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FAST TIME RESOLUTION CHARGE-EXCHANGE MEASUREMENTS DURING THE "FISHBONE" INSTABILITY IN THE POLOIDAL DIVERTOR EXPERIMENT

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FAST TIME RESOLUTION CHARGE-EXCHANGE MEASUREMENTS DURING THE "FISHBONE" INSTABILITY IN THE POLOIDAL DIVERTOR EXPERIMENT

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ABSTRACT

Measurements of fast ion losses due to the "fishbone" instability during high $\beta_{T}q$ neutral beam heated discharges in the Poloidal Divertor Experiment have been made using two new vertical-viewing charge-exchange analyzers. The measurements show that the instability has an n=1 toroidal mode number, and that it ejects beam ions in a toroidally rotating beacon directed outward along a major radius. Observations of ejected ions with energies up to twice the beam injection energy at $R \approx R_o + a$ indicate the presence of a non-μ-conserving acceleration mechanism.

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I. INTRODUCTION

Recently, a new instability, dubbed the "fishbone" instability from its characteristic signature on the Mirnov coils, has been observed during high $\beta_T q$ discharges in the Poloidal Divertor Experiment (PDX), with near perpendicular neutral beam injection.[1] The instability ejects bursts of fast ions at a repetition rate of 1-10 msec and causes a drop in the neutron emission as large as 40%. It may account for a 20-40% loss of the beam heating power and thus may be responsible for the observed saturation of beam heating at high $\beta_T q$.[2]

In this paper the efflux of fast neutrals from the plasma is used to study the features and dynamics of the fishbone instability. The results are compared to a fishbone model developed recently by White et al. to describe mode induced beam particle losses.[3]

II. APPARATUS

Two new charge-exchange analyzers were installed on PDX, viewing the plasma edge along the nearly-vertical sightlines shown in Fig. 1. For a plasma major radius of R_o = 145 cm and a minor radius of r = 40 cm, the sightlines of the outside (ODE) and of the inside (IDE) detector skim the outer and inner plasma edges, crossing the horizontal midplane at a major radius of $R = R_o \pm 37$ cm, respectively. The locations of the sightlines were chosen so as to determine the direction along the major radius in which the fast ions are preferentially lost during the fishbone activity.

The need for vertical sightlines made it necessary to locate ODE between two adjacent toroidal field coils. The toroidal field at this location was estimated to be as high as 0.5 T during at 2.5 T discharge, which imposed severe magnetic shielding requirements. The limited space available between the toroidal field coils, furthermore, meant that the analyzer had to be as compact as possible. These constraints resulted in the design of ODE as shown in Fig. 2. Instead of the usual gas stripping cell, a 5 mm diameter, 100Å thick carbon foil supported by a 90% transmission nickel mesh was employed to ionize incoming neutrals. The emerging ions were energy-analyzed using electrostatic deflection plates, and were detected using a Channeltron detector, operated in current mode within its linear amplification range. The analyzer was partially magnetically shielded by its vacuum enclosure, which was constructed of 2.5 cm thick soft iron. Additional shielding, consisting of 1.2 cm thick soft iron separated by a 1.2 cm wide air gap from the analyzer housing, sufficiently attenuated fields as high as ~ 1 T. This allowed particles with energies as low as 10 keV to be detected. The PDX vacuum system was used to maintain the vacuum in the analyzer housing and the flight tubes connecting the analyzer to PDX.

IDE was constructed similar to ODE, though no double shielding was employed since it was possible to place IDE in a region on PDX where the ohmic heating and equilibrium magnetic fields were much lower. The integration time of the analyzers and associated electronics was approximately 30 μsec, while the signals were digitized at a rate of 100 kHz.

The toroidal location of the new analyzers is shown in Fig. 3. Also shown is the horizontally scanning charge-exchange analyzer of the Fast Ion Diagnostic Experiment (FIDE). The toroidal angle between ODE and IDE is 36°, and between ODE and FIDE is 88°.

III. RESULTS

Typical 35 keV charge-exchange signals obtained with ODE and IDE for deuterium injection into a deuterium divertor plasma are shown in Fig. 4.

Strong fishbones are seen on the ODE signal about 50 msec after the start of neutral beam injection (t = 300 msec), and repeat about every 5 msec. During fishbone spikes, the fast neutral efflux is enhanced by factors of 10 to 100 over the background charge-exchange flux. In Fig. 4, the fishbone activity lasts until a disruption terminates the discharge at t ≈ 460 msec. Without disruptions, fishbone activity may persist throughout the entire beam heating phase. The IDE signal, on the other hand, shows no sign of fishbone activity, even at a greatly increased gain (by a factor of ~ 1000) relative to ODE. This marked difference in the ODE/IDE signals is present regardless of the plasma major radius, which was varied between 135 and 150 cm. Thus the difference in signal amplitude is not a sensitive function of the distance between a given sightline and the plasma edge, but rather indicates that particles escape the plasma primarily in the direction of increasing major radius. The FIDE analyzer is capable of viewing the plasma along many sightlines in the horizontal midplane, and the signal along its most perpendicular sightline (4.4° at R = 182 cm) is usually very similar to that measured with ODE.

