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Improvement of Interferometric Measurements on FIR Polarimeter/Interferometer Systems

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On many tokamaks the reconstruction of the magnetic field structure in the plasma is supported by polarimetric measurements. Recent proposed and realized methods are based on a far-infrared laser beam with a rotating polarization ellipse. The same instrument usually performs as an interferometer measuring the line integrated plasma density. It has been shown that the rotating polarization ellipse disturbs the interferometric measurements. A method based on the principle of a rotating polarization in which the interferometric measurement is unaffected is proposed. Bench test results are presented which show the feasibility of this method.

Introduction

Polarimetry is a well known technique used to determine the magnetic field structure in tokamaks since it was first proposed by De Marco and Segre[1,2]. On TFR Kunz[3] demonstrated the feasibility of Faraday rotation measurements. After a successful implementation of a multichannel system on TEXTOR by Soltwisch[4] several similar systems were installed on other tokamaks[5-9]. Recently B.W. Rice[10] used an FIR technique which allows the Faraday rotation induced by the plasma to be deduced from a phase measurement making the system independent of laser fluctuations. This method uses a minimum of detectors and can be incorporated relatively easily into existing interferometer systems. Therefore, it is intended to base the polarimeter upgrade of the TCV FIR interferometer on this method. According to Hofmann and Tonetti's[11] studies the accuracy of the equilibrium reconstruction would be substantially improved by utilizing Faraday rotation information.

Rice's Method

The polarimeter system installed by B.W. Rice on MTX is based on the method proposed by Dodel and Kunz[12]. Instead of a rotating linearly polarized beam Rice uses a rotating elliptically polarized probing beam and a frequency shifted linearly polarized reference beam. The rotating polarization ellipse is produced by passing an elliptically polarized beam through a rapidly rotating half-wave plate. On the detector the beat signal between the reference and probing beams is a modulated waveform where the modulation envelope, after some filtering, is proportional to

$$\cos(4\omega_r t + 2\Psi)$$

where ω_r is the rotation frequency of the half-wave plate. The Faraday rotation, Ψ, can be extracted from the phase shift 2Ψ of the modulation envelope. The interferometer information is determined by measuring the phase shift of the modulated carrier signal. In contrast with previous methods[4] both the interferometer and polarimeter data can be measured using only one detector per channel. It was shown that this method is limited by an additional time-varying phase term which is superimposed on the required interferometer data[13]. This term can be expressed as,

$$\Delta\Phi = \arctan\left[\varepsilon \tan(2\omega_r t + \Psi)\right] - \arctan\left[\varepsilon \tan(2\omega_r t)\right] \qquad (1)$$

where ε is a measure of the ellipticity of the FIR beam. This term becomes significant for large Faraday rotation angles and large ellipticities of the polarization of the probing beam. It should be noted that this term does not represent a plasma effect but is an artifact of the rotating polarization ellipse technique itself.

This extra term can be effectively removed by low-pass filtering the interferometer data with the subsequent loss of time resolution. Systems with separate lasers for probe and reference beams can in principle provide a time resolution which is determined by the difference in frequency between the lasers, usually in the order of 1 MHz. This excellent time resolution is lost by the necessity to low-pass filter at a frequency close to the rotating elliptical polarization frequency usually of order of some kHz.

Computational methods can also be employed to reconstruct the correct interferometer data once the Faraday rotation angle, Ψ, and the ellipticity of the polarization have been determined.

We propose a modification to this method which does not suffer from the inherent error in the interferometer phase measurement but still preserves the overall robustness of Rice's approach. The modified technique is also based on phase measurements.

