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MEASUREMENT OF THE POLOIDAL MAGNETIC FIELD IN THE PBX-M TOKAMAK USING THE MOTIONAL STARK EFFECT

BY

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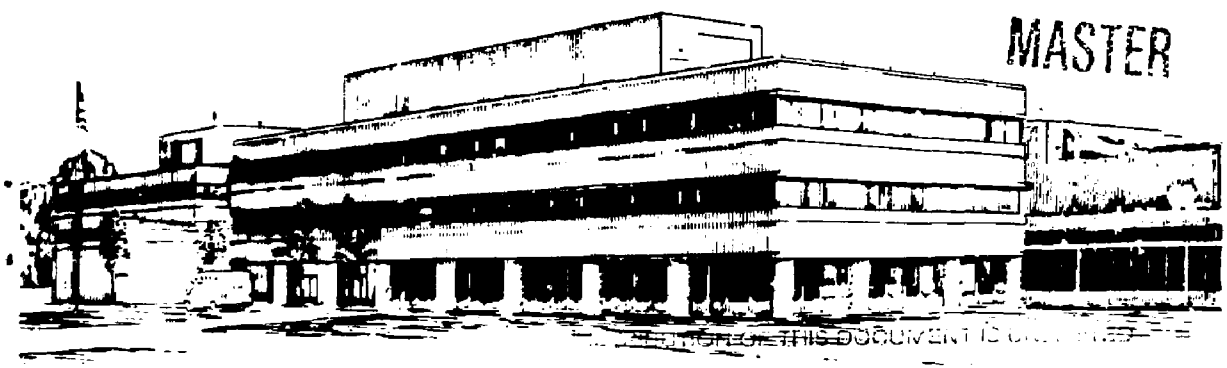

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Measurement of the Poloidal Magnetic Field in the PBX-M Tokamak using the Motional Stark Effect

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Abstract

Polarimetry measurements of the Doppler-shifted H_α emission from a hydrogen neutral beam on the PBX-M tokamak have been employed in a novel technique for obtaining $q(0)$ and poloidal magnetic field profiles. The electric field from the beam particle motion across the magnetic field ($\mathbf{E} = \mathbf{V_{beam}} \times \mathbf{B}$) causes a wavelength splitting of several angstroms, and polarization of the emitted radiation (Stark effect). Viewed transverse to the fields, the emission is linearly polarized with the angle of polarization related to the direction of the magnetic field.

The current density profile has played an important role for many years in the theoretical modeling of plasma stability and confinement. Current-driven instabilities have been observed or theorized under various conditions and may be an essential ingredient in plasma confinement and transport. To understand the effects of the current density profile, credible techniques for the measurement of the poloidal field distribution applicable to the present generation of fusion devices are essential. To date, most techniques attempted have suffered from one of several problems. Frequently, the measurement is line-integrated, which requires a numerical inversion process to obtain spatial information.[1,2] This introduces some uncertainty, particularly for non-circular plasma shapes. Neutral beam techniques have shown good spatial resolution, but so far have suffered from beam attenuation for densities above $\sim 1 \times 10^{13}$ cm^{-3}.[3,4]

In this Letter we report the first measurements of the central rotational transform, $q(0)$, using the motional Stark effect(MSE) to polarize the spectral emission from a 55 keV neutral hydrogen beam. One of the principal advantages of this technique is that it can provide a local ($\sim$ 1 – 2 cm resolution) measurement of the pitch angle, $\gamma_p(r) = \tan^{-1}(\frac{B_z(r)}{B_T(r)})$, where B_T is the toroidal magnetic field, and B_p is the poloidal field in the midplane. The pitch angle is related to the safety factor, $q(r) = r\ R\tan(\gamma_p(r))$. The safety factor on the magnetic axis ($B_p = 0$), for a circular plasma, is $q_{axis} = 1\ R(\frac{d\tan(\gamma_p)}{dr})_{r=0}$. Another important feature of this method is that beam attenuation is minimal for a hydrogen beam of $\sim$80 keV at the operating densities of present-day tokamaks and, hence, this approach extrapolates favorably for use at higher densities and or in larger machines.

