

PFC/RR-81-25

DOE/ET/51013-22

UC-20a, f

THE M-SPECTRUM ANALYZER ON ALCATOR C

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June, 1981

This work was supported by the U.S. Department of Energy Contract No. DE-AC02-78ET51013. Reproduction, translation, publication, use and disposal, in whole or in part by or for the United States government is permitted.

THE m-SPECTRUM ANALYZER ON ALCATOR C

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An experiment currently being developed on the Alcator C magnetic fusion device uses a set of poloidal B-field pickup coils and unique analyzing circuits to continuously yield the amplitudes, frequencies, and rotational directions of the $m=1,2,3,4$, and 5 resistive MHD tearing modes. The experiment is being used to study the growth and coupling of tearing modes of different helicities due to density, temperature, and current profiles. Effects of magnetic island size on confinement and disruptions will be investigated.

INTRODUCTION

In a perfectly conducting toroidal plasma, ideal MHD theory dictates that magnetic field lines form simple, nested flux surfaces. But in real plasmas, with finite resistivity, the plasma can obtain a lower energy state by filamentation of the plasma current. In recent years, much theoretical work has been done on these resistive tearing modes and the resulting "magnetic islands" which are formed [1-5]. In both experimental and theoretical work, confinement time has been found to decrease with increasing mode amplitude [6,7]. In addition, explosive growth of islands and extensive regions of ergodic magnetic field lines are thought to occur when modes of different helicity overlap spatially [8]. This currently is the leading hypothesis for explaining the major disruption [9,10].

EXPERIMENTAL APPARATUS

The Alcator C tokamak is a compact high B-field device

($B_T=4-10$ Tesla, $a \leq 0.17$ m, $R=0.64$ m) which operates with line-average plasma densities, \bar{n}_e , from $0.4 - 7.0 \times 10^{20} \text{ m}^{-3}$, plasma current between 200 and 600 kiloamps, and very low impurity concentrations ($Z_{\text{eff}} \approx 1.2$) [11]. In addition, there is no copper shell surrounding the vacuum vessel.

At one toroidal location, there are twelve small coils equally spaced around a poloidal circumference, on the outside surface of the vacuum vessel (Fig. 1). The coils are oriented in such a way that they pick up fluctuations in the poloidal (i.e. θ -) component of the magnetic field.

Resistive tearing modes have a helical structure of the form:

$$\psi(r)e^{i(m\theta - nz/R)}$$

where " ψ " is the perturbed flux function and " z " represents the coordinate in the toroidal direction. (Theory usually approximates the torus as a straight cylinder of length $2\pi R$.) The integers m and n are the poloidal and toroidal mode numbers respectively, and n/m is proportional to the degree of helical twisting of the mode. For some poorly understood reason, these magnetic island structures appear to rotate, so that at any one spatial position, the poloidal magnetic field has a small, relatively high-frequency (3-20 kHz) fluctuation superimposed on the nearly D.C. field due to the toroidal plasma current. This motion may be due to a non-zero fluid velocity or to mode propagation, although there is no absolute agreement on whether this motion is in the poloidal or toroidal direction, or both

[12].

The amplitude and poloidal mode number can be determined by examining the signals of the twelve B_θ coils when a single pure mode exists (Fig. 2). However, this normally would involve digitizing the twelve signals at rates of approximately 100 kHz for the half-second lifetime of plasma discharges in Alcator C. Practically, this strains our data acquisition, processing, and storage systems beyond present capabilities. In addition, if more than one m-mode is present, the magnetic field fluctuations produced by each will be superimposed at the pickup coils. A polar graph of the twelve signal amplitudes would yield a distorted curve, not clearly recognizable as any single m-mode. In order to separate the amplitudes of the different modes it is necessary to get the Fourier components of B_θ vs θ in terms of $\sin m\theta$ and $\cos m\theta$.

All of the aforementioned reasons provided a strong motivation to design an instrument which would separate and measure each Fourier component of B_θ , in real time and continuously throughout the discharge, thus reducing the volume of data acquisition by more than an order of magnitude and virtually eliminating the immense amount of digital data processing otherwise required. With the circuitry that was envisioned, it is also possible to obtain the individual frequencies and effective directions of rotation for each mode; something which can not be done by simply looking at the individual pickup coil signals.

ELECTRONIC CIRCUITRY

Since the coils are on the outer surface of the vacuum vessel, they are strongly coupled to fluctuations in externally applied magnetic fields, particularly the equilibrium (vertical) and ohmic heating (O.H.) fields. These exhibit substantial 60 Hz and 360 Hz components caused by the ripple on the rectified output of the various tokamak power supplies. This low frequency noise must be attenuated by high-pass filters (3 dB point at 3 kHz) on each coil signal. However, some of this noise still remains and ultimately forms the background noise baseline (see Figs. 6 & 7 before and after the plasma discharge).

The twelve \dot{B}_θ -loop signals are next fed into a multiplexer which samples all the inputs in a cyclic pattern, outputting each voltage for 500 nanoseconds before switching to the next (Fig. 3). Thus every 6 microseconds the multiplexer has sampled all the way around the poloidal cross-section. The output is \dot{B}_θ/dt as a function of θ , repeated every 6 μsec . There is a reason for such fast switching; it is desired to have a "frame" of \dot{B}_θ/dt vs. θ on a time scale which is much faster than the mode rotation. Since these MHD modes have effective rotation frequencies of up to approximately 20 kHz, a "frame" time of 6 μsec is more than an order of magnitude faster and thus satisfies our requirements.

If there happened to be an $m=1$ perturbation in the poloidal magnetic field, for example, the output would be one complete sinusoid in the 6 μsec cycle time of the multiplexer. Since the multiplexer continues cycling around the twelve inputs, the

sinusoid is repeated over and over, and the result is a 167 kHz sine wave. If there happened to be a pure $m=2$, the multiplexer output would also be a sine wave, but twice the basic cycle frequency, i.e. 333 kHz (Fig. 3). Obviously an arbitrary magnetic island of mode " m " would yield a multiplexer output sine wave of frequency:

$$f_m = m/6 \text{ MHz}$$

Of course, since there are only twelve coils, the highest mode which theoretically can be accurately detected is an $m=6$, due to the Nyquist limit.