An expanded view of the charge-exchange flux during a single fishbone (Fig. 5) reveals its internal, oscillatory structure. This feature is used to determine the toroidal mode number by comparing phases between signals observed with ODE and with FIDE. After compensating for the their different integration times, it is found that the FIDE signal leads the ODE signal by an average phase difference of 98° ± 15°. Since ODE and FIDE are separated by a toroidal angle of about 88°, this result indicates a toroidal mode number of n=1 and is consistent with Mirnov coil data.[1]

The internal frequency for the fishbone in Fig. 5 is plotted versus time in Fig. 6. The frequency decreases exponentially in time at a rate of about 450 Hz during the initial 1 msec of the instability, and decreases at a slower rate towards the end. Exponential decay rates as fast as 700 Hz and as slow as 200 Hz have been observed during the initial phase of the instability. The average duration of the particle efflux versus energy during the fishbone instability is plotted in Fig. 7. Here the fishbone width is defined as the full temporal width of the particle efflux at half maximum. The figure provides an indication of the duration of the mode-particle interaction for ions of a given energy. Although the fishbone width plotted in Fig. 7 may be affected by the particle distribution in the plasma, the figure implies a resonance between the mode and 35 keV particles. The energy of the particles with which the mode predominately interacts may actually be higher, since according to the model by White _et_ _al_. existing particles will typically have lost some of their energy to the mode.

With somewhat different discharge parameters it was possible to measure the ejected particle flux levels versus energy in the 25 to 60 keV range (Fig. 8). The flux here is defined as the average height of the fishbone minus the background charge-exchange flux, times the full width at half maximum of the fishbone. The data have been corrected for the foil stripping efficiences at each energy. Figure 8 shows that the fishbone instability primarily expels ions with energies around 37 keV, while fewer ions are ejected near the injection energy. A second ejection peak is observed for ions with $E \approx 47$ keV. Similar results have been obtained with FIDE's most perpendicular channel, where again, only few ions are found to be lost at E_{inj}. The ratio of the second peak ($E > E_{inj}$) to the first peak ($E < E_{inj}$), however, is considerably smaller than the ratio observed with ODE. This may suggest that unlike the orbits of the low energy ions, the orbits of those with $E > E_{inj}$ are located primarily near $R = R_0 + a$. Thus ODE would be more sensitive to those orbits than FIDE. On other run days, strong fishbones were seen at energies as low as thermal energies on FIDE and as high as the detection limits of the analyzers (80 keV on ODE, 100 keV on FIDE).

IV. DISCUSSION

The results indicate that the plasma ions are expelled in a toroidally rotating "beacon" in the direction of increasing major radius. This is consistent with a mode particle pumping model developed recently by White *et al.*[3] The toroidal frequency of rotation of the mode causing this beacon lies between 12 and 19 kHz as seen in Fig. 6. The precession frequency f for fast ions of energy E can be estimated by

$$f = \frac{cE}{2\pi R_o^2 e B_\theta} \left(1 - \frac{a}{R_o}\left(\beta_p + \frac{\ell_i}{2}\right)\right) ,$$

where B_θ is the poloidal field at the minor radius a, e is the electron charge, β_p is the poloidal beta, and ℓ_i is the plasma inductance. Thus beam ions in the energy range of 30 to 50 keV have precession frequencies comparable to the rotation frequency of the mode. This is consistent with the resonance between the mode and particles in this energy range, as implied in Fig. 7. Again, such a resonance agrees with the model developed by White *et al.*

The energy distribution of exiting ions within a fishbone reveals a double peak. Monte Carlo calculations by White *et al.* have shown that such a double-humped distribution may result, provided that toroidal plasma rotation is included in the mode particle pumping model.[3] If the double-humped feature of the distribution in the experimental data is due to a toroidal plasma rotation which shifts the energy distribution of the exiting ions, the shift in energy is consistent with a rotation speed on the order of 10^7 cm/sec. Central rotation speeds found by Brau et al.[4] using optical techniques on PDX are close to this value, although the rotation speed drops off with increasing minor radius.

In the mode particle pumping model developed by White et al., exiting particles will almost always lose energy, so that the maximum energy for an exiting ion is $\lesssim E_{inj}$. Even including the effects of toroidal rotation as described above, the maximum attainable energies according to White et al. should be less than $1.2 \times E_{inj}$.[3] On the other hand, strong particle bursts at energies as high as the detection limits of ODE (80 keV) and FIDE (100 keV) have been observed during fishbone activity. Since ODE in particular views these particles at the large major radius (low field) periphery of the plasma, a non-μ-conserving acceleration mechanism in addition to toroidal rotation is needed. Such a mechanism, however, has not yet been identified, although microinstability of the highly anisotropic exiting beam ion distribution in the cold scrape-off plasma seems a likely candidate. Acceleration due to this microinstability may explain the strongly enhanced flux of bulk plasma ions observed by the mass-resolving charge-exchange analyzer[5] and by FIDE in the energy range below 10 keV.

Thus, it appears that the fishbone activity is characterized by two perhaps distinct processes. One of them is the mode particle pumping mechanism responsible for the ejection of particles, and the other process causes the acceleration of beam ions. Together these processes may then be responsible for the high energy particles seen during some fishbones.