As a neutral beam propagates through a plasma, collisions of the beam particles with the background ions and electrons will excite beam atoms, leading to emission

of radiation. In addition, the motional Stark effect,[5] which arises from the electric field induced in the atom's rest frame due to the motion across the magnetic field ($E = V_{beam} \times B$), causes both a wavelength splitting of several angstroms, and strong polarization of the emitted radiation. The $\Delta m = 0$ transitions, or π lines, are linearly polarized parallel to the electric field and the $\Delta m = \pm 1$ transitions, σ lines, are linearly polarized perpendicular to the electric field, in other words, parallel to the magnetic field when viewed transverse to the field. However, in contrast to the Zeeman effect, the emission is unpolarized when viewed parallel to the field direction. The use of hydrogen has the unique characteristic that the Stark effect is linear with the electric field, producing a large spectral shift. For a magnetic field of 1.3 T and a beam energy of 55 keV, which are typical parameters for the Princeton Beta Experiment (PBX-M) tokamak,[6] the electric field on the atom is $\sim$ 40 kV cm. The average spectral shift of the π lines for this field is $\sim$ 4 Å. The spectral shift due to the Zeeman effect under these conditions is much less than the Stark shift. This has no effect on the direction of the linearly polarized plane wave. It can change the polarization fraction, but only by a few percent, so this effect can be ignored. The Stark effect pattern of the Balmer-alpha (H_α) lines showing the relative line intensities and polarization from Ref. 5, along with a measurement of the polarization fraction profile is shown in Fig. 1. Each data point is a time average of 40 msec from a single PBX-M discharge. Also shown is a numerically computed fractional polarization profile based on the convolution of the Stark shift and filter profile.

The experimental apparatus for these measurements on PBX-M consists of a highly collimated ($\sim 0.5°$) diagnostic neutral hydrogen beam.[7] The energy can be varied from 40-80 keV with a maximum injected power of $\sim$ 40 kW in the full energy

component. The beam power and energy for all the data shown here is 10 kW and 55 keV, respectively. The beam has a cross section of 5 cm vertically and 1.5 cm in the horizontal direction. The injection angle can be varied to change the radial intersection of the viewing cone with the beam, as shown in Fig. 2. The beam angle with respect to the optic axis of the instrumentation is typically 30-40 degrees. A lens mounted on the machine, normal to the magnetic field components, collects the light from the torus. A second lens collimates it through the two photo-elastic modulators, the polarizer, and the interference filter before it is focused onto a photomultiplier tube (PMT). The signal output from the PMT is amplified before going into a lock-in amplifier or waveform digitizer for later analysis. The interference filter is designed to have peak transmission at 6630 Å and a spectral width of 4 Å. The width is chosen to transmit only the σ lines from the H_α spectra in order to maximize the polarization fraction. The filter can be tuned to different wavelengths by tilting it, which shifts the passband towards the blue. This is necessary for maximizing the signal and compensating for different Doppler shifts when the beam angle is changed, as during a radial scan.

The polarimeter design uses a photoelastic modulator (PEM)[8,9] which has a large etendue and very good sensitivity to small variations in the polarization angle. A PEM consists of a birefringent crystal such as quartz with a piezoelectric transducer coupled to the crystal and driven at its resonant frequency ($\leq 50\,kHz$). Due to the birefringence of the crystal, the transducer causes a time-varying phase shift of the electric field between the $\hat{x}$ and $\hat{y}$ directions through the crystal. This results in a rotation of the input polarized light. In general, with incident linearly polarized light at an angle γ, a PEM at an angle α and a polarizer analyzer at an angle δ, the

transmitted intensity is

$$I_\tau = \frac{I_0}{2}\,1 - \cos 2(\gamma - \alpha)\cos 2(\theta - \alpha) - \sin 2(\gamma - \alpha)\sin 2(\theta - \alpha)\cos(A_0 \cos \Omega t)\,. \quad (1)$$

where the following Bessel series expansion can be used for

$$\cos(A_0 \cos(\Omega t)) = J_0(A_0) - 2J_2(A_0)\cos(2\Omega t) - 2J_4(A_0)\cos(4\Omega t) - \ldots\ldots \quad (2)$$

with A_0 the phase shift amplitude, and Ω the resonant frequency of the PEM. The phase shift amplitude, A_0, is adjusted to the maximum of the J_2 Bessel function, so as to maximize the $\cos(2\Omega t)$ term. This term is optimized because there is no modulation of the J_0 term, so it can be ignored, and the modulation frequency of J_4 and higher terms is too high for the amplifier. The J_2 term has a convenient modulation frequency between 50 – 100 kHz.