As described so far, every component of this diagnostic is linear. Therefore if several modes of different helicity are in the plasma at the same time, the output of the circuit will simply be the linear sum of several different frequency waves.

A frequency spectrum analyzer will show the amplitude of each m -mode (Fig. 4). However, such an instrument operates by repeatedly sweeping through the range of frequencies of interest, and therefore any one particular frequency (within some narrow resolution) is scanned for a minute fraction of realtime. Unfortunately, it is impossible to sweep fast enough over the desired frequencies with the required resolution to make a spectrum analyzer useful for our experiment. However, we are not interested in looking at the entire frequency spectrum in Fig. 4. In fact, we are only interested in five narrow frequency bands corresponding to the multiplexer outputs for $1 \leq m \leq 5$. Therefore custom multi-stage bandpass filters were designed to be centered

at the $m=1,2,3,4$, and 5 output frequencies. Each filter has a 3 dB width of 15% around f_m and then attenuates the signal by 50 dB at $0.73f_m$ and $1.31f_m$. Each of these five signals is then passed through a peak follower to give the amplitudes of dB_θ/dt for the $m=1,2,3,4$, and 5 modes simultaneously.

In addition, each mode frequency can be determined by measuring the Doppler shift due to the effective mode "rotation". An $m=3$ set of magnetic islands moving with apparent rotation frequency of 15 kHz in the same direction as the multiplexer sampling will yield an output frequency of 485 kHz--still well within the bandpass filter width. The same rotation frequency in the opposite direction will yield a 515 kHz sine wave. This Doppler shift is measured with frequency-to-voltage convertors.

The five amplitude signals and the five frequency signals are then digitized by CAMAC modules, transferred to a PDP-11 and stored on magnetic tape (Fig. 5). At some later time, each B_θ amplitude signal can be divided by the appropriate frequency signal to yield the magnitude of \tilde{B}_θ for each m -mode.

PRELIMINARY FINDINGS

First observations indicate that when MHD activity occurs, it almost always consists of two or more m -modes. Evidently this is not an instrumental artifact, since bursts of a single mode are occasionally seen.

The m -spectrum analyzer has been used thus far to study resistive MHD activity predominantly in hydrogen plasmas at a toroidal magnetic field of 6 Tesla, although some data has been

taken at 8 Tesla and/or in deuterium plasmas. Two different plasma discharges are shown in Figs. 6 and 7. Both ended with major disruptions, but the MHD activity measured on each was distinctly different. In the first discharge, as the plasma density increases above $2.9 \times 10^{20} \text{ m}^{-3}$ (5 interference fringes) at 180 msec, $m=2$ and $m=3$ modes begin to appear. Resistive MHD tearing theory predicts a growth time in Alcator C of less than a millisecond [13] for the island to reach the non-linear regime where its width may saturate at a finite size [14], depending upon the equilibrium plasma current profile. Therefore, from the time scale of the graph it appears as though both the $m=2$ and $m=3$ magnetic islands are in a quasi-steady state equilibrium at their saturated widths. As the density slowly increases to about $3.2 \times 10^{20} \text{ m}^{-3}$ during the next 70 msec, the amplitude of \dot{B}_θ for the $m=2$ and 3 modes also increases. If one postulates that the equilibrium current profile changes slowly as the density increases, then the behavior of MHD activity in the discharge is still consistent with the islands always being near their equilibrium saturation widths. (The mode frequency decreases somewhat, but this information has not been utilized as of this writing.)

As stated previously, current theory predicts that if two modes of different helicity grow so large that the islands overlap in the plasma, the magnetic field lines will form a large ergodic region, resulting in loss of confinement and a major disruption. The behavior in Fig. 6b might be explained with this theory, although no determination of island size has been made

yet. In fact data taken over many shots gives a fairly consistent picture which indicates that when the $m=2$ and $m=3$ mode amplitudes are more than approximately 0.5% of $B_{\theta 0}$, a disruption ensues. Also, the onset of MHD activity at $\bar{n}_e \leq 2.9 \times 10^{20} \text{ m}^{-3}$ is confirmed. Eventually we hope to infer plasma current profiles from measured electron temperature profiles and feed these into the MHD equations which predict the saturation width of the magnetic islands and the amplitude of \hat{B}_{θ} and directly compare theory with experiment.

In contrast to this reasonably well-understood discharge, a small percentage of shots was observed to have the behavior shown in Fig. 7. At first glance the two shots are quite similar; the second one did not have quite as high a density. There was also a minor disruption early in the discharge, but this is fairly common. The important difference is that at 210 msec, the MHD activity suddenly jumped from a quiescent level to a disruptive level in just 800 μsecs . Prior to this there was no apparent hint of the impending disruption. Even the plasma impurity level, as measured by Z_{eff} , was typically low [15]. We have no explanation for this phenomenon.

FUTURE WORK

Substantial data from this experiment have so far only been obtained at one B-field in one working gas. We will be extending this study to higher and lower fields, deuterium and helium plasmas, and various plasma currents. The measured mode amplitudes will be checked against levels predicted by MHD

theory, using experimentally determined temperature profiles.

An important study will be to correlate various levels of MHD activity with the energy confinement time. It is postulated that these modes should have deleterious consequences, but to what degree is unknown. Of course, much more work will be done studying major disruptions, particularly the coupling and amplitude of modes, overlap of magnetic islands, and the time scales involved.

All of this information may eventually be used in planning an experiment to employ active feedback stabilization in an attempt to avoid the major disruption [16-18]. It would seem that if these undesirable current terminations follow the scenario documented in Fig. 6, feedback stabilization could be feasible. Stabilization methods may focus on damping a single helicity mode in the plasma (such as $m=2/n=1$) and for this purpose, the m -spectrum analyzer would be particularly useful because of its realtime capabilities. Also it may be necessary to monitor other commonly occurring modes since they may be driven unstable during selective feedback. If however, the behavior shown in Fig. 7 predominates, feedback response times would have to be on the order of tens of microseconds--quite a formidable task.