V. CONCLUSIONS

The measurements of the fast ion losses during high $\beta_T q$ discharges in PDX have shown the fishbone instability as causing the ejection of beam ions in a toroidally rotating beacon with toroidal mode number n=1. This feature is in good agreement with the mode particle pumping model developed by White et al. The duration and strength of the mode-particle interaction predicted by the model are consistent with our measurements. The data, however, also suggest the presence of some additional mechanism capable of accelerating particles to energies at least as high as 2 E_{inj}. Further work is needed to explain these results.

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[4]K. Brau *et al.*, Princeton Plasma Physics Laboratory Report No. PPPL-2013, 1983; Nucl. Fusion (in press).

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FIGURE CAPTIONS

FIG. 1 Poloidal cross section of PDX showing the sightlines of the outside (ODE) and inside (IDE) detectors. For a plasma major radius of $R_0 = 145$ cm, the sightlines of ODE and IDE cross the horizontal midplane at major radii of $R = R_0 \pm 37$ cm.

FIG. 2 Schematic diagram of the outside detector.

FIG. 3 Layout of PDX showing the location of the inside, outside, and FIDE detectors.

FIG. 4 35 keV charge-exchange flux on (a) ODE and (b) IDE. Beam injection starts at t = 300; a disruption terminates the discharge at $t \approx 460$ msec. $B_T \approx 11$ kG, $I_p \approx 220$ kA, $\beta_T q \approx 0.042$, $R_0 = 140$ cm, $r = 40$ cm, 4 beams, $P_{inj} \approx 4.0$ MW.

FIG. 5 Expanded view of a single fishbone revealing its internal oscillations. The period of the oscillations increases with time.

FIG. 6 Semi-log plot of internal frequency versus time for the fishbone in Fig. 5. The initial decay rate is 450 Hz.

FIG. 7 Full temporal width of the charge-exchange flux at half maximum of the ulation amplitude during fishbone activity, versus energy. The error bars represent statistical uncertainties in the data.

FIG. 8 Energy distribution of exiting particles during a fishbone instability. The beam injection energy is about 44 keV. B_T = 17 kG, I_p = 380 kA, R_o = 140 cm, a = 40 cm. The data were taken during the low mode phase of a two deuterium beam (2.5 MW) heated deuterium divertor plasma.