With the appropriate choice of parameters, the modulation amplitude can be proportional to the sine or cosine of the angle of polarization of the incident light. With two PEM's at slightly different frequencies both the sine and cosine can be measured simultaneously using synchronous detection techniques. If the corresponding values for α in Eq.(1) are 0°, and 45°, and $\theta = -22.5^\circ$ then ,

$$I \propto (\sin(2\gamma)\cos(2\Omega_2 t) - \cos(2\gamma)\cos(2\Omega_1 t) - \ldots). \quad (3)$$

The angle of the linearly polarized light equals the ratio of the signal amplitudes at the two PEM frequencies, $\tan(2\gamma) = I(2\Omega_2)/I(2\Omega_1)$. The two amplitudes, $I(2\Omega_2)$ and $I(2\Omega_1)$, can be determined in several ways, such as using Fourier analysis or a lock-in

amplifier. Since only one channel is required, a single photomultiplier tube can be utilized.

An example of the H_α signal from the beam is shown in Fig. 3. The interference filter is set at ~ 6620 Å to compensate for the large Doppler shift from the beam emission. The signal intensity is estimated to be $\sim 5 \times 10^{12}$ photons sec-sr-cm^2. The data shown has been smoothed with a running average over one msec time intervals to eliminate the high frequency modulation from the polarimeter. The lock-in amplifier signal, with a one msec integration time constant, is also shown, which illustrates the polarimeter modulation at the PEM resonant frequency. This is also demonstrated, in Fig. 4, with a 16 msec fast Fourier transform(FFT) of the data. The amplitudes at $2\Omega_1$ = 75.48 kHz and $2\Omega_2$ = 84.09 kHz, corresponding to the resonant frequencies of the two PEM's, are proportional to the sine and cosine, respectively, of the pitch angle. As illustrated in Fig. 4(b) the uncertainty in the amplitude of the sine component is 1.6 units. This corresponds to ~ 0.3° for the 16 msec interval. This uncertainty has also been determined from a statistical analysis of the pitch angle variation from many successive discharges.

As discussed earlier in the text, in order to obtain a radial profile to determine $q(0)$, a shot-to-shot scan is required. This was done for an Ohmic discharge with a plasma current of 330 kA, major radius of 1.64 m, minor radius of 0.3 m, density of 3×10^{13}cm^{-3}, and toroidal field of 1.2 T. Only discharges with the plasma current within 5% of 330 kA were used in the analysis to minimize shot-to-shot variations. The radial scan of the pitch angle is shown in Fig. 5. Each data point in the figure is a time average of 40 msec from three discharges. This reduces the uncertainty to 0.1°, corresponding to ~ 20 Gauss. The safety factor at the magnetic axis, using the

central 7 points from the graph for the linear regression, is $q_{cyl} = 0.63 \pm 0.02$ assuming a circular plasma. Systematic errors due to the beam viewing geometry amount to an absolute error of $\sim \pm 2$ cm. Also the zero reference angle of the toroidal field with respect to the polarimeter axis, which is measured with beam injection into a gas-filled torus, introduces some error. However, both these errors cause a shift of the data and do not contribute to the uncertainty in q_{cyl}. Systematic errors that do contribute to the q_{cyl} uncertainty include the relative beam viewing geometry error, and vertical displacement from the midplane of the plasma or the field of view. The contribution of these errors increases the uncertainty so that $q_{cyl} = 0.63 \pm 0.03$, which illustrates the high precision obtainable with MSE polarimetry. For a noncircular, low beta plasma, such as those described here, $q(0) = \kappa q_{cyl}$, where κ is the elongation of a plasma with an elliptical cross section. This correction factor can be derived using the definition for q(r) and the solution of the Grad-Shafranov equation for a noncircular cross section.[10] Based on results from an equilibrium code and measurements from an X-ray pinhole camera, $\kappa = 1.36$, which results in $q(0) = 0.86 \pm .05$.

