LOSS OF BEAM IONS TO THE INSIDE OF THE PDX TOKAMAK DURING THE FISHBONE INSTABILITY

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W.W. HEIDBRINK, P. BEIERSDORFER

Plasma Physics Laboratory,
Princeton University,
Princeton, New Jersey
United States of America

ABSTRACT. Using data from two vertical charge-exchange detectors on the Poloidal Divertor Experiment (PDX), we have identified a set of conditions for which loss of beam ions inward in major radius is observed during the fishbone instability. Previously, it was reported that beam ions were lost only to the outside of the PDX tokamak.

In high $\beta_T q$ discharges with near-perpendicular neutral beam injection in PDX, an MHD instability called the fishbone instability ejected beam ions from the plasma [1]. Theoretical studies by White *et al.* [2] found that rotating MHD modes similar to those observed in the experiment resonate with the toroidal precession of the beam-ion orbits, resulting in the loss of many of the injected beam ions. The mode resonance was predicted to produce a beacon of outwardly exiting beam particles correlated with the mode rotation [2]. Studies of the charge-exchange efflux with toroidally displaced detectors found the predicted $n = 1$ modulation of the beam-ion loss [3]. The mode-particle resonance theory also correctly predicted experimental observations that the beam-ion loss scales linearly with the amplitude of the mode [4]. The loss of non-resonant fusion products also could be explained using White's fishbone model [5]. Further support for the model was given in Ref. [3], where measurements with two vertically viewing neutral-particle analyzers indicated that beam ions were lost to the outside of the plasma but not to the inside.

In this letter, data from the inner vertical charge-exchange detector (IDE) of Ref. [3] are presented that indicate that 50 keV beam ions were lost to the inside of the PDX tokamak during the fishbone instability when the ions measured by IDE were on confined orbits.

Fig. 1 shows bursts of charge-exchange flux on IDE that correlate with bursts of fishbone MHD activity. In this discharge, the plasma underwent a transition into the High-mode [6] at 480 msec. Prior to the transition, large ($\gtrsim 10\%$) variations in H_α emission were not observed but, after the transition, sudden changes in neutral density associated with Edge Relaxation Phenomena (ERP) [7] correlate with charge-exchange bursts and fishbones. Conceivably, variations in neutral density might account for the bursts on IDE in the High-mode but in the Low-mode the charge-exchange bursts are almost certainly due to an increase in the number of fast ions in the IDE sightline. From the relatively gradual decay of the MHD bursts (~ 1 msec), the possibility that sawteeth were coincident with the fishbones can be excluded [4,8], so the bursts are not due to the transport of the fast ions at sawteeth [9]. Since the IDE sightline skims the inner radius of the plasma, these bursts indicate that fishbones transport beam ions inward in major radius as well as outward.

Usually the signal-to-noise ratio on IDE was inadequate to ascertain if the charge-exchange flux was modulated by the fishbone oscillations (as it was on the outer edge of the plasma [1,3]). Fig. 2 shows one of the few events where internal structure seems to be present. This burst was synchronous with a large fishbone (fractional change in neutron emission $\Delta I_n / I_n = 25\%$) in a discharge with relatively large neutral density

(P_b = 4.7 MW). It is estimated that the peak signal level corresponds to less than one hundred counts at the IDE channeltron detector, so even in this case errors associated with counting statistics are appreciable. A peak in the Fourier spectrum occurs near the frequency of peak amplitude of the Mirnov oscillations, suggesting that the spikes are due to beam-ion motion induced by the mode.

A further indication that ions were lost to the inside of the tokamak is that the change in flux at a fishbone scales approximately linearly with the severity of the fishbone (Fig. 3). The quantity $\Delta I_n/I_n$ in Fig. 3 is approximately the fraction of energetic ions lost at the fishbone event [4]. Fig. 3 shows that the flux depends much more strongly on $\Delta I_n/I_n$ than on the existence of a coincident ERP instability.

