EXPERIMENTAL TEST OF THE FEASIBILITY OF HEATING TOKAMAKS BY GUN INJECTION

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Manheimer et al. [1] have suggested using plasma beams as an alternative to neutral beams for refueling and heating tokamaks. The source of such a plasma beam could be a coaxial plasma gun such as described by Chang et al. [2]. The technology also exists for using a diode to produce an intense, high energy ion beam, which can then be charge neutralized by allowing it to drag along an equal number of electrons, resulting in an intense plasma beam.

A considerable amount of experience has been gained with coaxial guns for filling mirrors and multipoles. One possible mechanism for penetration of a plasma beam into a magnetic field is due to diamagnetism of the plasma. If the energy density of the plasma is larger than that of the magnetic field, the beam can push aside the field lines and propagate through the field. However, this does not apply to the present experiment. Use of coaxial guns in multipoles has verified that a plasma beam with low β but still sufficiently dense will propagate across magnetic field lines [3]. If the ion plasma frequency is larger than the ion cyclotron frequency in the plasma beam, so that it has a large dielectric constant, then as the drifting plasma enters a transverse magnetic field, a polarization electric field is induced. This electric field is of the right value to give an $\vec{E} \times \vec{B}$ drift velocity equal to the beam's original drift velocity, and the beam propagates unhindered by the magnetic field, except for the surface charge layer which is peeled off to produce the polarization electric field.

This mechanism requires the field lines at opposite edges of the beam to be at different electrostatic potentials. This is easily achieved in a multipole with a purely poloidal magnetic field, and in a vacuum. However, in a tokamak the field lines at opposite edges of the beam eventually connect, and with a background plasma already present to provide conduction along field lines the polarization electric field could be shorted out, preventing the beam from entering and propagating in the tokamak field.

The Large Wisconsin Octupole [4], shown in fig. 1, provided an opportunity to test this idea. The major radius of this device is 140 cm, the average minor radius about 50 cm. The poloidal field is provided by four inductively driven internal rings, and a toroidal field is produced by driving a poloidal current in the vacuum tank wall. There is a poloidal field null at the minor axis, and a separatrix divides field lines linking a single ring from those linking all four. The two fields have crowbarred decay times of the order of 100 msec, and the magnitudes of the two fields can be varied independently. Typical values for this experiment were an average poloidal field of 200 G near the walls and a toroidal field of 300 G at the midcylinder, giving a "safety factor" q of about 0.5. (q is defined as $\oint B_T d\ell/2\pi R B_p$.) This q was calculated halfway from the separatrix to the wall. Note that in a multipole, with any non-zero toroidal field, q always approaches ∞ at the separatrix due to the poloidal field null. However, to reach the separatrix a gun plasma must first penetrate the more tokamak-like region near the walls.

A Marshall-type coaxial gun [5] is located at the end of a drift tank, which keeps any un-ionized gas from the gun from entering the main chamber until after times of interest. The gas used in this experiment was helium. When injected into a vacuum the resulting ion density from the gun was about 5×10^9 cm^{-3}, the ion temperature about 10 eV but rapidly decaying, and the electron temperature about 4 eV.

The background plasma was the afterglow of an ECRH microwave discharge, with densities variable up to about 10^{10} cm^{-3}, an electron temperature of about 4 eV, and cold ions.

The main diagnostic was a Langmuir probe measuring ion saturation current at the separatrix field line, on which the majority of the particles are confined, since it connects to the low field region near the minor axis. Figure 2 shows typical oscilloscope traces for three cases. Fig. 2(a) shows the gun plasma injected into a vacuum, and 2(b) shows the ECRH background plasma by itself, and the gun plasma injected into the background plasma. It can be seen that the signal for the latter case is comparable to the sum of the two plasmas individually; that is, despite the toroidal field and background plasma, the gun plasma does penetrate the magnetic field and is trapped almost as well as in the vacuum case. Measurements of ion temperature using an electrostatic energy analyzer show that warm ions are present after injection into the background plasma, with about the same temperature as when the gun plasma is injected into a vacuum.