Independent confirmation of this value of $q(0)$ derived from the MSE polarimetry measurements has been obtained from two other $q(0)$ measurements on PBX-M for the same set of discharges. One technique uses an X-ray pinhole camera, which can obtain an image of the plasma and determine the shape of the magnetic flux surfaces in the plasma core.[11] The derived poloidal emissivity contours are compared with the poloidal flux contours calculated via a magnetics equilibrium code. An assumed parameterization of the internal current distribution is adjusted, along with $q(0)$, to match the measured shape to determine the internal current distribution and $q(0)$. The measured electron pressure profiles and several external flux values are used to

constrain the allowed equilibria. This measurement technique is sufficient to constrain the allowed value of the axial safety factor to $q(0) = 0.7 \pm 0.2$.

The Fast Ion Diagnostic Experiment (FIDE) is another technique for measuring plasma current profiles, and it has been demonstrated in two previous tokamak experiments.[12,13] A $q(0)$ of 0.8 ± 0.14, which represents an average over a sawtooth period, was obtained at 300 msec after the start of the discharge, and is in good agreement with the value from the MSE polarimetry diagnostic.

In conclusion, we have definitive measurements that motional Stark effect polarimetry can yield accurate pitch angle profiles. The result that $q(0) < 1$ for discharges exhibiting sawtooth behavior is consistent with measurements obtained elsewhere.[4,14] Expected improvements in the design of the diagnostic and the neutral beam will yield an improved signal-to-noise ratio and time resolution. The technique also has the potential for multichannel capability to obtain $j(r,t)$ profile evolution during a single discharge. Data with this system have also been obtained in beam heated discharges with $\overline{n_e} = 6 \times 10^{13}$ cm^{-3}, indicating this approach extrapolates favorably for use at higher densities and or in larger machines.

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References

[1]F. DeMarco and S E. Segre. Plasma Phys. **14**. 245 (1972).

[2]D. Wróblewski. L. K. Huang. and H. W. Moos. Phys. Rev. Lett. **61**. 1724 (1988).

[3]K. McCormick et al.. Phys. Rev. Lett. **58**. 491 (1987).

[4]W. P. West. D. M. Thomas. J. S. DeGrassie. and S. B. Zheng. Phys. Rev. Lett. **58**. 2758 (1987).

[5]E. U. Condon and G. H. Shortley. *The Theory of Atomic Spectra*. Cambridge University Press. 1963.

[6]M. Okabayashi et al.. "Initial Results of the PBX-M Experiment". in *Plasma Physics and Controlled Nuclear Fusion Research. 1988*. IAEA. Vienna(to be published).

[7]H. W. Kugel et al.. Nucl. Instrum. Methods(to be published) .

[8]J. C. Kemp. J. Opt. Soc. Am. **59**. 950 (1969).

[9]J. C. Kemp. G. D. Henson. C. T. Steiner. and E. R. Powell. Nature **326**. 270 (1987).

[10]J P. Freidberg. *Ideal Magnetohydrodynamics*. Plenum Press. New York. 1987.

[11]R. J. Fonck et al.. Rev. Sci. Instrum. **59**. 1831 (1988).

[12]R. J. Goldston. Phys. Fluids **21**. 2346 (1978).

[13]D. D. Meyerhofer et al.. Nucl. Fusion **25**. 321 (1985).

[14]H. Soltwisch. Rev. Sci. Instrum. **59**. 1599 (1988).

