callen and J.E. McCune).