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β MULTIPLE MIRROR PLASMAS

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ABSTRACT

A coaxial gun source injects a plasma of 1 - 10% β into a series of mirror cells. When the linked quadrupole minimum $|\beta|$ magnetic mirrors are used, the plasma appears MHD stable with smooth decays of $\sim 100\ \mu s$. In contrast, for the simple mirror configuration, the plasma is rapidly lost, suggesting MHD instability is present.

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The multiple mirror concept has been investigated [1,2] with steady state Q-machine plasmas [3] for which MHD stability was provided by line-tying. Transient plasma confinement [4,5] was later achieved in the two meter experiment using a set of linked Ioffe bars for stabilization. The worst interchange modes were observed to be effectively stabilized both for the Q-machine produced plasma ($n \sim 10^9 - 10^{10}$ cm^{-3}, $T_i \sim .2$ eV) as well as for a hydrogen theta-pinch produced plasma ($n \sim 10^{12} - 10^{13}$ cm^{-3}, $T_i \sim 10$ eV), although the linked quadrupole field could only reduce but not reverse the average magnetic field curvature. In those experiments, the plasma β did not exceed a fraction of one percent [5]. We report in this letter the first experiments in a new ten meter multiple mirror device [6], designed mainly to study multiple mirror confinement, MDH stability and diffusion of transient finite β plasmas in linked quadrupole fields. The experiments reported here address the stability question for plasmas with $\beta \sim 1 - 10\%$.

The experiment consists of a one meter guide field section followed by a series of eight mirror cells, as indicated in Fig. 1. The axial field consists of a uniform solenoid and nine sharp mirrors whose 75 cm spacing determines the cell length. In addition, two sets of quadrupole bars, a weak and a strong quadrupole, are present in each cell, and reverse polarities between cells. These have been optimized to give the best minimum-average-B operation [7]. The quadrupole components make the flux surfaces fan periodically as a series of ellipses with alternate vertical and horizontal axes as seen in Fig. 1. The solenoidal, mirror, weak and strong quadrupole current are provided by four separate capacitor banks, with the current rising in $\sim 500\ \mu s$ and decaying in ~ 2 ms . For a mirror ratio $M = 4$, the mirror throat ellipticity (major/minor radii) is ~ 24 ; for $M = 3$, the ellipticity is ~ 18 . In these experiments, the midplane magnetic field was operated between 1.5 and 2 KG which is less than 40% of the maximum field allowed by the 300 KJ capacitor banks. These operating conditions were chosen as a compromise between the conflicting requirement of high β and low radial diffusion given the density limitations of the plasma source. The straight stainless steel vacuum chamber has an inner diameter of 8.6 cm with a base pressure $\leq 5 \times 10^{-6}$ Torr . The plasma source is a coaxial gun with outer and inner copper electrode lengths of 10 and 7 cm and diameters of 5 and 1 cm , respectively. The gun is powered by a 15 μF , 10 KV capacitor bank discharging into a puff of hydrogen of $\sim 10^{19}$ particles. Initially the gun was operated in the self-switched deflagration mode [8]; however, most of the experiments are performed in the snowplow mode [9] with an ignition switch, since this regime provides a denser and cooler plasma more suited to our experiments. The optimum delay between the puff valve and the gun firing is found experimentally to be about 250 μs compared to 100 μs in the deflagration mode, with a factor of ten increase in density. A 5° focusing taper added later on the outer electrode provides another factor of two increase in density. The plasma pulse of half width $\sim 80\ \mu s$ is injected through a circular limiting aperture located at the first midplane M_{23} as indicated in Fig. 1, in order to force the plasma cross-section to be circular at a midplane as required [7]. The guide field allows time of flight separation of the neutral gas from the plasma. The basic diagnostic for these experiments is an axial array of Langmuir probes, biased at -50 V to collect the ion saturation current or used for electron temperature measurement. Compensated diamagnetic loops are also used to yield the plasma β . A plasma camera was used together with an electron beam to align the magnetic field. Photographs of the flux surfaces at the midplanes and throats are given in Fig. 1.