Proposed Method

In the modified method the rotating elliptically polarized probing beam is replaced by the combination of a rotating linearly polarized beam and a plain linearly polarized beam of amplitudes A and B, respectively. Part of this beam combination traverses the plasma, is altered by it and is superimposed with a frequency shifted linearly polarized reference beam on the plasma detector. The other part passes through free space before also being combined with the reference beam on the reference detector. Polarizers are placed in front of both detectors in order to pass only radiation parallel to that of the reference beam. The resulting intensity on the reference detector is given by,

$$\begin{aligned} I_{ref} &= \frac{A^2}{4} + \frac{B^2}{2} + \frac{E^2}{2} \\ &+ AB\cos\phi_0 \cos 2\omega_r t + \frac{A^2}{4}\cos 4\omega_r t \\ &+ AE\cos 2\omega_r t \cos\Delta\Omega t + BE\cos(\Delta\Omega t - \phi_0) \end{aligned} \qquad (2)$$

where E is the amplitude of the reference beam, ω_r the rotation frequency of the half-wave plate used to produce the rotating polarization and $\Delta\Omega$ is the frequency shift between the reference and probing beams. The term, ϕ_0, is the phase difference between the "A" and "B" beams. The presence of this term introduces an extra phase term in the measured data. DC blocking and appropriate low-pass filtering of the signal can extract the term,

$$AB\cos\phi_0 \cos 2\omega_r t.$$

By adjusting the optical path length of the non-rotating beam to maximize this signal the term ϕ_0 will be set to a multiple of π. This fine adjustment is undertaken using a precision micrometer driven translator. In this case the intensity can be represented as

$$\begin{aligned} I_{ref} &= \frac{A^2}{4} + \frac{B^2}{2} + \frac{E^2}{2} \\ &+ AB\cos 2\omega_r t + \frac{A^2}{4}\cos 4\omega_r t \\ &+ BE\cos\Delta\Omega t\left(1 + \frac{A}{B}\cos 2\omega_r t\right) \end{aligned} \qquad (3)$$

Band-pass filtering around $\Delta\Omega$ leaves,

$$S_{ref} = BE\cos\Delta\Omega t\left(1 + \frac{A}{B}\cos 2\omega_r t\right) \qquad (4)$$

The plasma probing beam undergoes a plasma induced phase shift, Φ, while the Faraday effect causes a rotation, Ψ, of it's polarization. The resulting signal, after filtering, is given by,

$$S_{plas} = BE\cos\Psi\cos(\Delta\Omega t - \Phi)\left(1 + \frac{A}{B\cos\Psi}\cos(2\omega_r t + \Psi)\right) \qquad (5)$$

These are amplitude modulated signals where the interferometer data, Φ, is measured by the phase shift between the carrier signals which have a frequency of $\Delta\Omega$ and the polarimeter data, Ψ, by that of the modulation envelopes at a frequency of $2\omega_r$.

The modulation indices for the reference and plasma signals are given by A/B and $A/B\cos\Psi$ respectively. Ideally these ratios should be kept below unity. If the modulation indices exceed unity the signals are said to be overmodulated and additional polarimeter phase terms are introduced. To prevent this the ratio of B to A should be set to an appropriate value to avoid overmodulation for all expected values of Faraday rotation.

The precision required in the setting of the ϕ_0 phase term to avoid an additional phase term in the measured data is dependent on the Faraday Rotation angle and the modulation index of the signal. The setting of ϕ_0 to a multiple of π is more critical for the interferometer data than for the polarimeter. It was seen that the required precision was less for smaller values of modulation index. Therefore, with a suitable choice of modulation index and realistic Faraday Rotation angles up to say 25°, the interferometer error due to this additional term can be kept to within a few percent with a precision in the phase difference, ϕ_0, of up to 20°.

The birefringence of the plasma will introduce some small changes in the ellipticity of the probing beam. These changes in ellipticity will be seen as small changes in the amplitude of the demodulated signal. As with Rice's method the modified method is based on phase and not amplitude measurements and will, therefore, be insensitive to small changes in the ellipticity.

This technique is very similar to Rice's modulation method with the following differences: (a) the modulation is a purely cosine variation without higher order harmonics; (b) the modulation frequency is lower by a factor of 2; (c) the measured polarimeter phase shift is the Faraday rotation, Ψ as opposed to 2Ψ and (d) the interferometer phase measurement Φ is not corrupted by additional terms provided $\phi_0 = 0$ or $n\pi$.

