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INSTABILITY DURING MONOENERGETIC NEUTRAL
INJECTION INTO A TARGET PLASMA

T. K. Fowler

December 27, 1974

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During neutral injection into a target plasma in 2XIIB and other mirror machines, the injected hot ions will create a peak in the energy distribution which is well separated from the colder target ion group if the injected ions are monoenergetic. These two separate ion groups are expected to undergo a "two-component" microinstability similar to the two-stream instability.¹ While it would be possible to avoid this circumstance by injecting additional neutral beams at different energies, it would be cheaper and simpler if these additional beams could be eliminated. Moreover, as there is limited access for neutral beams into the containment volume, the need for additional beams at lower energies would restrict the amount of current that could be injected at the more useful higher energies.

In this note we argue that multiple-energy injection is not required because the two-component (or "double-hump") instability is self-limiting and creates little losses during the process. The main point is that the electric field fluctuations $\vec{E}_{\perp}$ are nearly perpendicular to the magnetic field. As we shall see, despite some coupling of parallel and perpendicular velocity components $v_{\perp}$ and $v_{\parallel}$ by the mirror field, the $\vec{E}_{\perp}$ fluctuations mainly cause the hot and cold ion groups to diffuse toward each other in $v_{\perp}$, thereby eliminating the cause for instability. Since $v_{\parallel}$ is little changed, no losses occur.

The main ideas are illustrated in Fig. 1. This is a plot of the position of ions in $v_{\perp}$, $v_{\parallel}$ space as they cross the midplane. As usual in such a plot, the containment zone is a cone within pitch angles satisfying $\theta \leq \theta_c$ where θ_c is the loss cone angle determined by the mirror ratio. Note that on account of collisions among the lower energy target plasma ions, these ions would generally fill in their allowed containment space, while the hot ions are injected nearly perpendicular to the field with $\theta_{\text{INJ}} \ll \theta_c$ and hot-ion collisions are negligible during the buildup process over the lifetime of the target plasma. Consequently, the two ion populations are well separated, as discussed above, and two-component instability causing $E_{\perp}$ fluctuations would be expected.

The effect of these $E_{\perp}$ fluctuations on a test ion is illustrated in Fig. 1. To calculate the effect on the $v_{\perp}$, $v_{\parallel}$ components at the midplane actually requires a proper average over the bounce motion to take into account the axial variation of $E_{\perp}$ and the mirror coupling of $v_{\perp}$ and $v_{\parallel}$. Instead we plot the two extremes of instantaneous collisions at the turning point and at the midplane. Now, an instantaneous $E_{\perp}$ collision changes the local $v_{\perp}$ with no change in $v_{\parallel}$. Hence, at the turning point where $v_{\parallel} = 0$, an $E_{\perp}$ collision increases or decreases the energy but preserves the pitch angle; locally $\theta = 0$, and the mirror action translates $\theta = 0$ into the same $\theta = \theta_1$ at the midplane (as plotted) independent of the energy. Thus, a turning point collision neither traps nor untraps the ion with respect to escape through the loss cone. On the other hand, an $E_{\perp}$ collision at the midplane changes the pitch angle except for the special case of $v_{\parallel} = 0$ at the midplane. As illustrated, if the collision increases $v_{\perp}$ (and hence the total energy), the pitch angle decreases toward $\theta = 0$, tending to trap the ion better; and

if the collision decreases $v_{\perp}$, the pitch angle increases toward θ_c , tending to untrap the ion.

If the $E_{\perp}$ fluctuations are stochastic, they will give rise to diffusion in $v_{\perp}$ locally and it is clear from the above that upon proper bounce averaging this will translate to diffusion in both $v_{\perp}$ and $v_{\parallel}$, at the midplane with diffusion coefficients $D_{\perp}$ and $D_{\parallel}$, respectively. Since the change in $v_{\parallel}$ is solely a consequence of the mirror action as described above, $D_{\parallel}$ would be estimated to be of the order:

$$D_{\parallel} = \sin^2 \theta D_{\perp} = \frac{v_{\parallel}^2}{v_{\parallel}^2 + v_{\perp}^2} D_{\perp}. \quad (1)$$

Again, note that ions are being described here by their perpendicular and parallel components of velocity as they cross the midplane and $D_{\parallel}$ and $D_{\perp}$ refer to these midplane quantities. Alternatively we could describe the transport as diffusion in energy and midplane pitch angle, or energy and magnetic moment.