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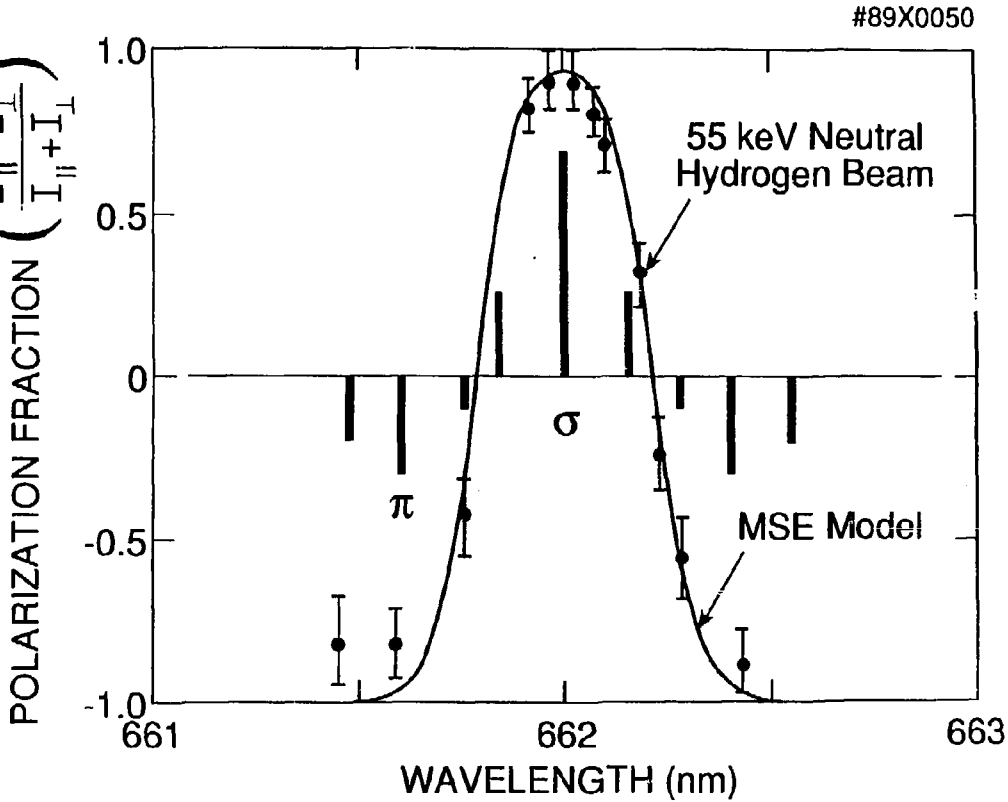
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POLARIZATION FRACTION $\left(\frac{I_{\parallel}-I_{\perp}}{I_{\parallel}+I_{\perp}}\right)$
1.0
0.5
0
-0.5
-1.0
661
662
663
WAVELENGTH (nm)
55 keV Neutral
Hydrogen Beam
MSE Model
π
σ

