magnetic lines of force. In this way the particle will shift around within the machine, remaining always on a surface on which the $\int p_{\parallel} dq$ is conserved. When the particle arrives back in the original neighborhood, it will as a general rule actually embrace the same magnetic line from which it had started. While this statement is not absolutely correct, it holds with a very high precision for small Larmor radii. Unfortunately, the conservation of the adiabatic invariants is not valid if the field varies with a sufficiently high frequency. Under those conditions, of course, the energy is not conserved either.

INSTABILITIES

Let us consider a time-independent distribution of magnetic lines of force in space, and let us also consider a static distribution of a plasma of vanishing electric resistivity. The magnetic lines need not be curl-free because we may assume electric currents in the plasma to account for the curl. No electric fields will be present: if they were parallel to the magnetic fields, they would give rise to a change in the electric current; while if they were perpendicular to the magnetic lines, they would cause the plasma to move, which is contrary to our assumption of a static situation.

Now the stability of this situation may be decided by investigating infinitesimal virtual displacements. In such a displacement the material of the plasma may slide along magnetic lines of force, but, in any motion transverse to the lines, the plasma and the lines must move together. Furthermore, any expansion or compression of the plasma accompanying the displacement must be considered as adiabatic. If some of these displacements lead to a linear change of the energy of the plasma, then the system is not in equilibrium. If all changes depend quadratically on the displacement, and if all infinitesimal displacements are connected with positive energy changes, then the plasma is stable. If some displacements are connected with negative quadratic terms we expect an unstable equilibrium. Many such instabilities have been discussed and the discussion has been carried to a detailed consideration of the way the particle distribution, magnetic fields and currents change during the displacement. The hydromagnetic consideration given above appears to be, however, a simple and general description which in many cases is satisfactory.

The first models that have been considered for the pinch machine and for the stellarator turned out to be unstable. Appropriate modifications of the field distribution have given rise to reasonable hopes for circumventing various troubles, but experience connected with the rather well-explored pinch effect seems to show that hydromagnetic instabilities continue to represent a considerable difficulty.

The general question whether a moving steady-state hydromagnetic system is stable or not has been discussed in some interesting special cases but has not been treated along similarly simple lines as has the corresponding static problem. These dynamic effects probably play a very important role during the constriction of the electric current in the pinch process and during the heating of the plasma in the stellarator. At the same time, runaway electrons (with velocities greatly exceeding the Maxwellian values) are produced. These probably give rise to plasma vibrations which also might arise by

614 7