After about one msec following injection the ion temperature has decayed below the electron temperature and the electron temperature is about the same for all three cases, so the ion saturation current can be taken as proportional to density with the same proportionality constant for all three cases. This was confirmed by analysis of the full I-V characteristics for the probe and by comparison to density measurements made with a Fabry-Perot microwave

Figure 3(a) shows the ratio of the amount of gun plasma trapped in the presence of the background plasma to the amount of gun plasma trapped without the background plasma. A ratio of 0.5 for a particular case means half as much gun plasma was trapped on injection into the background plasma as was trapped on injection into a vacuum. The data are ion saturation currents from the Langmuir probe measured 1.5 msec after injection, which is assumed to be proportional to density as mentioned earlier.

Figure 3(b) shows the same ratio plotted vs. background plasma density for a fixed gun plasma, and vs. gun plasma density for a fixed background plasma. The error bars are due to a 10% non-reproducibility of the gun. The q value was 0.5 for all these data. Evidently the background plasma does not have much effect, typically decreasing the trapping only to 0.8 of the vacuum value, with little dependence on either density.

Figure 4 shows the ratio for varying q, obtained by varying the toroidal field, at two different background densities and with the gun parameters fixed. The trapping actually seems to improve with increasing toroidal field. The reason for this is not understood.

In summary, it is evidently possible to inject a plasma beam into a pre-existing plasma confined by a magnetic field with rotational transform. At the larger values of q nearly as much gun plasma was trapped as without the background plasma, with little dependence on the density of either plasma. This problem deserves further study of the mechanisms involved and their dependence on the toroidal field.

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FIGURE CAPTIONS

Fig. 1 Large Wisconsin Octupole. The gun used in the present experiment is labelled "injector."

Fig. 2 Oscillographs of ion saturation current at separatrix. Each trace consists of three shots superimposed. (a) Gun plasma injected into vacuum. (b) ECRH background plasma alone (lower trace) and gun plasma injected into background plasma (upper trace).

Fig. 3 Ratio of gun plasma trapped in background plasma to gun plasma trapped in vacuum, 1.5 msec after injection. $q = 0.5$. (a) vs. background plasma density. Gun plasma density (after injection into vacuum) fixed at 6×10^9 cm^{-3}. (b) vs. gun plasma density (after injection into vacuum). Background plasma density fixed at 5×10^9 cm^{-3}.

Fig. 4 Ratio of gun plasma trapped in background plasma to gun plasma trapped in vacuum, vs. q, 1.5 msec after injection. Gun plasma density (after injection into vacuum) fixed at 7×10^9 cm^{-3}. (a) Background plasma density fixed at 7×10^9 cm^{-3}. (b) Background plasma density fixed at 1.4×10^{10} cm^{-3}.