Fig. 1

#89X0053

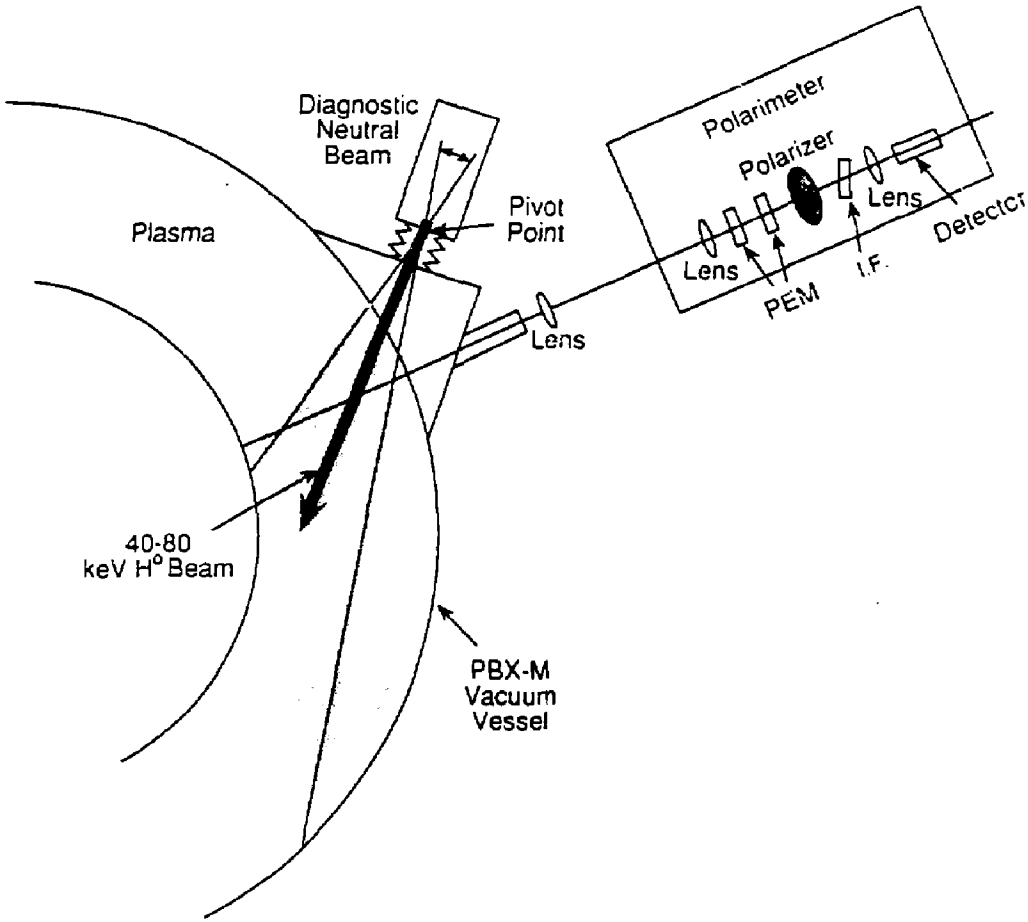
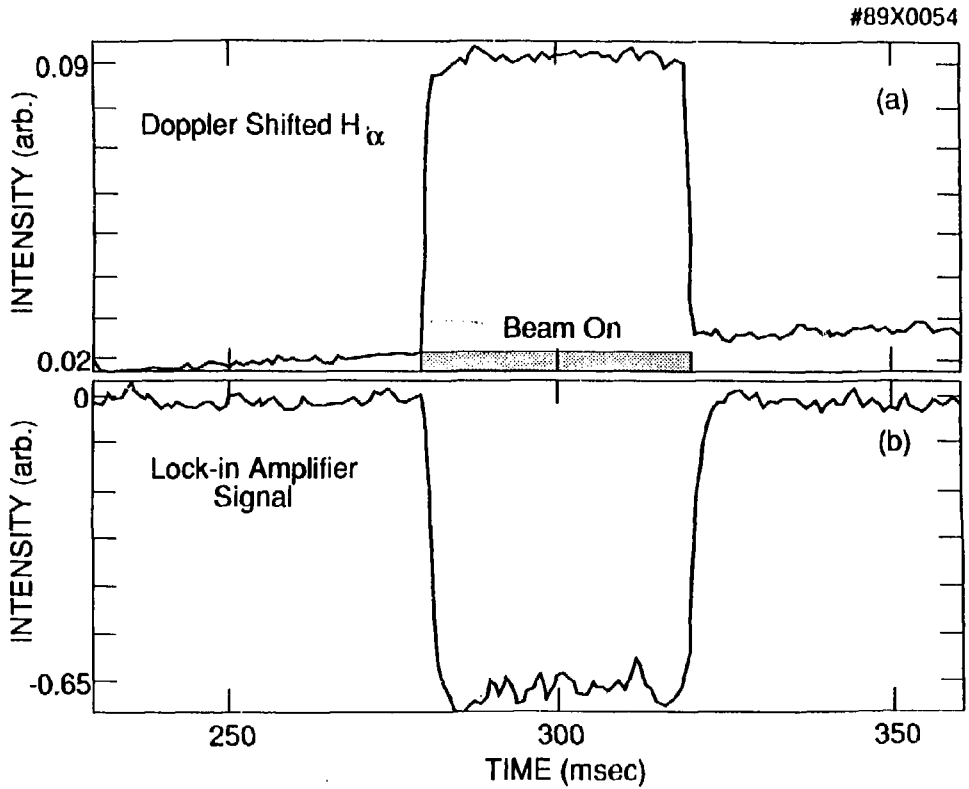


Fig. 2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0.02
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Doppler Shifted H α
(a)
Beam On
0
-0.65
INTENSITY (arb.)
Lock-in Amplifier
Signal
(b)
250
300
350
TIME (msec)