All of the above data are for neutrals with energy E approximately equal to the neutral beam injection energy E_{inj} and $I_p \gtrsim 350$ kA. For energies well above E_{inj} ($E - E_{inj} \gtrsim 10$ keV) or slightly below E_{inj} ($E - E_{inj} \lesssim -3$ keV), bursts of beam ions were not clearly observed on IDE unless an ERP or sawtooth instability was coincident with the fishbone (Fig. 4). For $E - E_{inj} \lesssim -10$ keV, a combined fishbone and ERP sometimes increased the flux an order of magnitude relative to the flux at either a fishbone or an ERP alone. It appears that ions with E = 25–35 keV were not moved into the IDE sightline unless the fishbone instability was assisted by transport from another instability.

Bursts on IDE during the fishbone instability were not observed unless the plasma current was sufficiently large to confine beam ions in the IDE sightline (Fig. 5). For deuterons with energy E = 45 keV, most of the ions in the IDE sightline hit vacuum vessel hardware when the plasma current was below $I_p \lesssim 275$ kA. The corresponding cutoff for the outer detector (ODE) at 45 keV was $I_p \lesssim 225$ kA. PDX rarely operated below 225 kA, however, so a reduction in the amplitude of the burst at low plasma current was not observed on ODE for $E \lesssim E_{inj}$. In fact, ODE measured bursts during the fishbone instability even if the detected ions were on unconfined orbits: for example, large bursts were observed with ODE at E = 80 keV at $I_p \simeq 225$ kA.

In conclusion, for $I_p \gtrsim 350$ *kA and* $E \gtrsim E_{inj}$, *fast ions were lost to the inside of the* tokamak at the fishbone instability. These losses still were two orders of magnitude less than the losses to the outside of the tokamak observed on ODE, however. Detailed Monte Carlo simulations of fishbones predict [10] that some ions should move inward in major radius due to a combination of mode-particle pumping [2] and classical Coulomb scattering. Thus, the observation of some transport to the inside of the tokamak is not inconsistent with either mode-particle pumping theory [2] or with the major conclusions of the PDX paper that first reported results from IDE [3].

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Figure Captions

Fig. 1 (a) *Time evolution of $\dot{B}_\theta$, IDE flux at $E = 45$ keV, and H_α emission from the PDX dome in a discharge that underwent a transition into the High-mode at 480 msec. $P_b = 2.5$ MW; $E_{inj} = 43.9$ keV; $\bar{n}_e \simeq 1.6 \times 10^{13}\,\mathrm{cm}^{-3}$ (at 480 msec); $I_p \simeq 360$ kA; $B_t \simeq 1.7$ T.* (b) *Cross-correlation functions of $\dot{B}_\theta$ with IDE flux and IDE flux with the H_α signal during the Low-mode (400–470 msec). The IDE signal correlates strongly with the Mirnov signal but less strongly with the H_α emission. The correlation of IDE flux with H_α emission from the midplane is even weaker.*

Fig. 2 (a) *Time evolution of the IDE signal ($E = 40$ keV) through a large fishbone ($\Delta I_n/I_n = 25\%$) in a plasma with relatively large neutral density. $P_b = 4.7$ MW; $I_p = 320$ kA; $B_t = 17.8$ kG; $\beta = 1.1\%$.* (b) *Fast Fourier transform (amplitude) of the IDE signal in* (a)*. The lines indicate the range of frequencies over which large amplitude oscillations were observed on a Mirnov coil. The peak in the Fast Fourier transform amplitude at the fishbone frequency is roughly ten times larger than the amplitude which results from analyzing IDE signals without a concurrent fishbone instability.*

Fig. 3 Change in flux averaged over a fishbone burst versus the drop in the neutron emission, $\Delta I_n/I_n$. $E - E_{inj} = 3$–8 keV; $I_p > 345$ kA. The error bars are estimates of the effect of noise on the measurements.

Fig. 4 Flux averaged over a fishbone burst versus energy for moderate amplitude fishbones ($\Delta I_n/I_n > 5\%$). $I_p > 345$ kA. The hatched region is the flux observed in the absence of fishbones; statistically significant bursts lie above this hatched region. Below $\sim 10^{-2}$, the noise is comparable to the signal. The solid points indicate that a spike in the H_α emission (an ERP) was coincident with the fishbone.