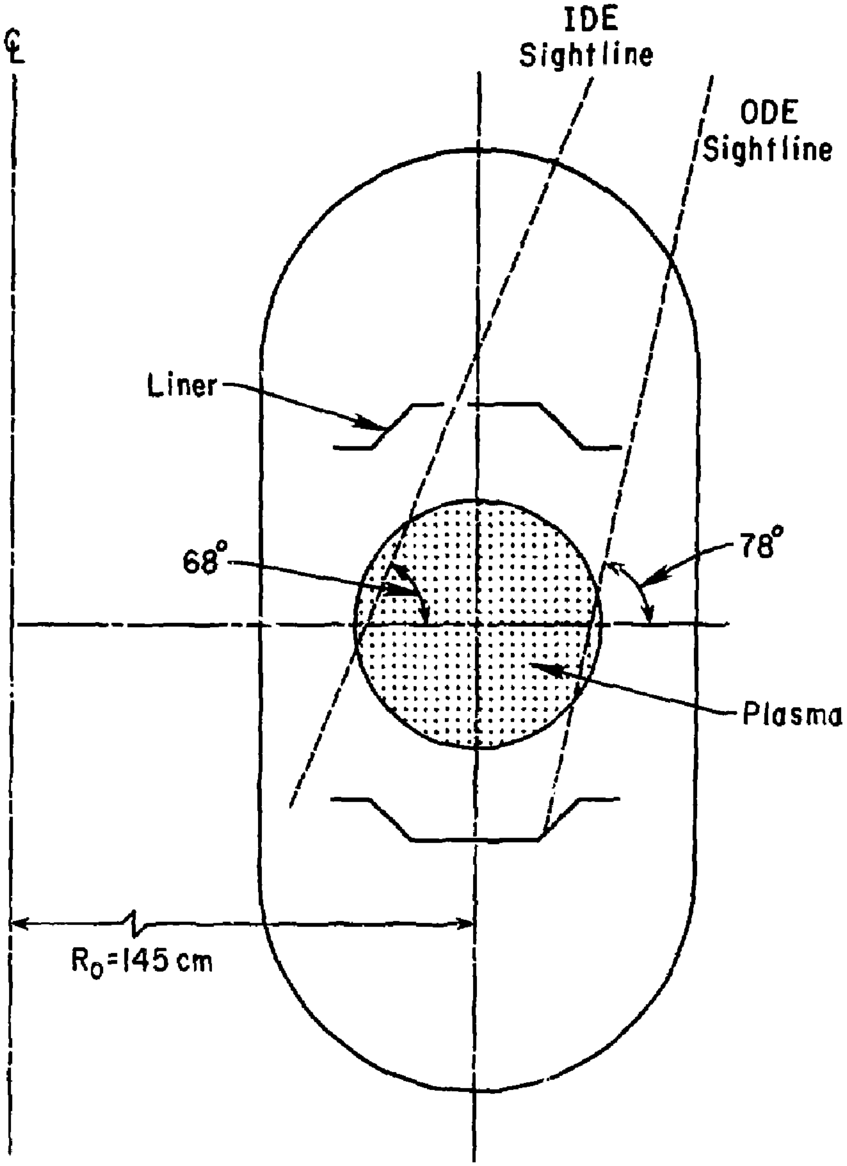


Fig. 1

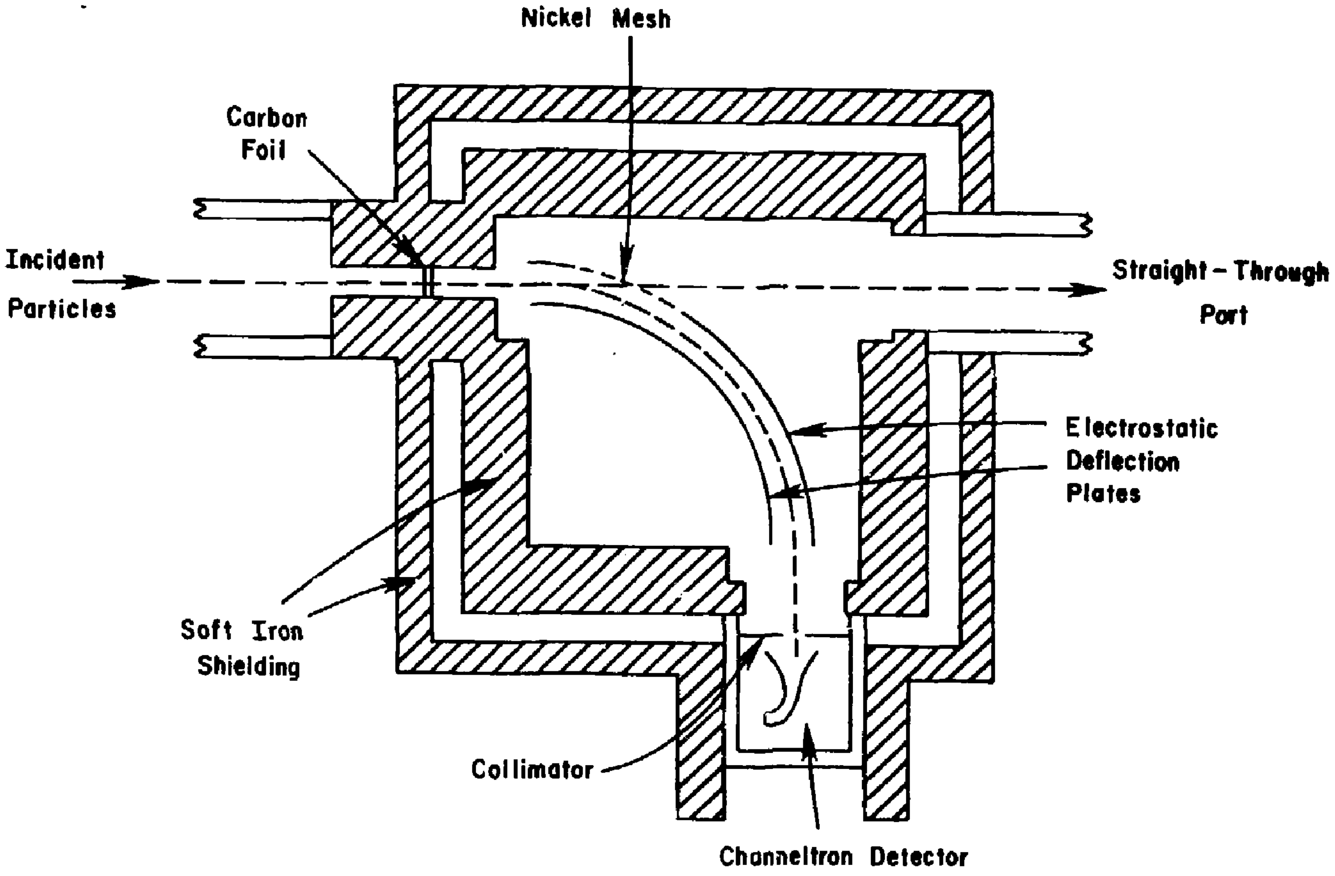

#83X1090
Nickel Mesh
Carbon Foil
Incident Particles
Straight-Through Port
Electrostatic Deflection Plates
Soft Iron Shielding
Collimator
Channeltron Detector