Fig. 3

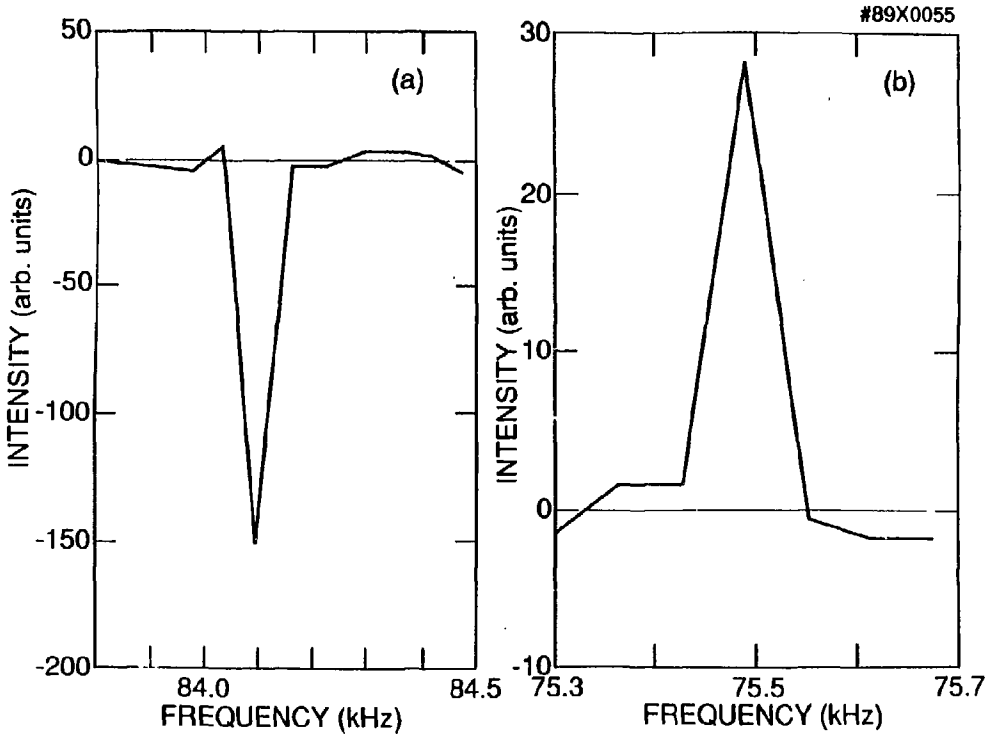
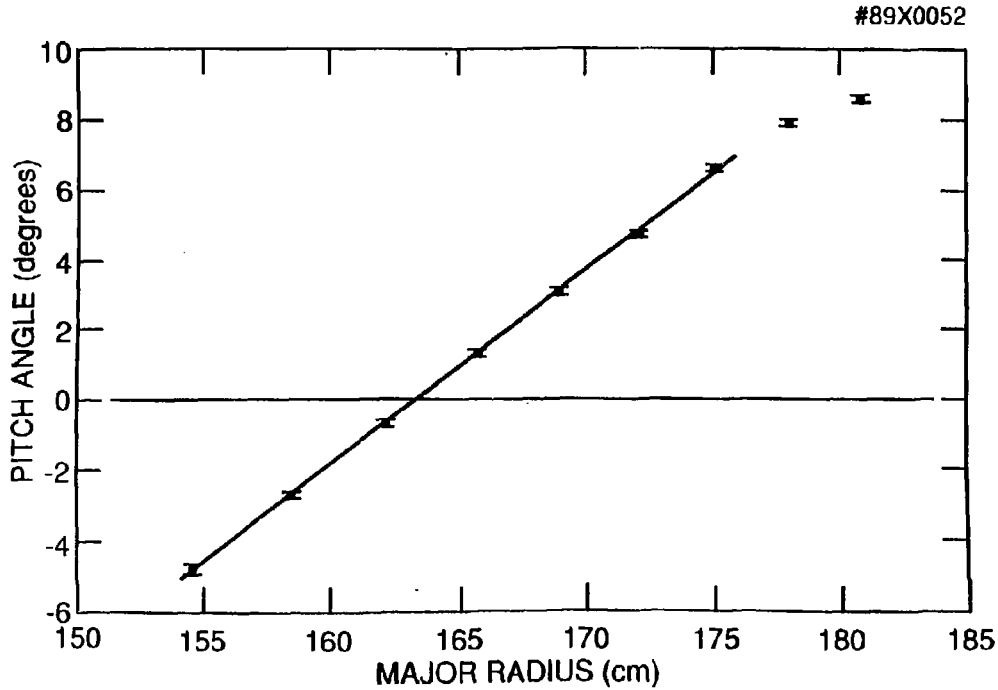

#89X0055
(a)
(b)
INTENSITY (arb. units)
INTENSITY (arb. units)
50
0
-50
-100
-150
-200
30
20
10
0
-10
84.0
84.5
75.3
75.5
75.7
FREQUENCY (kHz)
FREQUENCY (kHz)

Fig. 4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PITCH ANGLE (degrees)
10
8
6
4
2
0
-2
-4
-6
150
155
160
165
170
175
180
185
MAJOR RADIUS (cm)

Fig. 5

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