FIGURE CAPTIONS

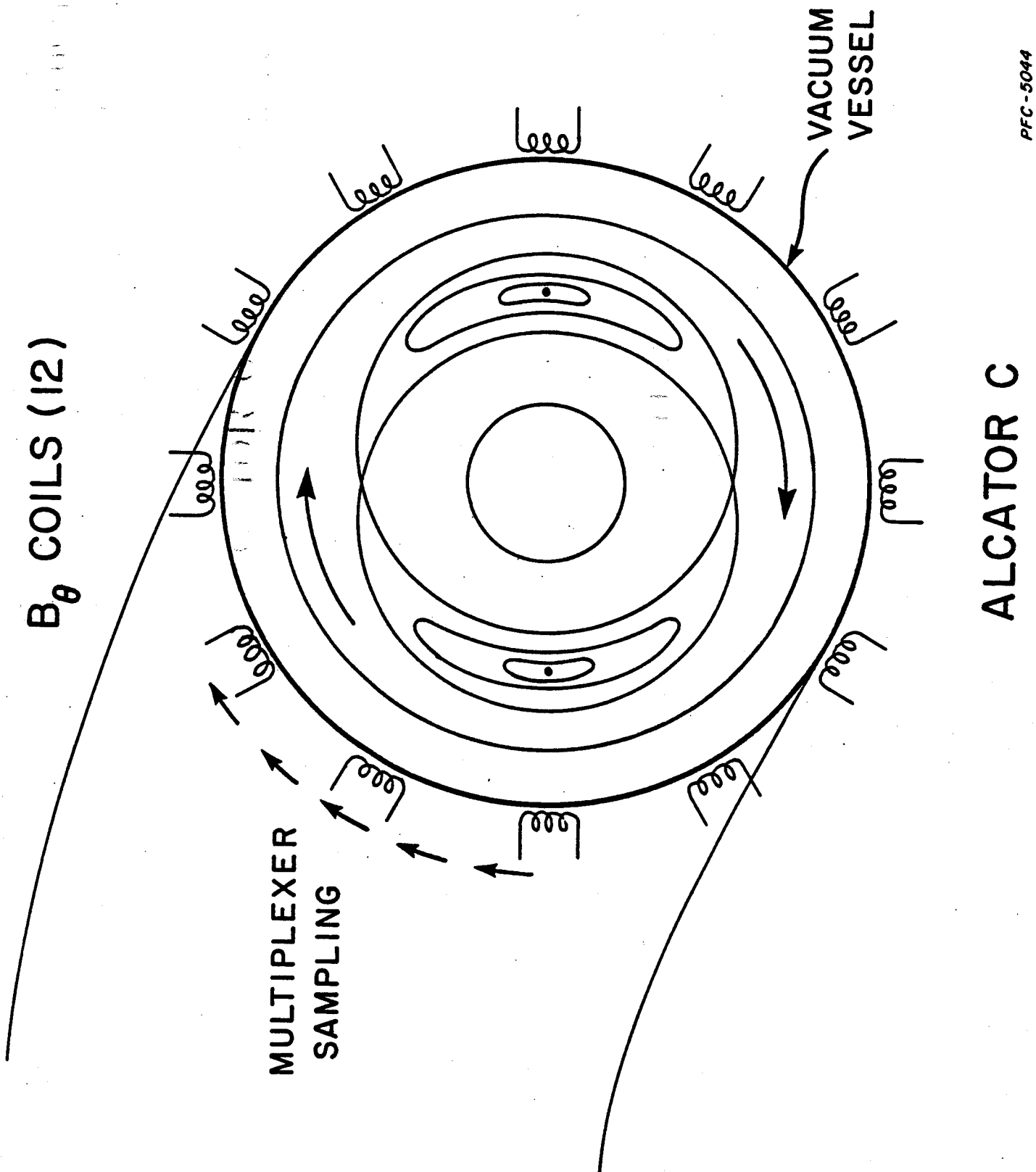
- Fig. 1 Schematic of set of B_θ pickup coils around a poloidal circumference on Alcator C. Also shown is a rendition of the flux surfaces in the presence of a large, rotating $m=2$ mode.
- Fig. 2 Polar graphs of B_θ vs. θ measured on Alcator A during plasma current rise phase. (Taken from ref. [19])
- Fig. 3 Signals output by ideal multiplexer for pure $m=1$ and $m=2$ modes.
- Fig. 4 Frequency spectrum of multiplexer output showing amplitudes of $m=1, 2, 3, 4$, and 5 modes.
- Fig. 5 Block diagram of major components of m -spectrum analyzer.
- Fig. 6a Plasma current, electron density (line-averaged central chord measured by laser interferometer) and soft x-ray emission (central chord) for a hydrogen discharge with $B_T=6.0$ Tesla.
- Fig. 6b MHD activity on this shot. Note the time scale is the same as Fig. 6a.
- Fig. 7a Another plasma discharge under similar conditions, which also ended in a major disruption.
- Fig. 7b MHD activity on this shot.