Fig. 2

83X0657

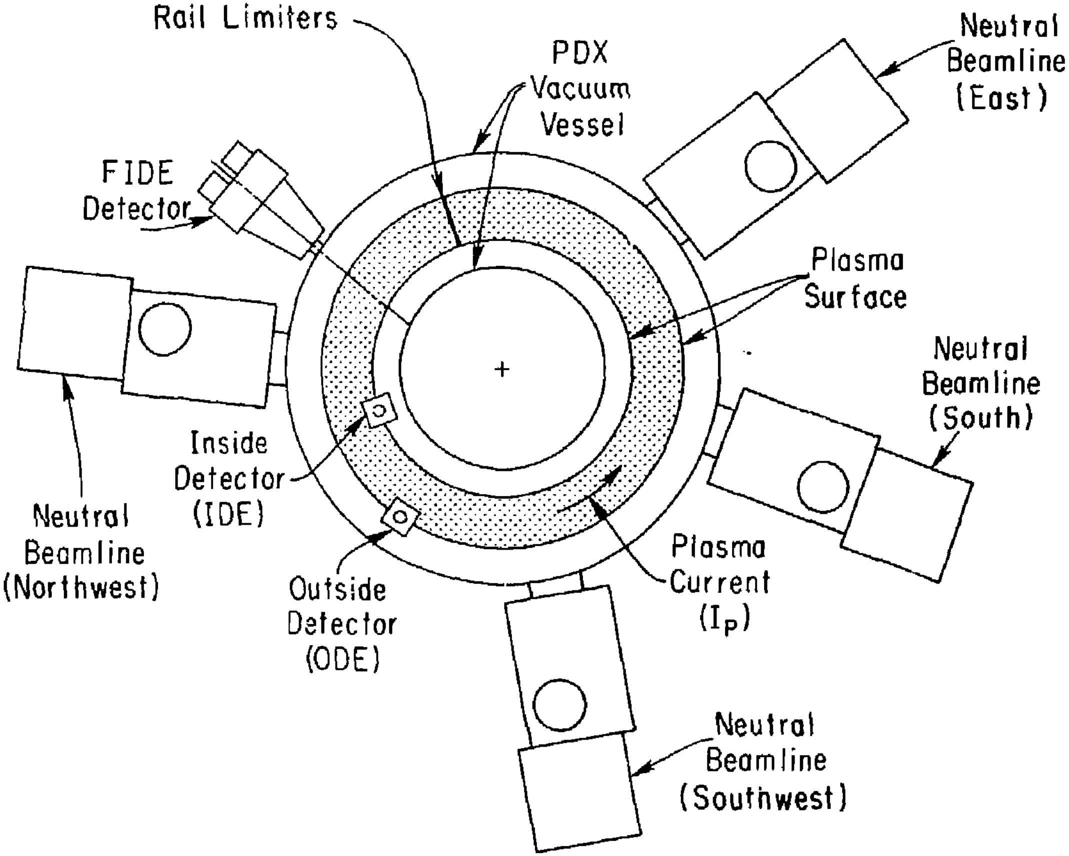
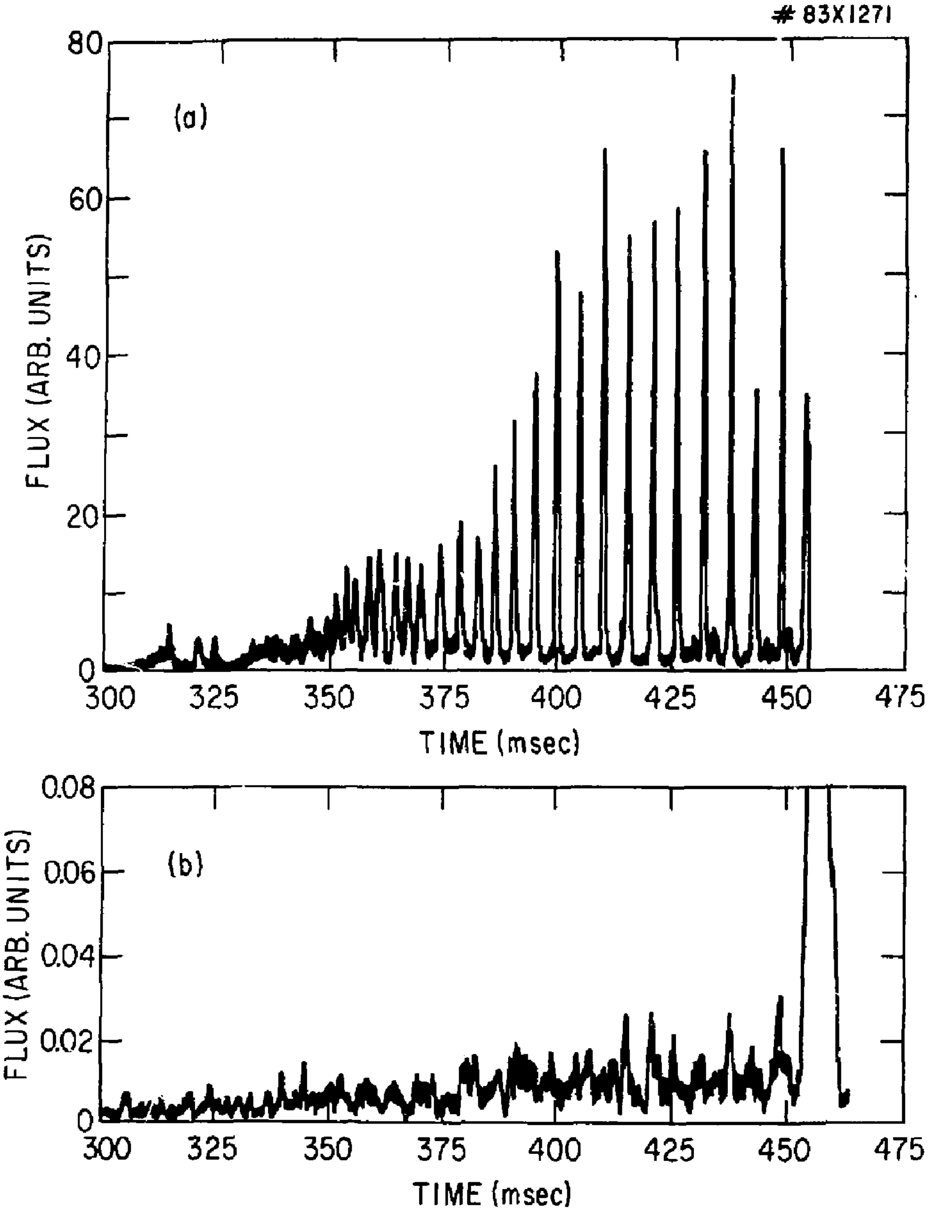