Fig. 5 Change in flux averaged over a fishbone burst versus plasma current for moderate amplitude fishbones ($\Delta I_n/I_n > 5\%$). $E - E_{inj} = 3$–8 keV. The line indicates the approximate current level where orbits of 50 keV deuterons in the IDE sightline become confined.

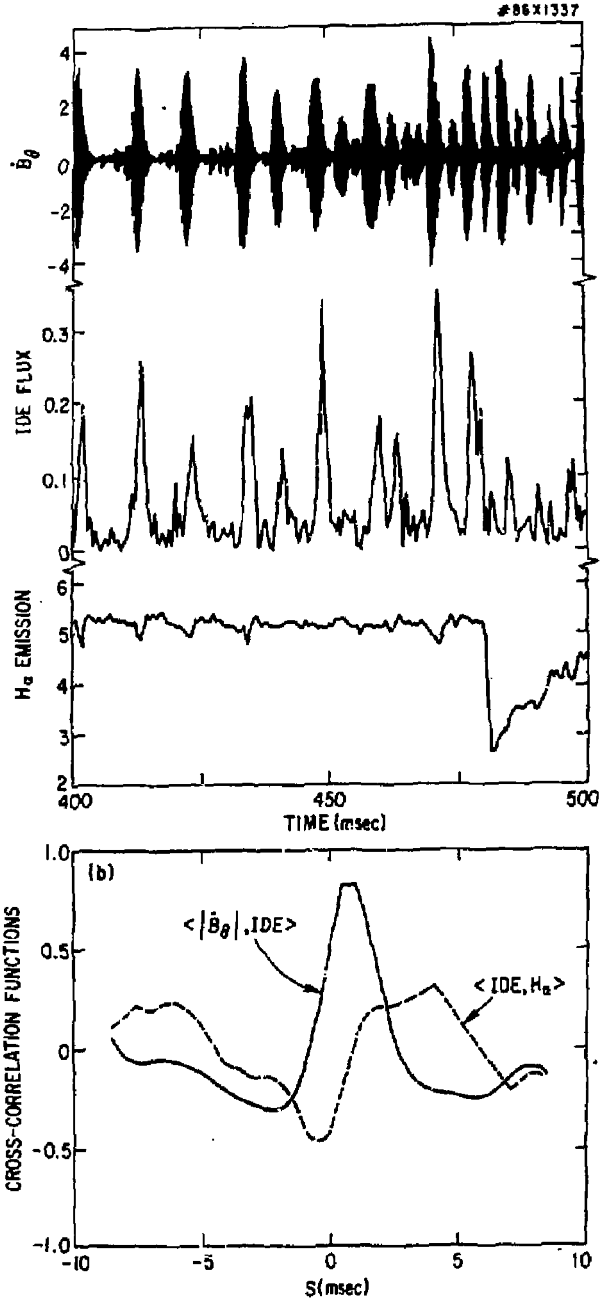
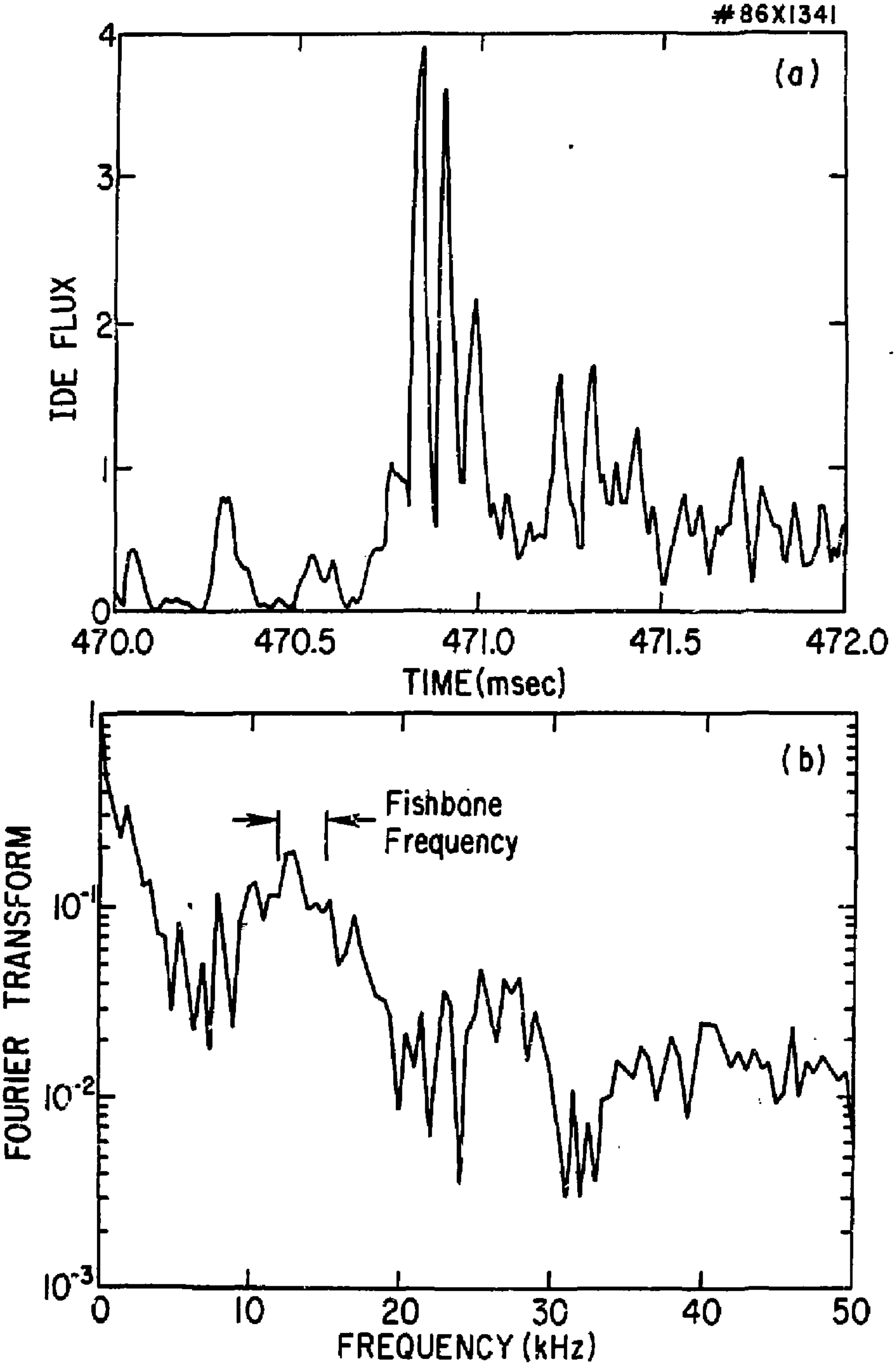