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FIGURE 1



MHD ACTIVITY DURING CURRENT RISE IN ALCATOR A

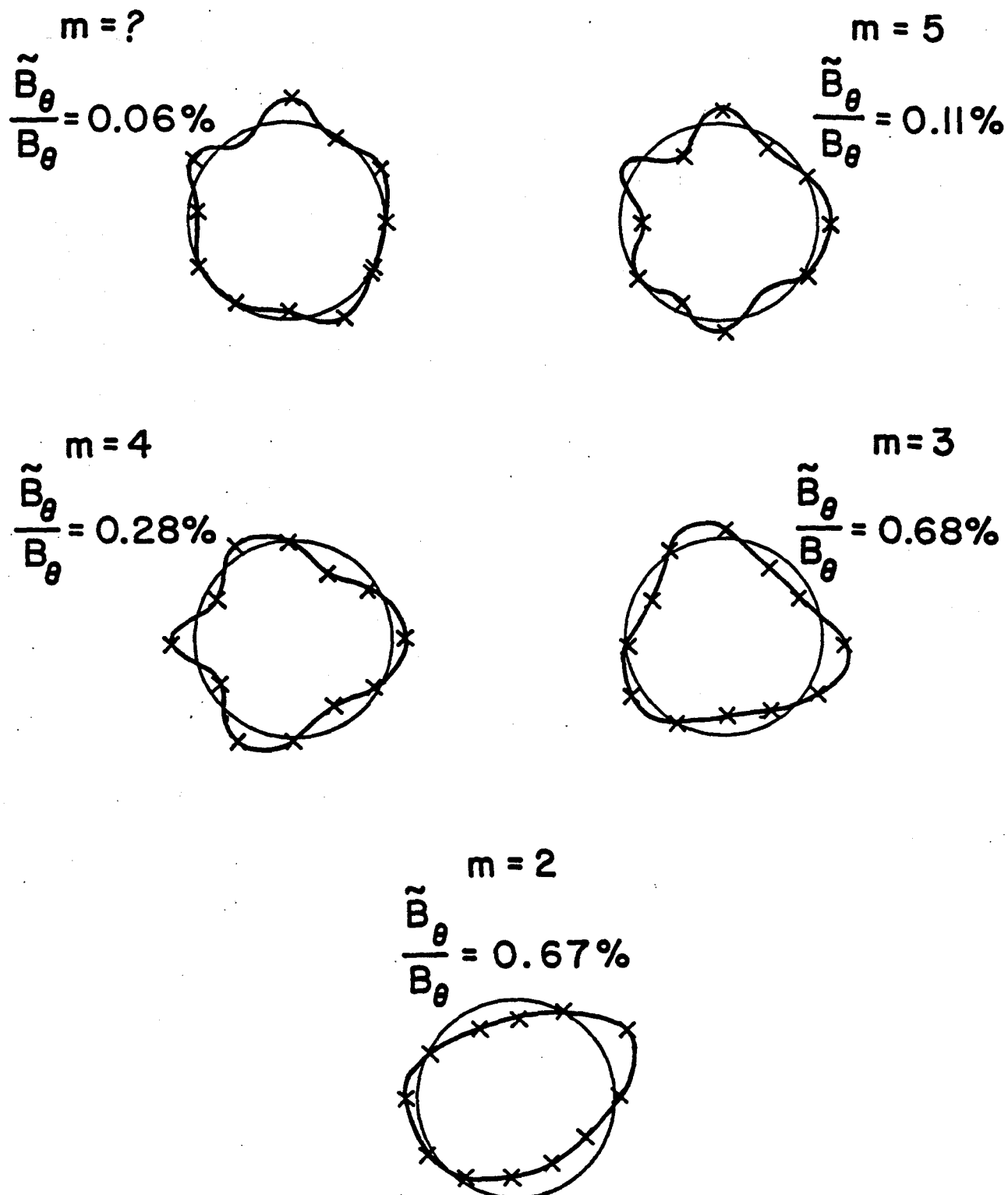


FIGURE 2