The results of different modes of operation of the gun are given in Fig. 2 as axial density profiles from Langmuir probes located on axis at various midplanes. The relation used between the ion saturation current collected and the density shown in Fig. 2 is obtained from Laframboise's probe theory [10]. Each point is an average over several shots, the bars referring to the typical gun scatter of 30 - 40% from shot to shot. The axial profiles of Fig. 2 were taken with linked quadrupole mirrors as described earlier. In Fig. 3(a) we give the Langmuir probe ion saturation current as function of time for one of the shots of Fig. 2(d). All curves (a) to (f) correspond to qualitatively similar traces. The probes indicate an initial fast plasma component, $\leq 50\ \mu s$ after the gun firing, which propagates through the entire system. Following this, large fluctuations occur until at about $100\ \mu s$ after the gun firing, the smooth decay of a plasma trapped in the mirrors cells begins. A maximum density of the trapped component is observed at intermediate gun voltage ~ 7 KV . At low voltage ≤ 4 KV , very little plasma overcomes the mirror field barrier, while at about 9 - 10 KV , most of the plasma is observed in the initial fast component. The decays, although not purely exponential, can be interpreted in terms of 1/e times of 80 , 120 and 150 μs for the first, second and third probes, respectively. In Fig. 3(b) are given the traces obtained with the same experimental parameters as in Fig. 3(a) except that the quadrupole currents are zero. In this unstabilized mirror configuration, one observes, in contrast with Fig. 3(a), large amplitude density fluctuations and a very rapid plasma loss, evidence suggesting gross MHD instability. We note, however, in the first trace of Fig. 3(b) a somewhat stable behavior sometimes observed near the beginning of the device, which we interpret as partial stabilization from the gun residual plasma stream and/or from line-tying to the graphite limiter. This is never obserbed in the middle (M_{56}) or towards the end (M_{78}) of the device. We conclude that the quadrupole currents do provide an effective stabilization of the most dangerous MHD modes. This stabilization is obtained over a range of quadrupole currents; at $M = 4$ a variation of 20% in the weak and strong quadrupole currents does not change appreciably the above results. Similar stable decay is obtained at $M = 3$.

For the highest densities corresponding to the parameters of Fig. 2(f), a direct measure of the plasma β is obtained with a compensated double diamagnetic loop. Fig. 4 shows the output of the loop at the center of the device (M_{56}), together with the trace of a Langmuir probe placed on axis just in fron of the loop. We obtain from the peak of the second hump (trapped component) in Fig. 4(a) a reasonable estimate of β . The integrated loop voltage v_s is related to the plasma diamagnetism to obtain the centerline value of β by $\beta = kv_s/(B_o r_p^2)$, where the radial plasma profile $n(r) = n_o[1-(r/r_p)^2]^{\frac{1}{2}}$ has been assumed, and k is determined by the physical parameters of the loop and the integration circuit. The measured radial profile is in rough agreement with this assumption, with $r_p \sim 1.5$ cm . The data in Fig. 4(a) with a value of $B_o = 1.6$ KG yields $\beta = 2 \pm 0.8\%$. Similar measurements at M_{34} gave $\beta = 8 \pm 3\%$. In Fig. 4(a) the Langmuir probe collected current yields a centerline density of 3.7×10^{13} cm^{-3} with an uncertainty of about 50% . The corresponding value of $T_e + T_i$, inferred from the value of β , is 34 eV , with an uncertainty of a factor of 2 . The electron temperature was measured using a Langmuir probe at M_{56} to be 8 ± 2 eV . No measurements of ion temperature were made but the inferred value of T_i is consistent with the gun operation [11] ($\sim$10 - 30 eV).

Finally, we make the point that for these low magnetic field experiments, the plasma confinement inside the device appears dominated by radial losses. Assuming an average density of 2×10^{13} cm^{-3} , $T_e = 8$ eV and $T_i = 15$ eV , we estimate an MHD flow time enhanced by the mirror ratio of 200 μs [12] and an ideal multiple mirror axial diffusive time of about 1 ms [1]. These have to be compared with radial losses due both to electron-ion collisions and higher order ion-ion collisions, both enhanced by the non-uniform cross-section [13]. The classical radial losses alone are estimated to give a decay time of 100 μs , which is about equal to that observed.

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REFERENCES

[1] Logan, B. G., Lichtenberg, A. J., Lieberman, M. A., Makhijani, A., Phys. Rev. Lett. 28 (1972) 144

[2] Budker, G. I., Mirnov, V. V., Ryutov, D. D., ZHETF Pis. Red. 14 (1971) 320

[3] Logan, B. G., Brown, I. G., Lieberman, M. A., Lichtenberg, A. J., Phys. Rev. Lett. 29 (1972) 1435

[4] Riordan, J. C., Tuszewski, M., Lichtenberg, A. J., Plasma Physics 20 (1978) 139

[5] Tuszewski, M., Lichtenberg, A. J., Eylon, S., Nucl. Fusion 17 (1977) 893

[6] Lichtenberg, A. J., Lieberman, M. A., Bravenec, R., Hartman, C., Price, D., Puri, S., Riordan, J., Tuszewski, M., Bull. Am. Phys. Soc. 23 (1978) 911