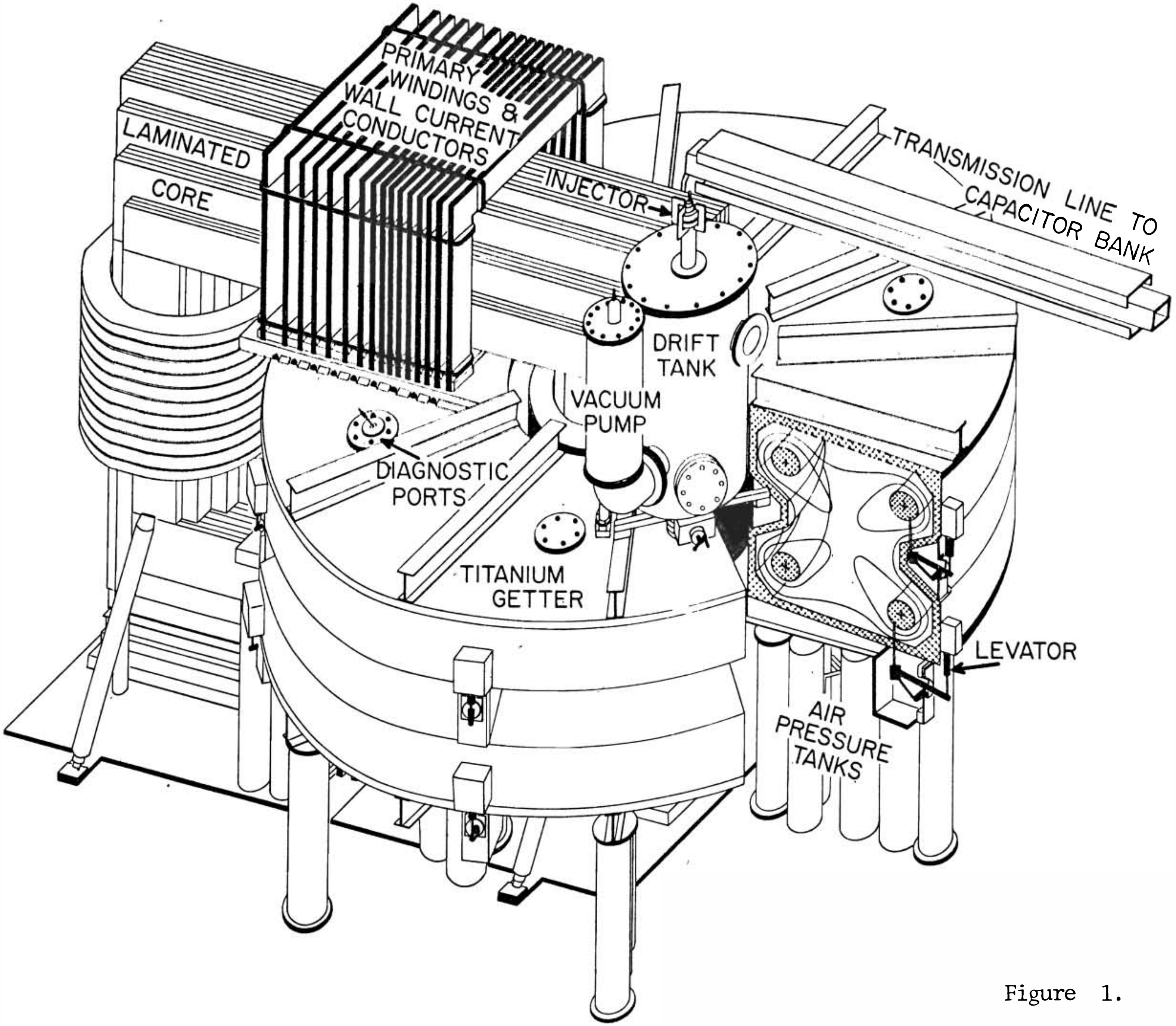

Figure 1.