IDEAL MULTIPLEXER OUTPUT

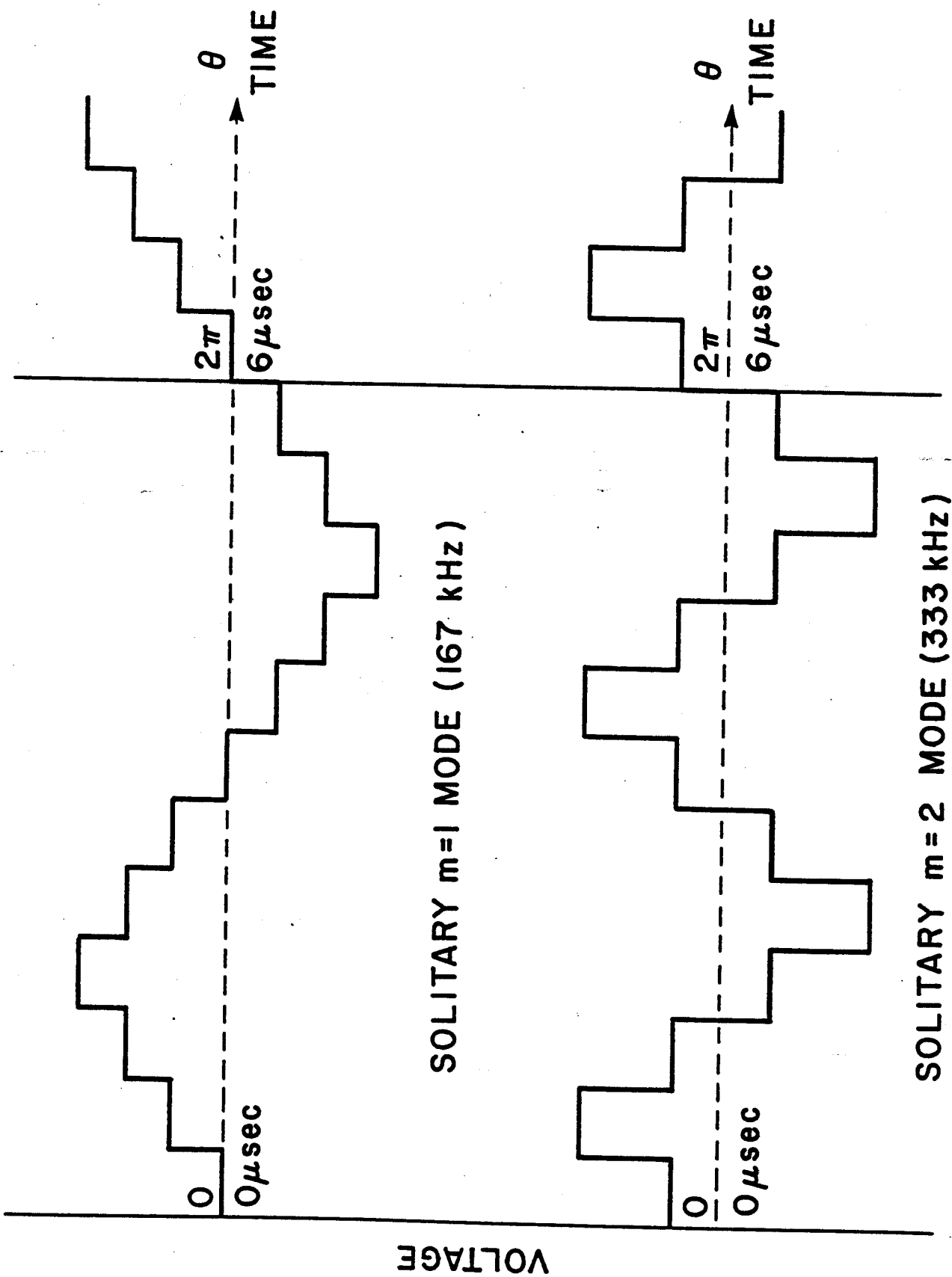


FIGURE 3

FIGURE 4

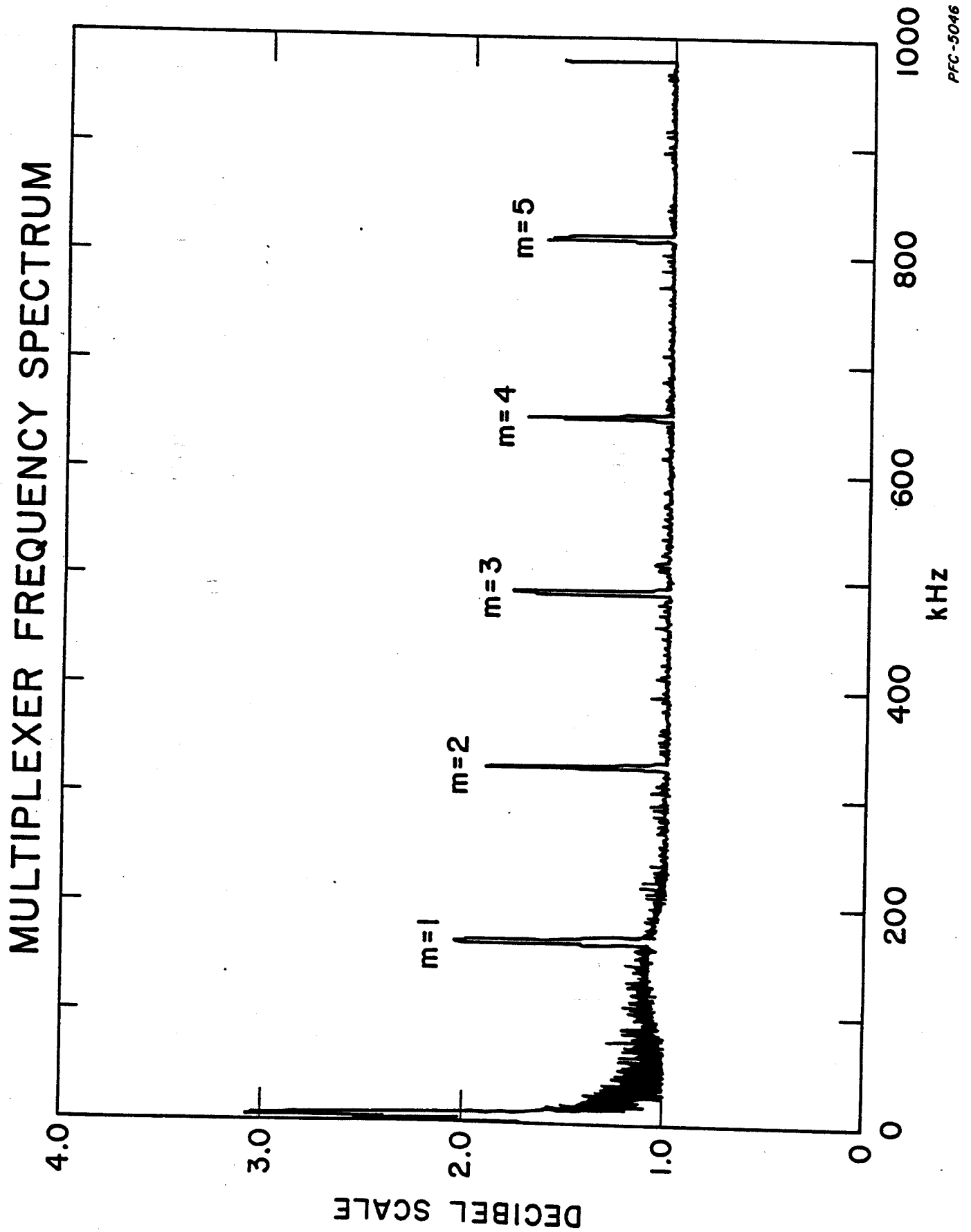
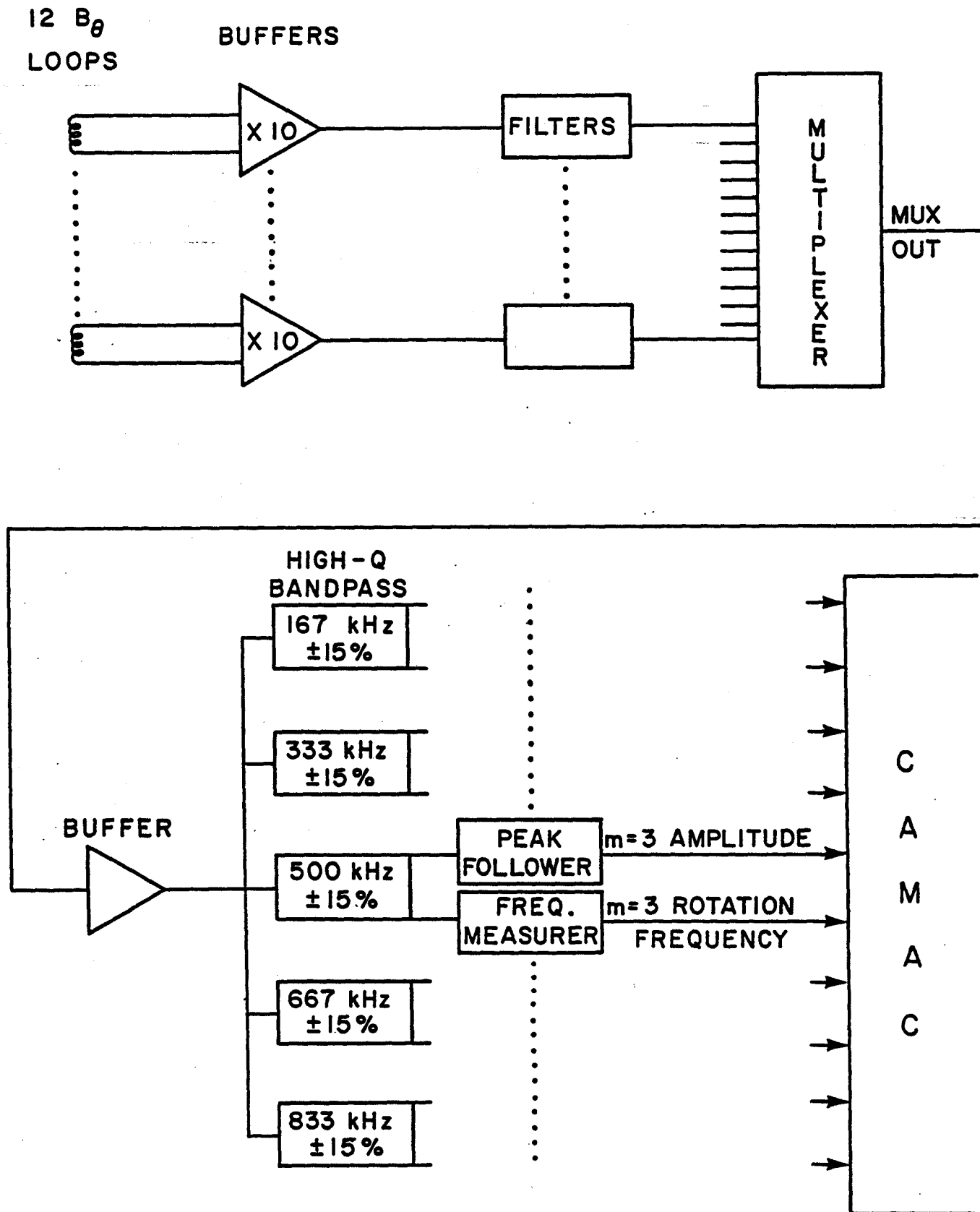