[7] Riordan, J. C., Lichtenberg, A. J., Lieberman, M. A., Nucl. Fusion 19 (1979) 21

[8] Cheng, Dah Yu, Nucl. Fusion 10 (1970) 305

[9] Marshall, J., Phys. Fluids 3 (1960) 135

[10] Laframboise, J. G., Univ. of Toronto, Inst. for Aerospace Studies, Report UTIAS-100 (1966)

[11] Chang, C. N., private communication

[12] Makhijani, A., Lichtenberg, A. J., Lieberman, M. A., Logan, B. G., Phys. Fluids 17 (1974) 1291

[13] Tuszewski, M. and Lichtenberg, A. J., Phys. Fluids 20 (1977) 1263

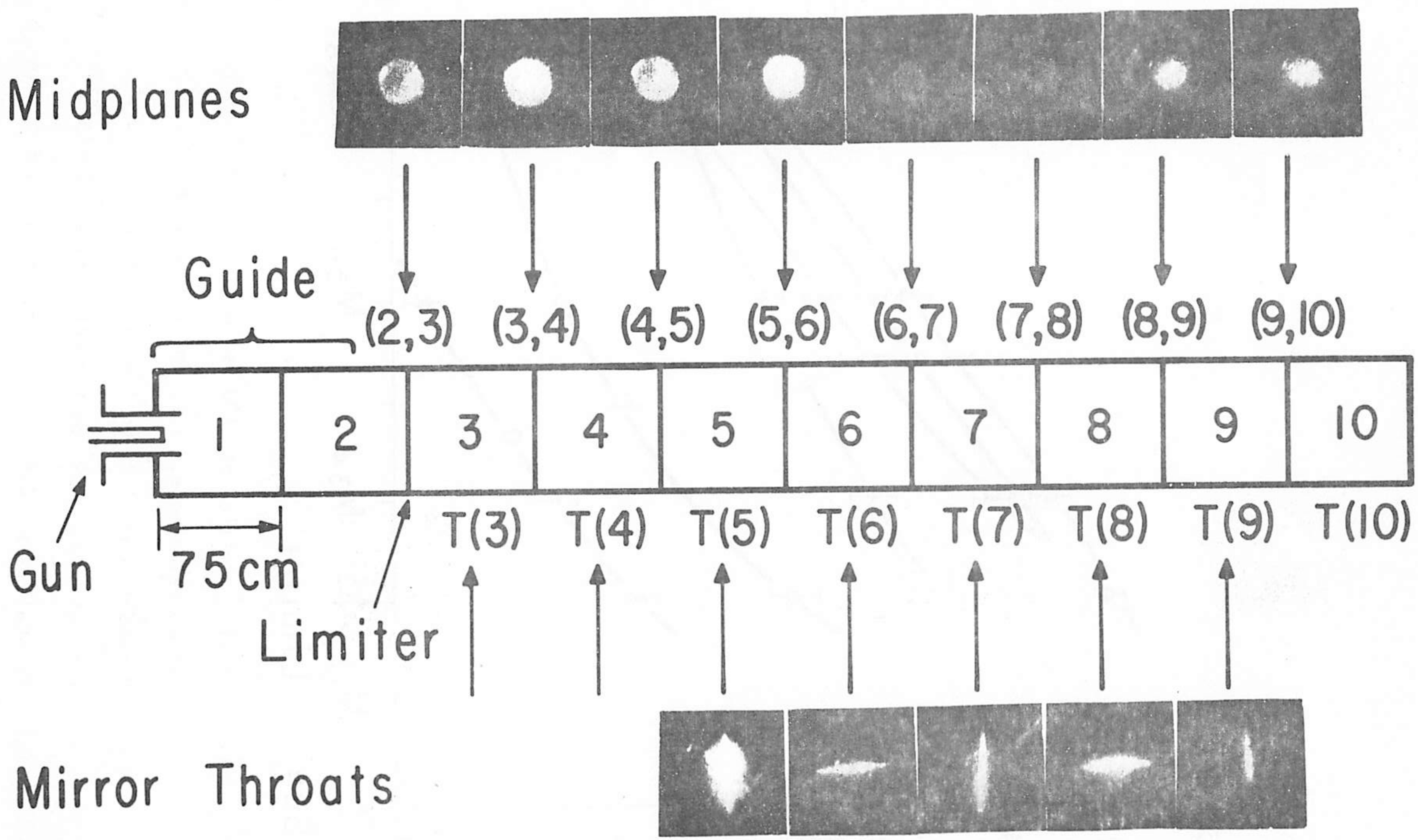

FIG. 1. Schematic of the 10 meter multiple mirror experiment.