#86X1337
$\dot{B}_\theta$
4
2
0
-2
-4
IDE FLUX
0.3
0.2
0.1
0
H_α EMISSION
6
5
4
3
2
400
450
500
TIME (msec)
(b)
CROSS-CORRELATION FUNCTIONS
1.0
0.5
0
-0.5
-1.0
$<|\dot{B}_\theta|, IDE>$
$<IDE, H_\alpha>$
-10
-5
0
5
10
S(msec)

Fig. 1



#86X1341
(a)
IDE FLUX
0
1
2
3
4
470.0
470.5
471.0
471.5
472.0
TIME (msec)
(b)
Fishbone Frequency
FOURIER TRANSFORM
1
10^{-1}
10^{-2}
10^{-3}
0
10
20
30
40
50
FREQUENCY (kHz)

Fig. 2

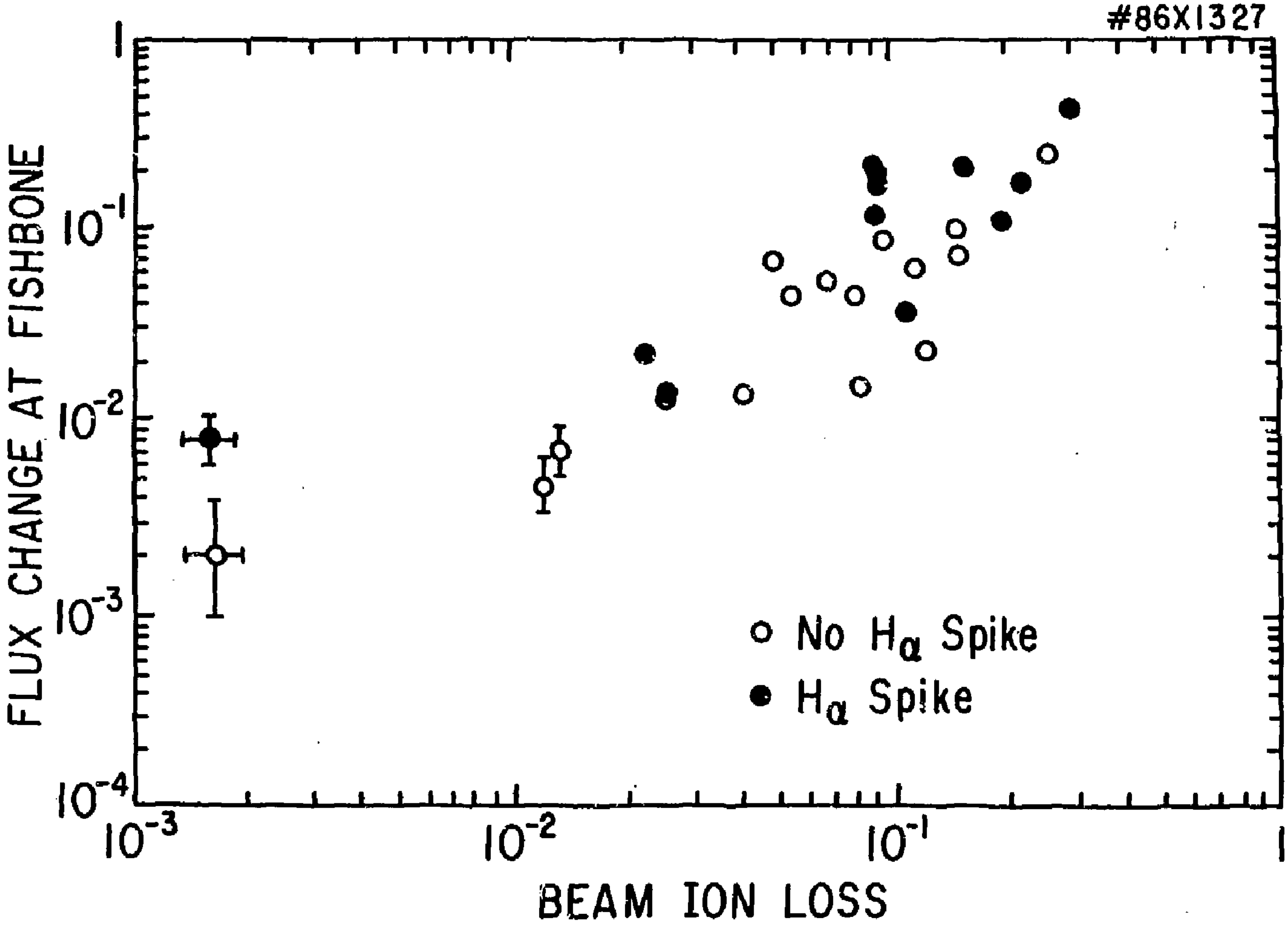

#86X1327
FLUX CHANGE AT FISHBONE
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
BEAM ION LOSS
○ No H_α Spike
● H_α Spike