Fig. 3



83X1271
(a)
FLUX (ARB. UNITS)
0
20
40
60
80
300
325
350
375
400
425
450
475
TIME (msec)
(b)
FLUX (ARB. UNITS)
0
0.02
0.04
0.06
0.08
300
325
350
375
400
425
450
475
TIME (msec)

Fig. 4

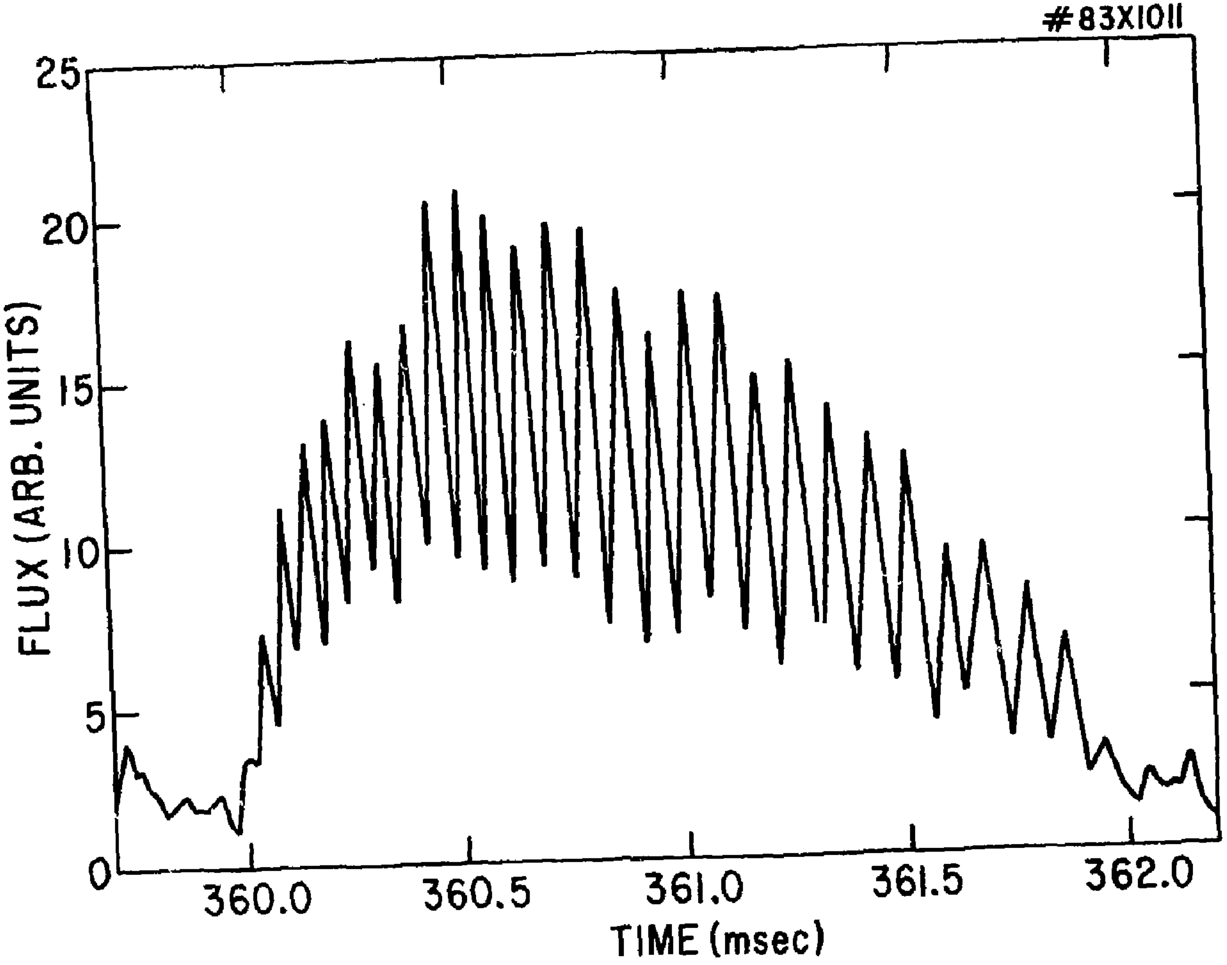

#83X1011
FLUX (ARB. UNITS)
0
5
10
15
20
25
360.0
360.5
361.0
361.5
362.0
TIME (msec)