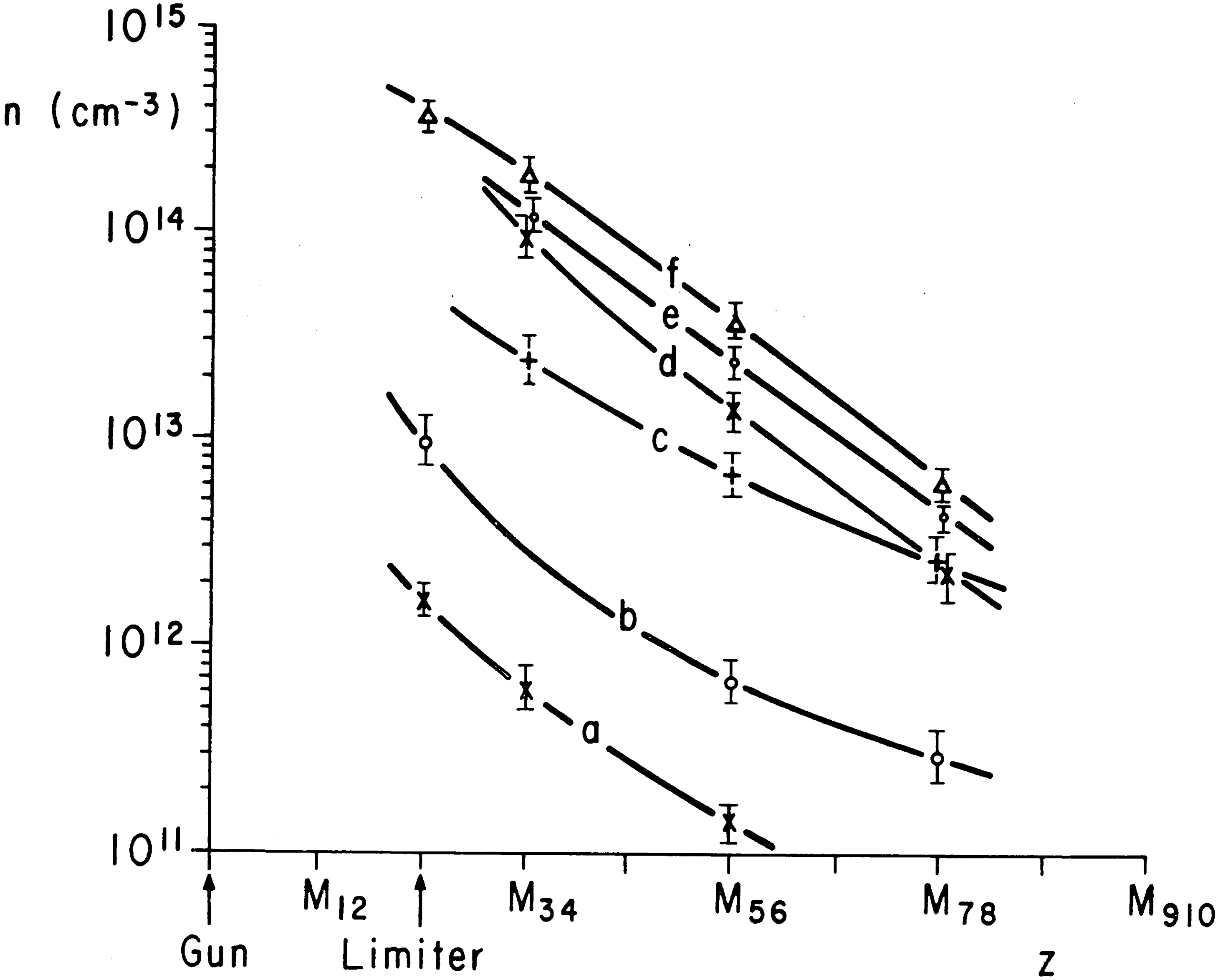

FIG. 2. Axial density profiles at 100 μs after the gun firing.