Fig. 3

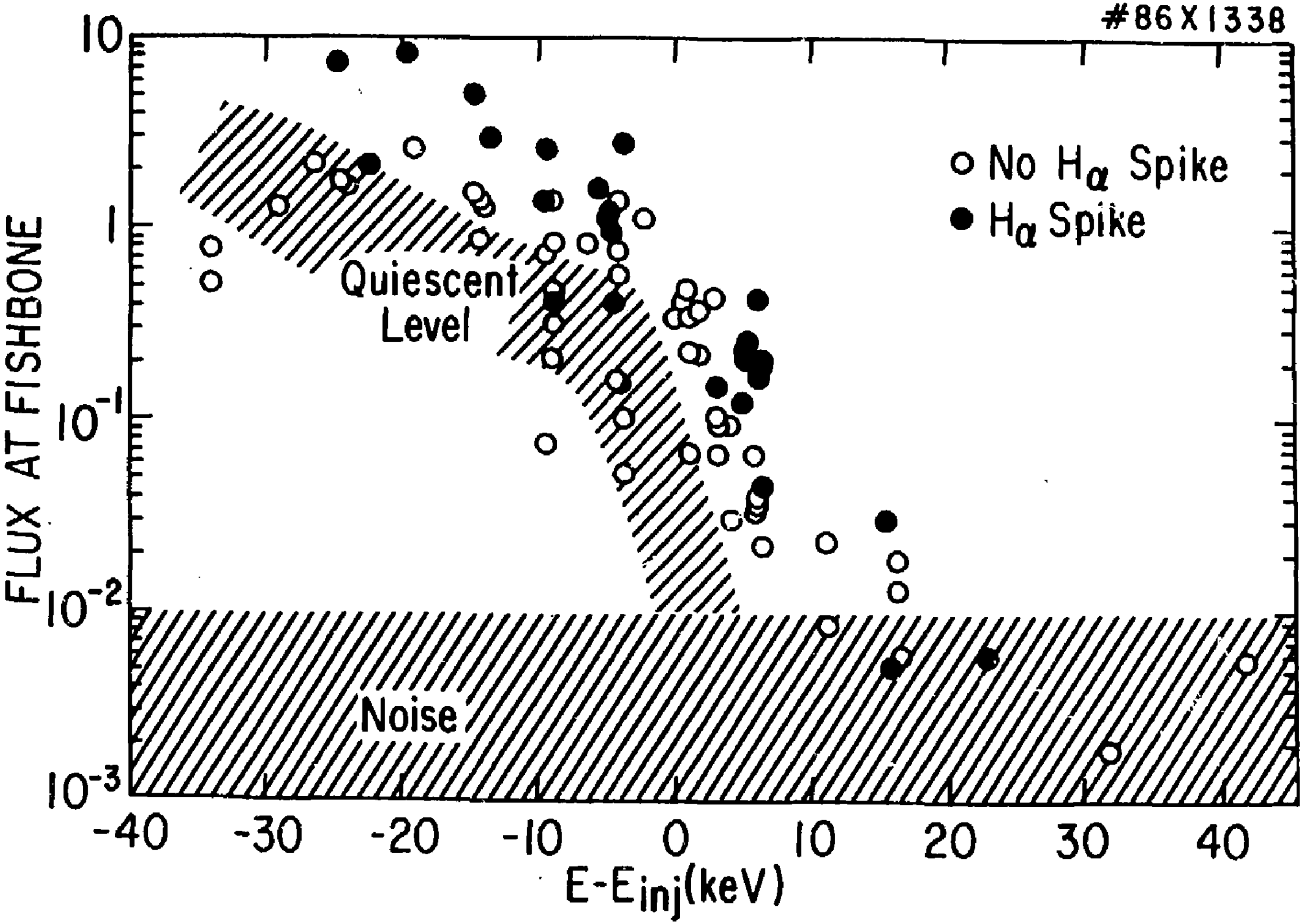

#86X1338
FLUX AT FISHBONE
10
1
10^{-1}
10^{-2}
10^{-3}
-40
-30
-20
-10
0
10
20
30
40
E-E_{inj}(keV)
○ No H_α Spike
● H_α Spike
Quiescent Level
Noise