It follows from Eq. (1) that $D_{\perp}$ causes the injected ions and target plasma to diffuse toward each other in $v_{\perp}$ in a time short compared to the hot ion escape time by $D_{\parallel}$ diffusion. Since the extremum injected ion has a pitch angle θ_{INJ} , we estimate for injected ions

$$D_{\parallel} < \sin^2 \theta_{\text{INJ}} D_{\perp}. \quad (2)$$

Now the time required for the two distributions to merge is

$$t_1 = \frac{\epsilon}{D_{\perp}} \quad (3)$$

where $\epsilon = v_{\perp}^2 + v_{\parallel}^2$ is the mean energy of injected ions. In a time t_1 , the

change in pitch angle is given by

$$\int \sin^2 \theta = \frac{t_1 D_{\perp}}{\epsilon} < \sin^2 \theta_{\text{INJ}} \quad (4)$$

Hence the distributions do merge before much change has occurred in the pitch angles; in particular, since $\theta_{\text{INJ}} \ll \theta_c$, it is still true at $t = t_1$ that $\theta \ll \theta_c$.

If the distributions merge, the two-component instability ceases and the diffusion would cease. However, as the monoenergetic injection proceeds, a peak in the velocity distribution at the injection energy would again develop and instability would reoccur. What actually happens is that the system remains weakly unstable during injection so long as the target plasma remains. The distribution would depart from a stable one just enough to produce on the average a weak fluctuation level that would yield a small perpendicular diffusion coefficient $D_{\perp}$ at just such a value as to maintain this nearly stable state on the average. From the above considerations there would be a corresponding $D_{\parallel}$ coefficient caused by mirror coupling and $D_{\parallel}$ would cause some losses. However, these losses would be very small by the following argument.

From the above discussion it follows that $D_{\perp}$ is just large enough to smooth out the peak in the distribution at the injection energy that would otherwise develop as buildup proceeds. Hence t_1 must be of the order of the buildup time. But by Eq. (4), in a time t_1 negligible losses occur. Therefore, negligible losses occur in a buildup time. After that, the target is gone and two-component instability ceases.

These ideas could be made quantitative by a quasi-linear calculation with a source term to represent injection and initial conditions representing a target plasma. Probably a calculation in $v_{\perp}$ -space would suffice, relying on the above type of estimate of $D_{\parallel}$ in terms of the calculated quasi-linear $D_{\perp}$. Other important corrections would be superadiabatic effects which restrict stochastic behavior at small amplitudes, and non-resonant diffusive losses, especially of the lowest energy target plasma ions. The superadiabatic calculation should take account of the spectral spread of waves, probably with random phase.

It would also be interesting to compare such a model with data from 2XII.² In the circumstance designated Mode C in Ref. 2, the ion energy distribution initially has several peaks and significant observed plasma losses were attributed to instability associated with this "multi-component" structure.

At first sight these 2XII results might seem to be in conflict with the above conclusions that two-component instabilities will not produce losses during neutral injection. A possible explanation suggested by Coensgen lies in the very different nature of the distribution in the two cases. Whereas the high energy component created by neutral injection has little $v_{\parallel}$ and lies well within the containment zone, all components in 2XII are generated by time-of-flight capture of a gun plasma fired axially and have a substantial $v_{\parallel}$, and hence tend to fill the containment zone out to the loss cone. Thus, in this case, the stabilizing diffusion in $v_{\perp}^2$ required to eliminate the peaked structure is comparable to the diffusion in $v_{\parallel}^2$ required to reach the loss cone. Moreover, by Eq. (1), $D_{\parallel} \approx D_{\perp}$ for those particles

already nearest to the loss cone and hence most subject to being lost. For both of these reasons, one would expect substantial losses initially, though the losses should diminish later in time after the particles initially with largest $v_{\perp}$ have escaped.

References

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2. F.H. Coensgen, W. F. Cummins, W.E. Nexsen, Jr. and T.C. Simonen, "Initial Operation of the 2XII Experiment", UCRL-51208, March 10, 1972.

Fig. 1. Midplane phase space map of target plasma and injected ions; also, the consequences of a "collision" of a test ion with $\vec{E}$ fluctuations if it occurs (a) at a turning point, which does not affect the pitch angle at the midplane, and (b) at the midplane, which does affect θ .

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