FIGURE 5



SHOT #39 10/29/80

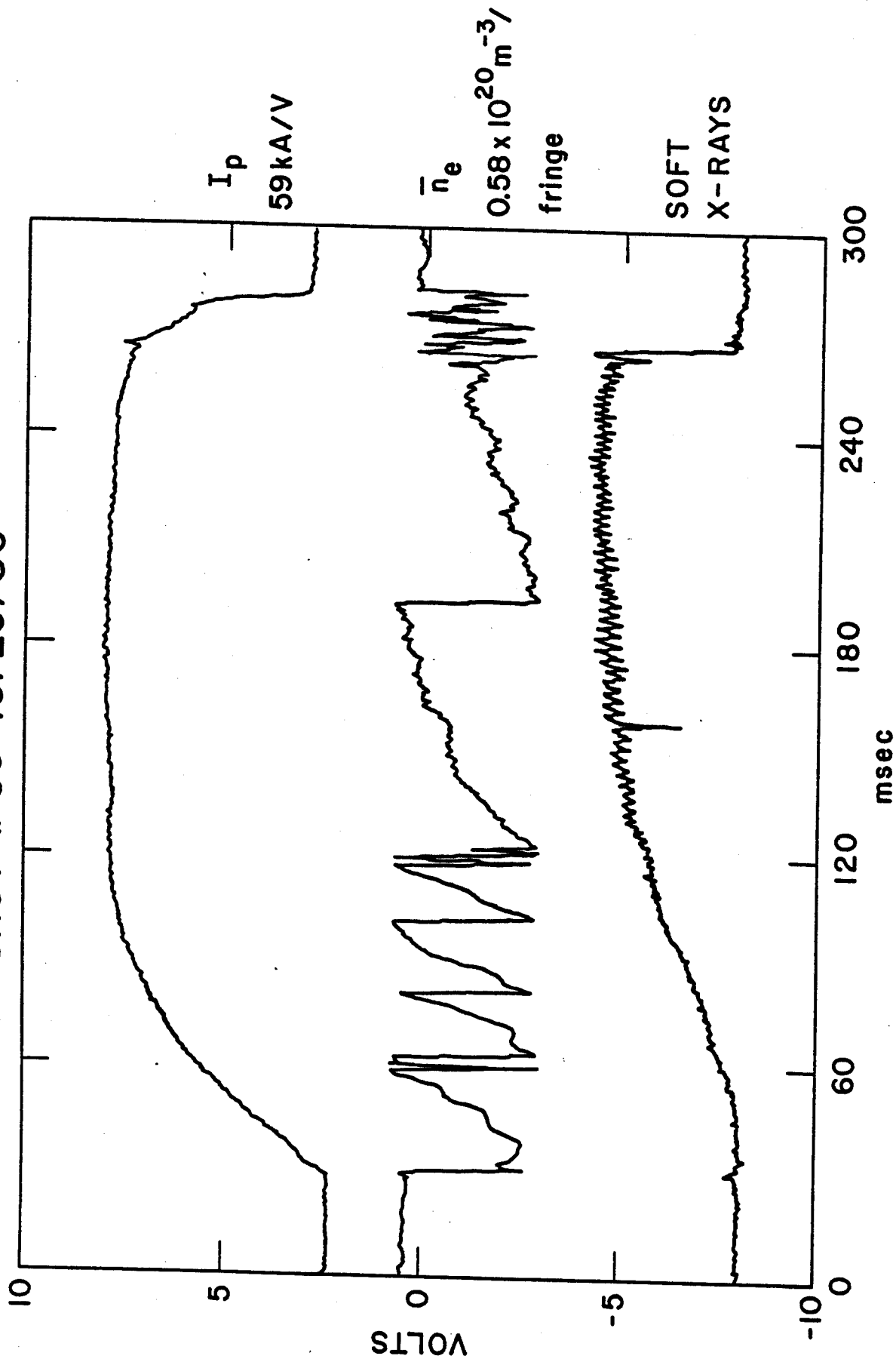


FIGURE 6a

SHOT # 39 10/29/80