Fig. 4

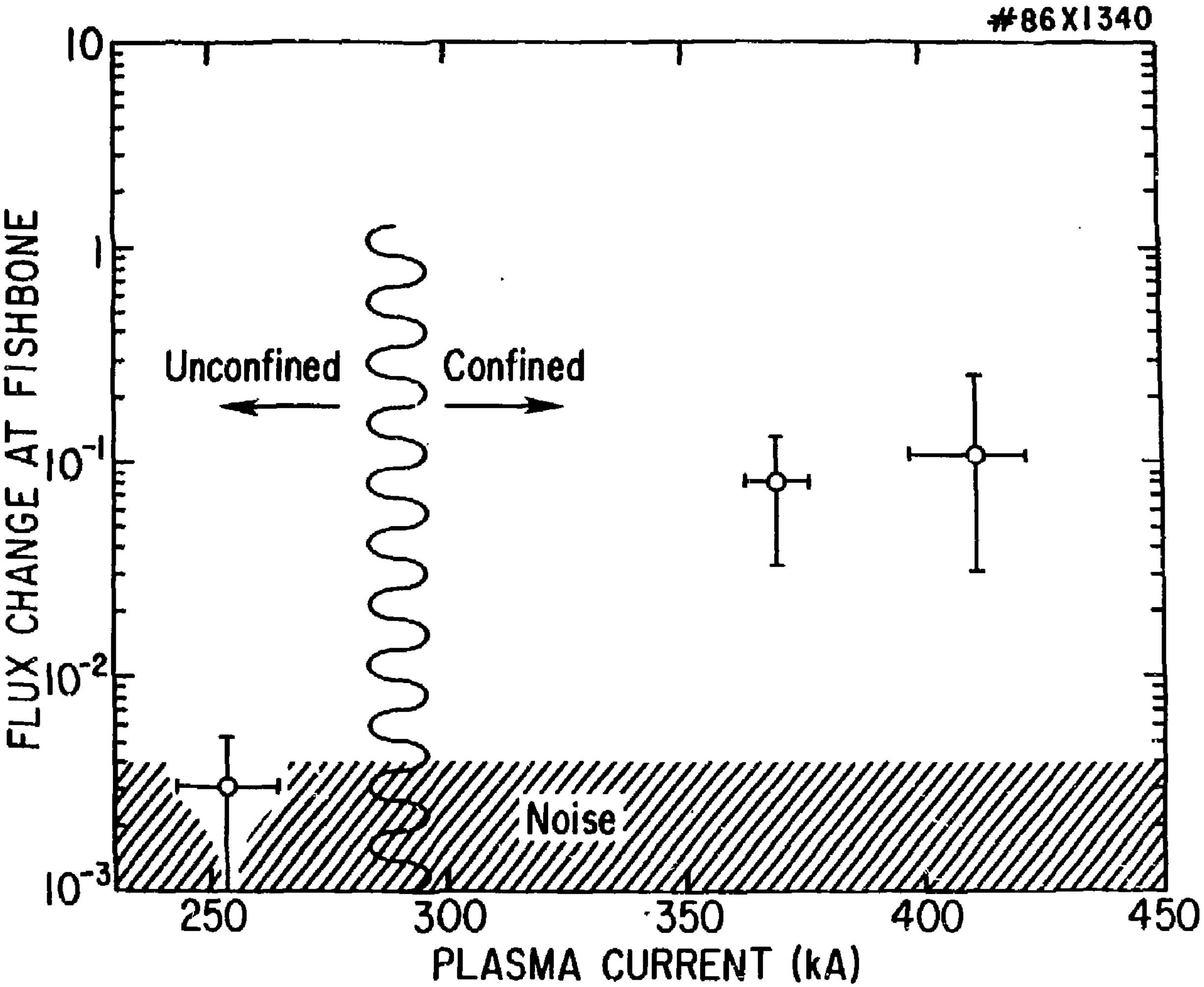

#86X1340
FLUX CHANGE AT FISHBONE
10
1
10^{-1}
10^{-2}
10^{-3}
Unconfined
Confined
Noise
250
300
350
400
450
PLASMA CURRENT (kA)

Fig. 5

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