(a) Deflagration mode, 1.25 cm limiter, $M = 4$, $C = 15$ μF

(b) Marshall mode, 1.25 cm limiter, $M = 4$, $C = 15$ μF

(c) Marshall mode, 1.9 cm limiter, $M = 4$, $C = 15$ μF

(d) Marshall mode, 2.5 cm limiter, $M = 4$, $C = 15$ μF, 5° taper

(e) Marshall mode, 2.5 cm limiter, $M = 3$, $C = 15$ μF, 5° taper

(f) Marshall mode, 2.5 cm limiter, $M = 3$, $C = 23$ μF, 5° taper

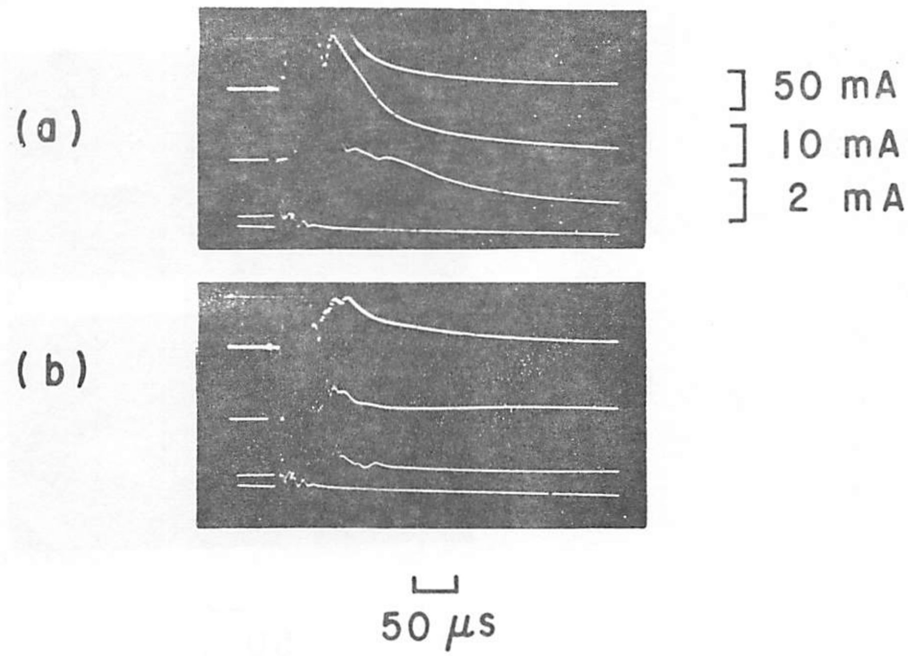

FIG. 3. Plasma density decay as function of time. Langmuir probes at M_{34} (1^{st} trace), M_{56} (2^{nd} trace), M_{78} (3^{rd} trace), and gun current (4^{th} trace).

(a) Stabilized system

(b) Unstabilized system

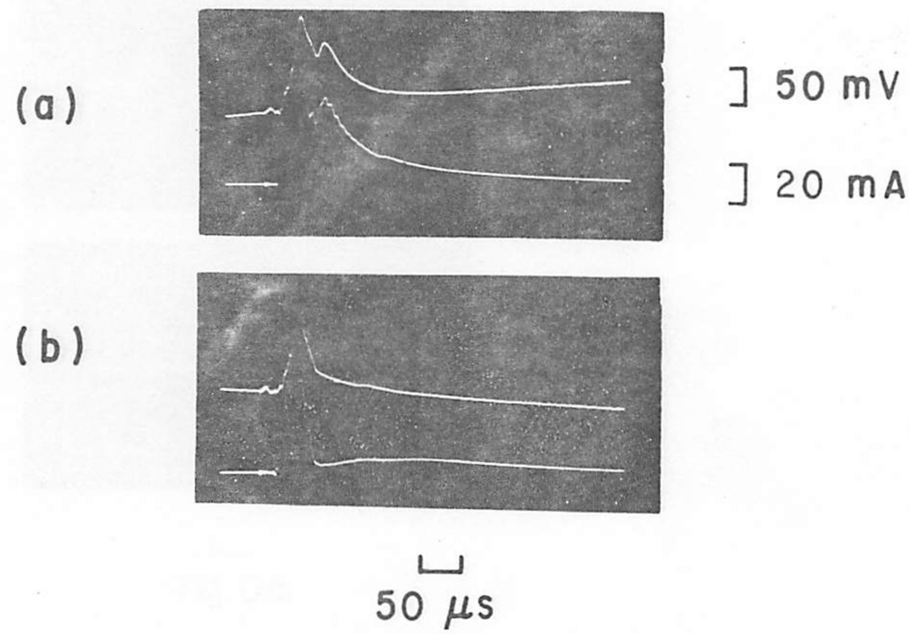

FIG. 4. Plasma β and density decays as function of time. Diamagnetic loop (top trace) and Langmuir probe (bottom trace) at M_{56} .

(a) Stabilized system

(b) Unstabilized system