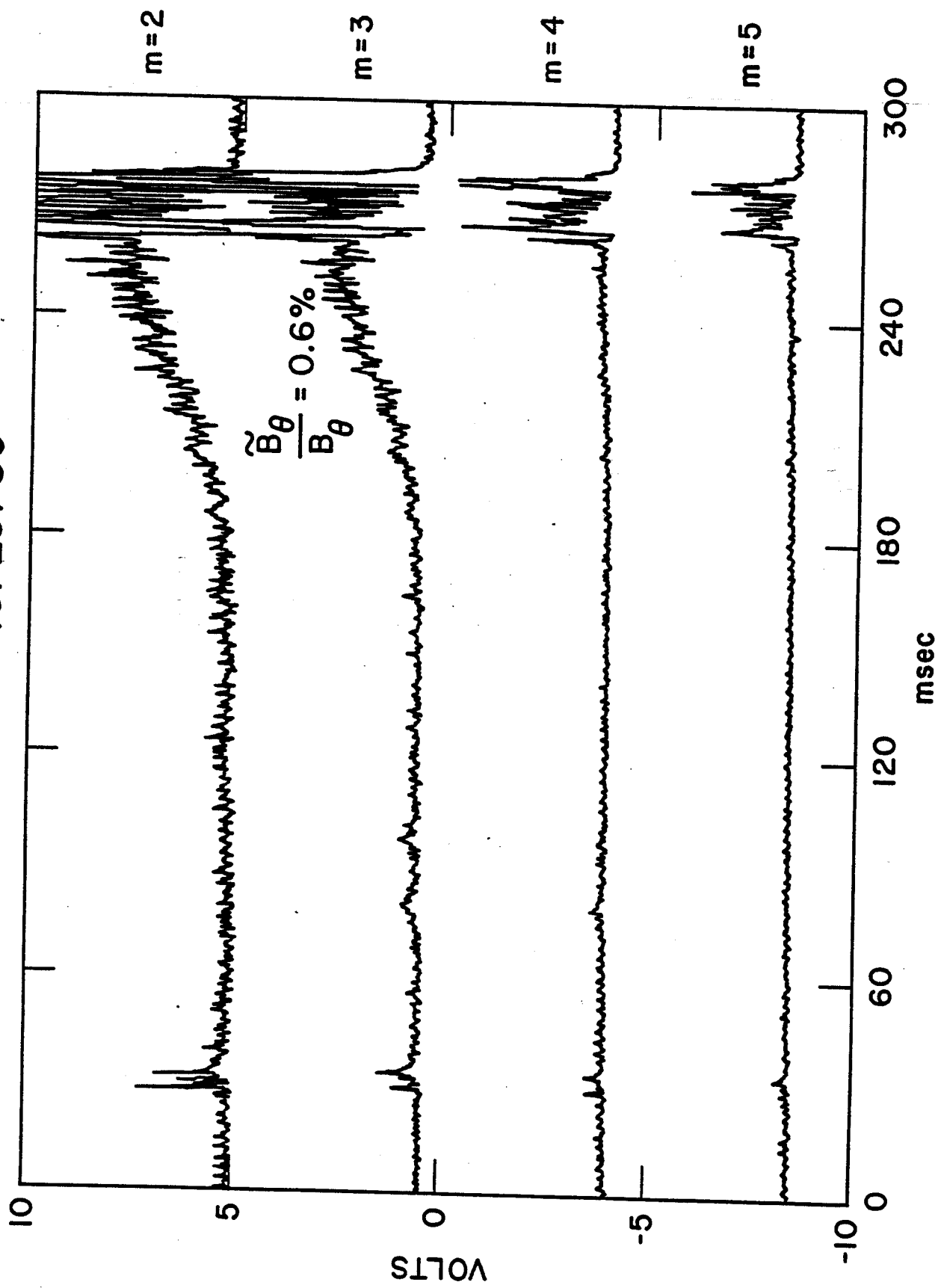


FIGURE 6b

SHOT # 37 10/29/80

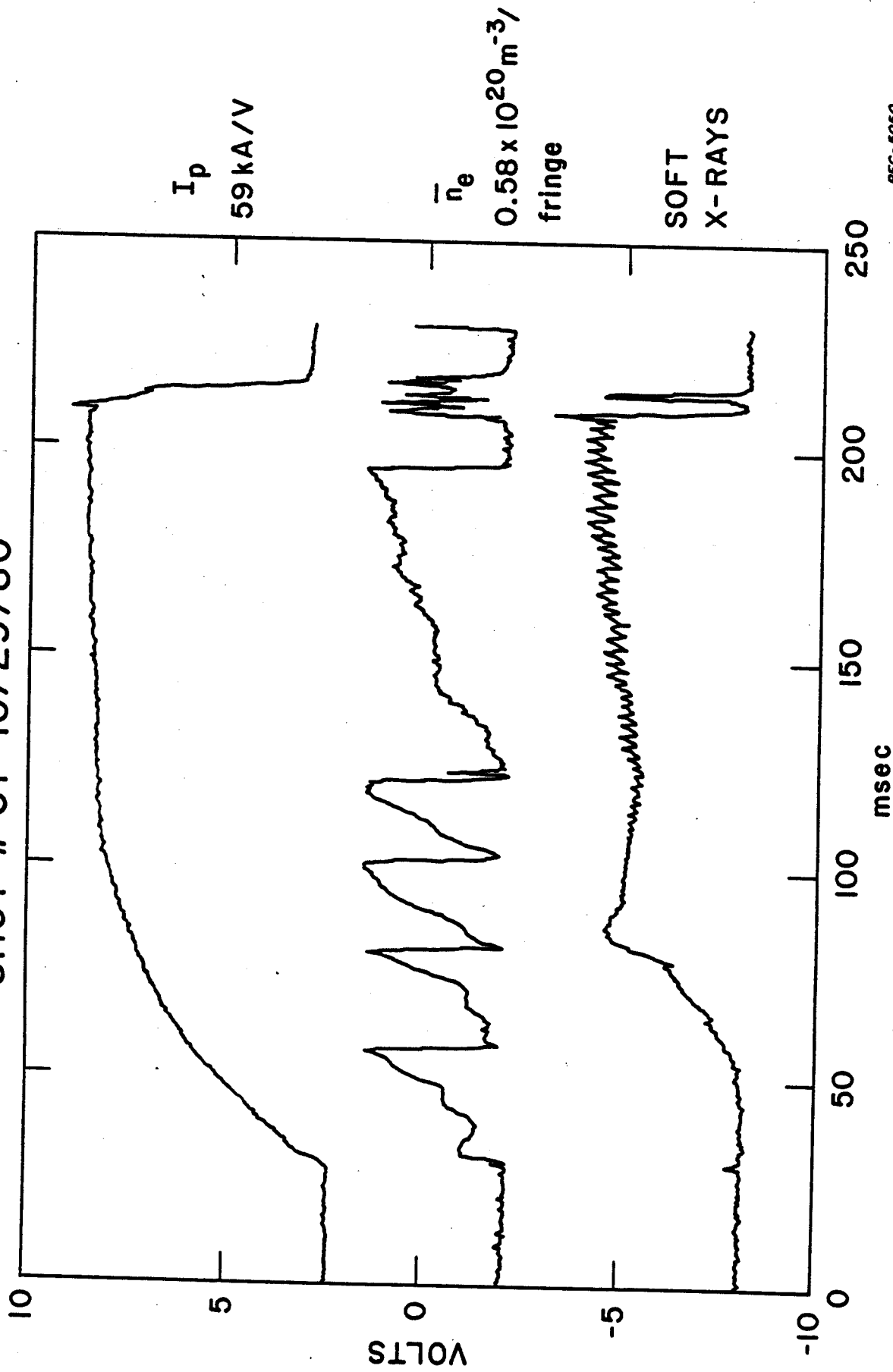