Fig. 5

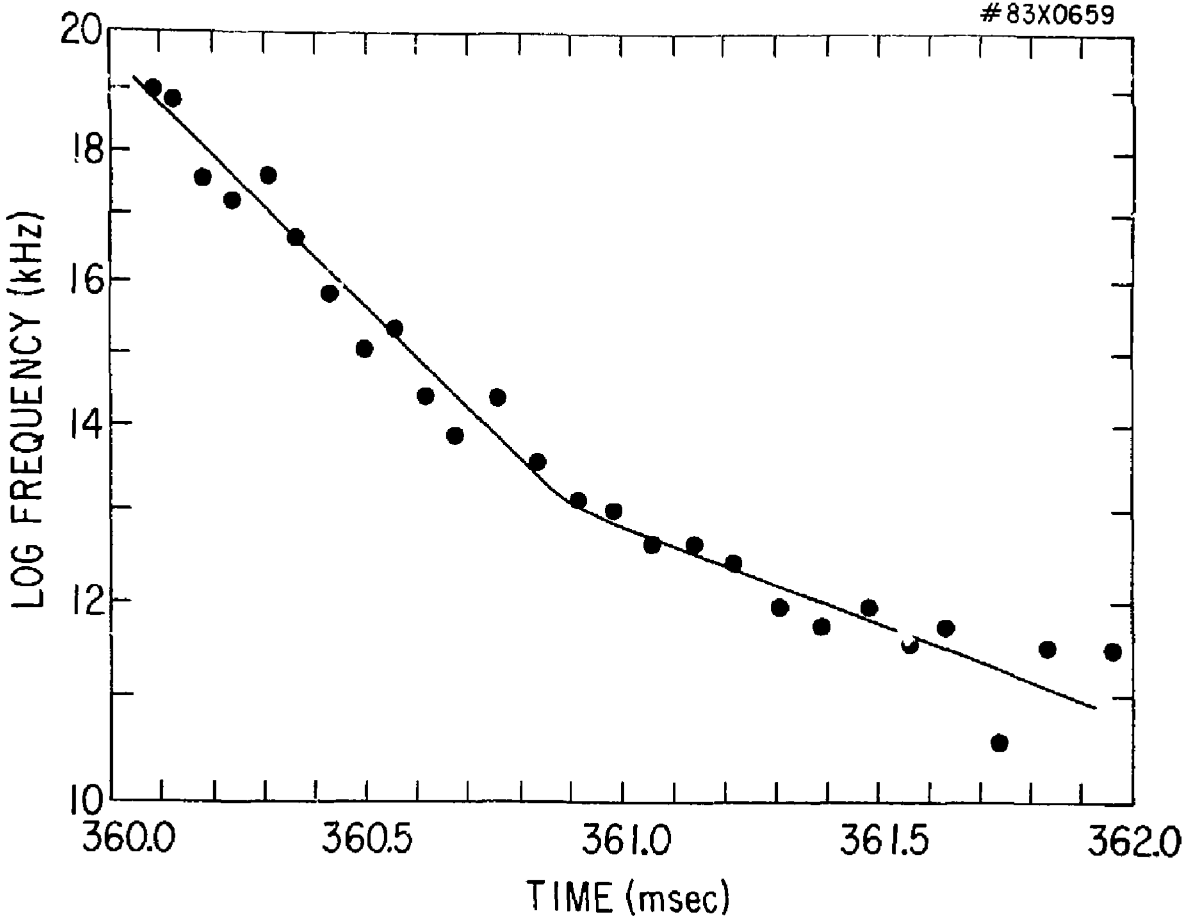

#83X0659
20
18
16
14
12
10
LOG FREQUENCY (kHz)
360.0
360.5
361.0
361.5
362.0
TIME (msec)