WISCONSIN LEVITATED OCTUPOLE

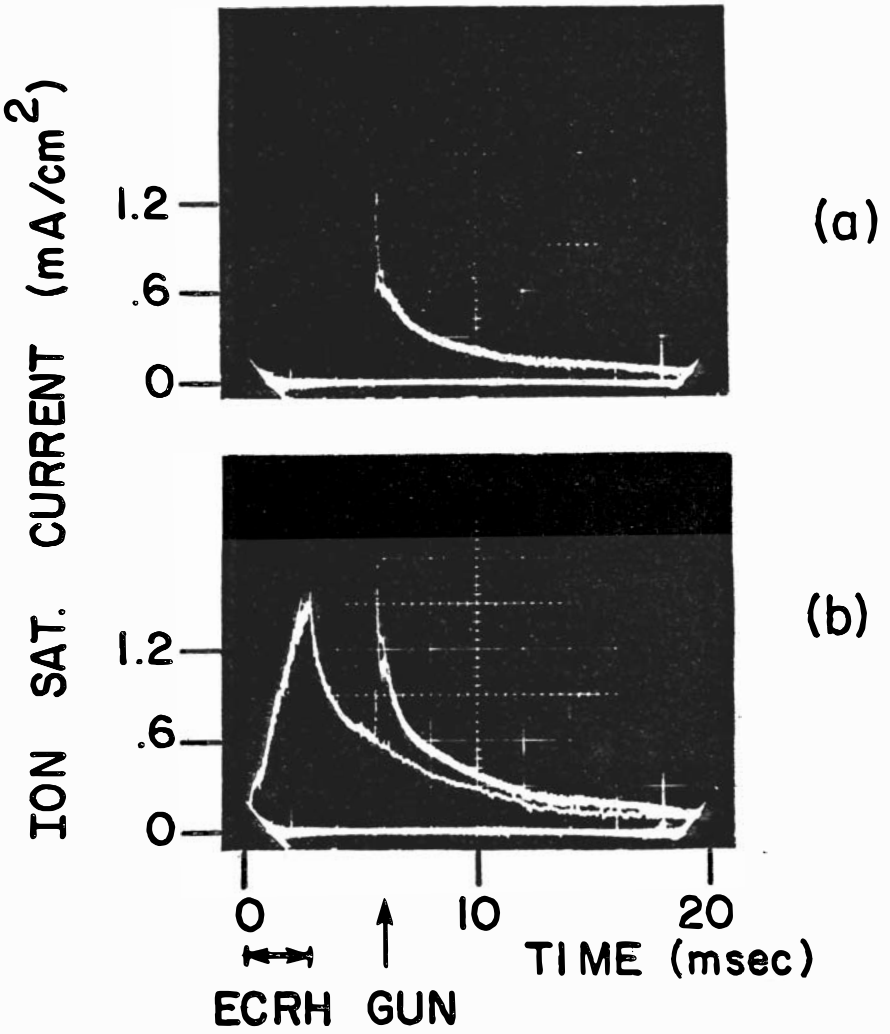

Figure 2.

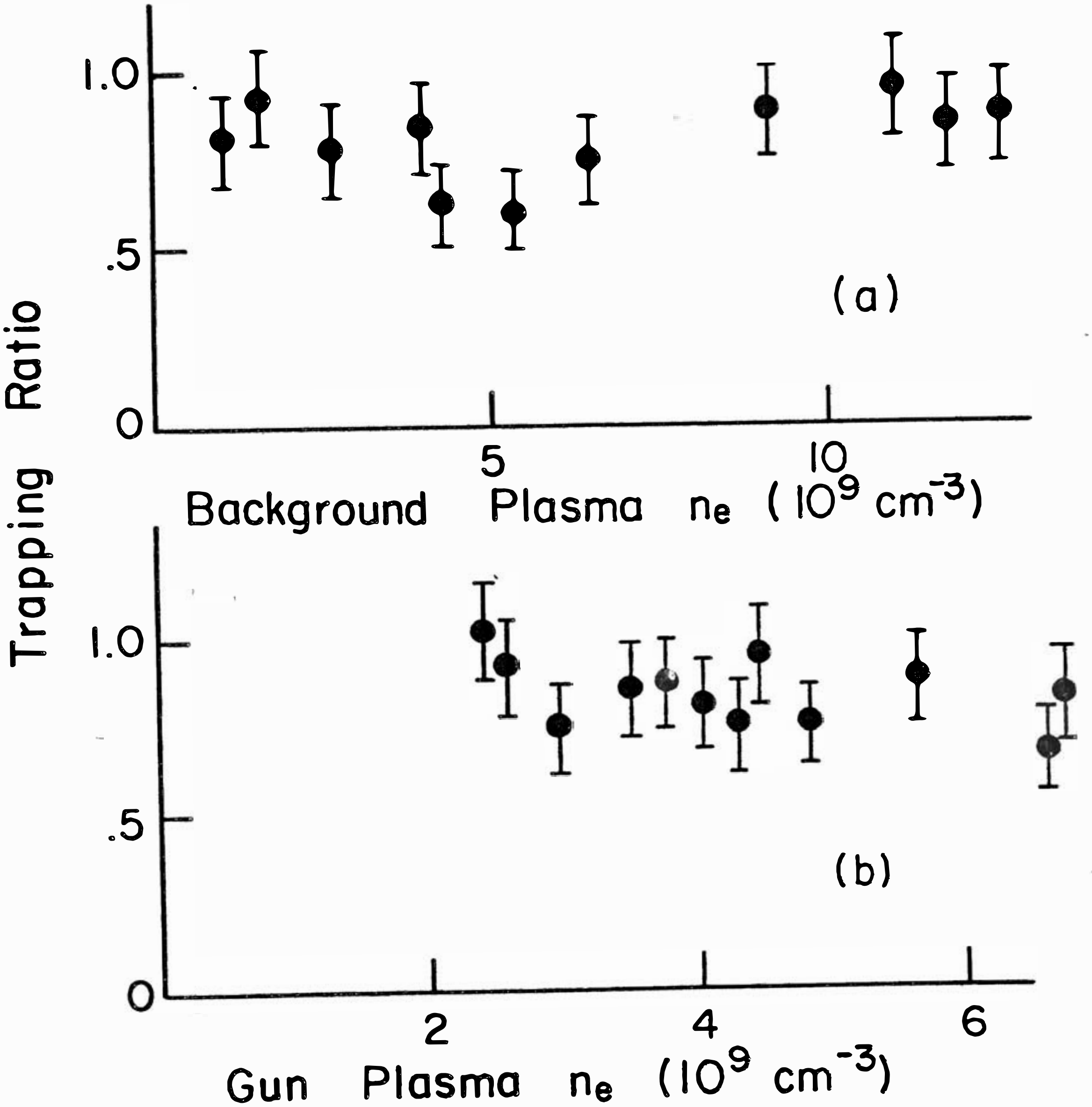
Trapping Ratio
1.0
.5
0
5
10
Background Plasma n_e (10^9 cm^{-3})
(a)
1.0
.5
0
2
4
6
Gun Plasma n_e (10^9 cm^{-3})
(b)

Figure 3.