FIGURE 7a

SHOT # 37 10/29/80

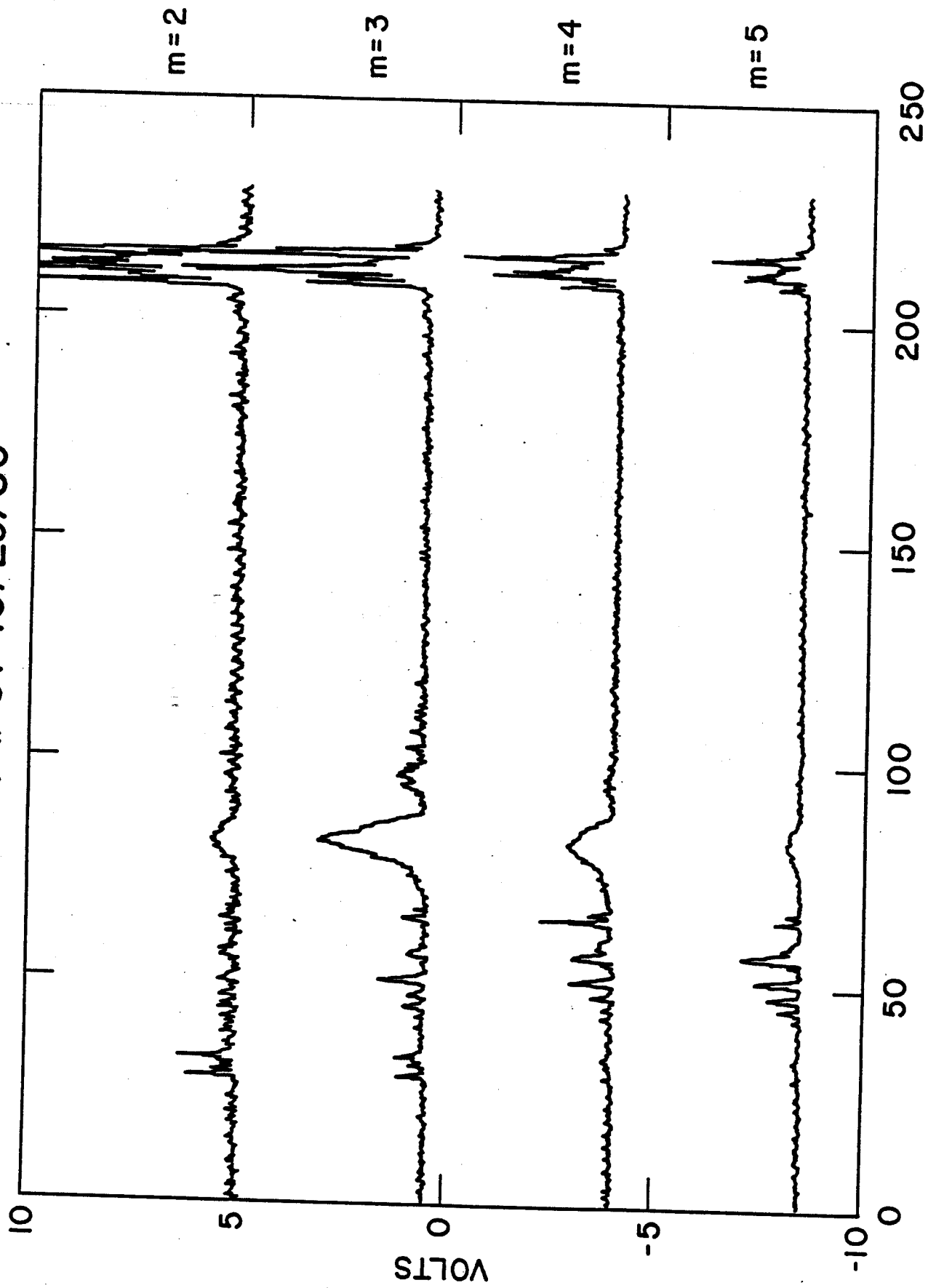


FIGURE 7b