Fig. 6

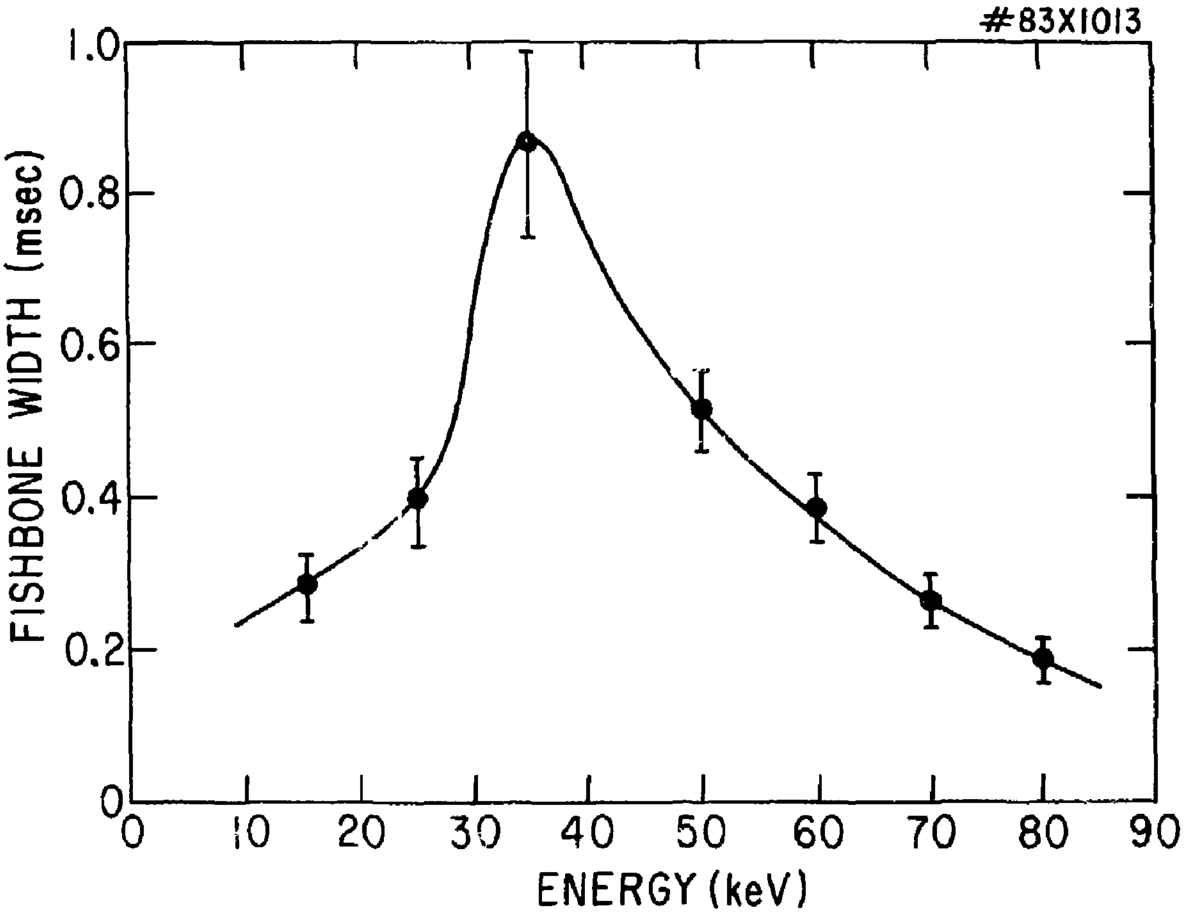

#83X1013
FISHBONE WIDTH (msec)
1.0
0.8
0.6
0.4
0.2
0
0
10
20
30
40
50
60
70
80
90
ENERGY (keV)

Fig. 7

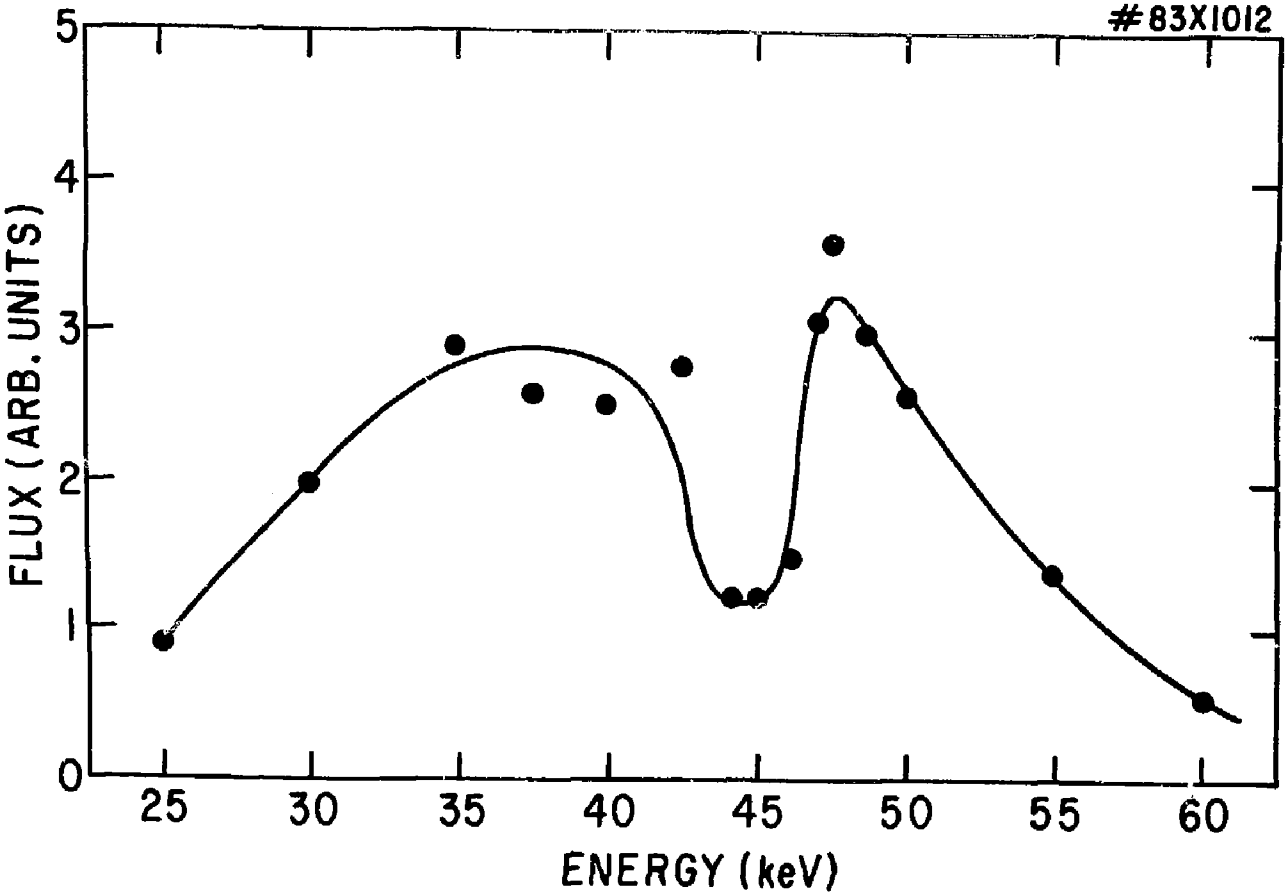

#83X1012
FLUX (ARB. UNITS)
0
1
2
3
4
5
25
30
35
40
45
50
55
60
ENERGY (keV)

Fig. 8

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