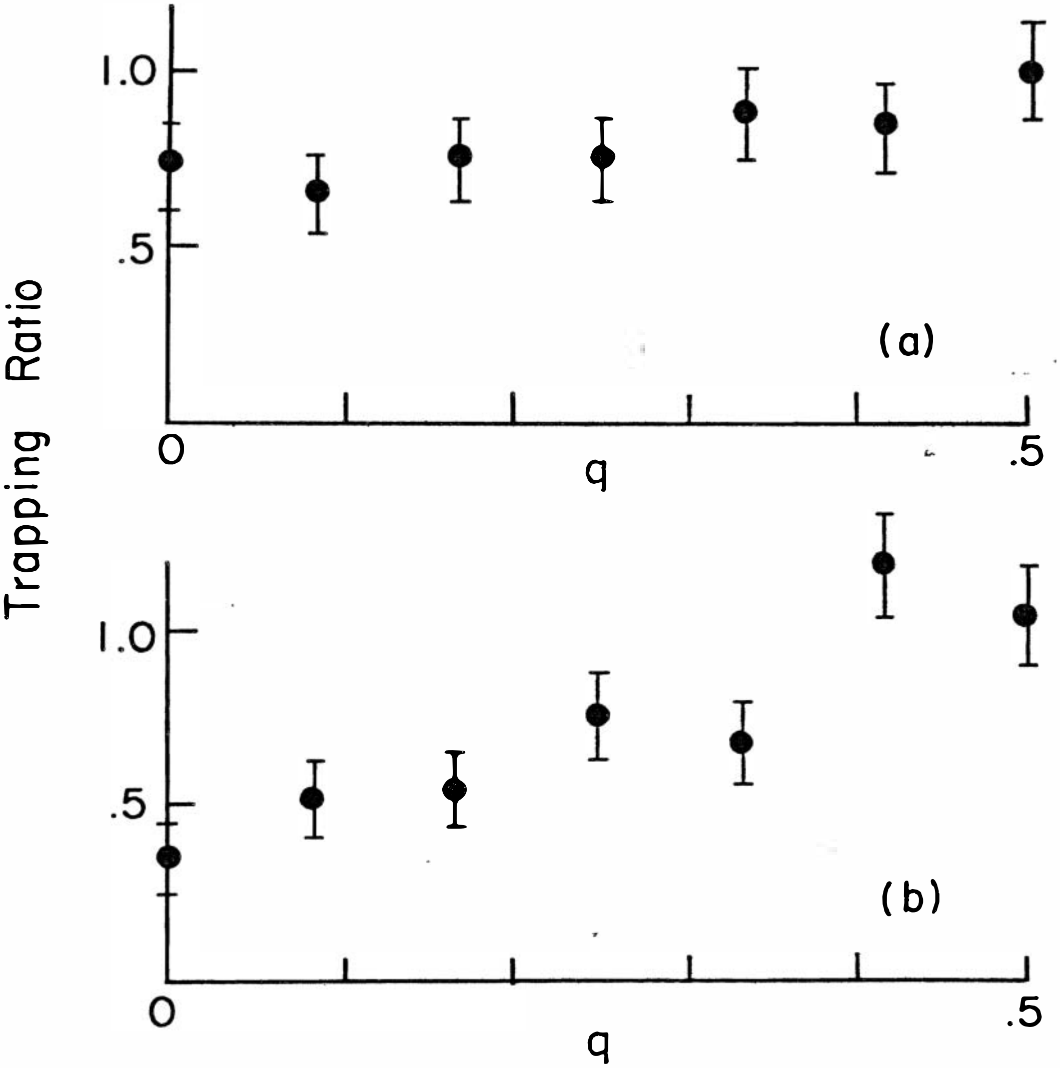

Figure 4.