Bench Test

The layout of the optical arrangement shown in Fig. 1 for a direct comparison of both methods has the following features. The laser system produces a 118 μm vertically polarized Gaussian beam. After some beam forming mirrors a small fraction of this beam is reflected by a Mylar beamsplitter towards the rotating half-wave plate, which is turbine driven in the hollow shaft of a air-bearing spindle, to form the A beam. The transmitted beam is further divided by a 1:2 Cu mesh into the B and E or reference beams. The splitting ratio afforded in particular by the Mylar ensures that the relative ratio of the A and B beams does not result in overmodulation. The remaining beamsplitters are 50:50 splitters for vertical polarization. The beamsplitter, BS, should have a 50:50 reflection to transmission ratio for both polarizations for ideal operation. However, small deviations from the ideal which introduce additional polarimeter phase shifts can be compensated for during calibration of the system. Vertical polarizers are placed in front of each of the Schottky diode detectors.

The same optical set-up can also be employed to simulate Rice's method by simply inserting a beam-stop in the B beam path and introducing a quarter-wave plate just prior to the rotating half-wave plate. For the simulations we adopted a carrier frequency of 10 kHz set by the rotating grating and a modulation frequency of 500 Hz corresponding to a mechanical rotation frequency of the spindle of $\omega_r/2\pi$ = 250 Hz and 125 Hz for the modified and Rice's method, respectively. The plasma phase shift (Φ) and the Faraday rotation (Ψ) are simulated using a perspex plate and a precision rotatable half-wave plate, respectively. The quartz plates used are anti-reflection coated on both sides.

The optical arrangement was initially set up to simulate Rice's method and to confirm it's inherent interferometer error. The precision half-wave plate was adjusted prior to the measurement to give a constant Faraday rotation of 50° with the quarter wave plate set to produce an average modulation index of 0.59. The uncertainty in modulation index arises from the slightly differing modulation depths of the two AM waveforms and additional modulation due to the non-uniformity of the rotating grating. The detector signals are squared up using high-gain limiting amplifiers to remove the modulation and the resulting signals are fed into a lock-in amplifier set to produce an output proportional to their relative phase shift. An arbitrary interferometer phase shift of -180° is introduced using the perspex plate. In Fig. 2 the time-dependent phase error is shown which is consistent with expectations (see Eq. 1). From similarly recorded plots we provide in Fig. 3 a comparison between theory and experiment of the maximum interferometer error in degrees as a function of Faraday rotation. The experimental uncertainty in phase measurements is about ±5°. It is clear from this plot that the results obtained are quite consistent with theoretical predictions.

The modified method was then simulated to show experimentally the absence of any additional interferometer phase terms. The precision half-wave plate was stepped from zero through 25 mechanical degrees, corresponding to a Faraday rotation of 0-50°. The resulting interferometer phase shift with an arbitrary initial value of 180° is shown plotted in Fig. 4. It can be seen that the phase is not affected by the rotation of the half-wave plate apart from the noise which limits the measurement accuracy to ±5°. The absence of additional phase terms in the measured interferometer data implies that a real-time measurement of line integrated plasma density with a time resolution corresponding to the carrier frequency is possible.

Conclusion

A modification to the interferometer/polarimeter system installed by B. W. Rice on MTX has been presented. It retains the major advantages of the original method with the additional benefit that the interferometer data is not disturbed by the extra time dependent phase term.

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FIG. 1 Illustration of the optical arrangement used during bench tests.

FIG. 2 The measured Interferometer phase shift, Φ (set to -180°) for Rice's method showing the inherent time dependent phase error $\Delta\Phi$ for a Faraday rotation angle of 50° and a modulation depth of 0.59 where ω_r is the rotational speed of the half wave plate.

FIG. 3 Maximum theoretical and experimental Interferometer phase error in Rice's method as a function of Faraday rotation for a modulation depth of 0.59.

FIG. 4 The time history of the measured Interferometer phase shift Φ (set to 180°) for the modified method as the Faraday rotation is stepped from 0-50° in steps of 5° where ω_r is the rotational speed of the half wave plate.

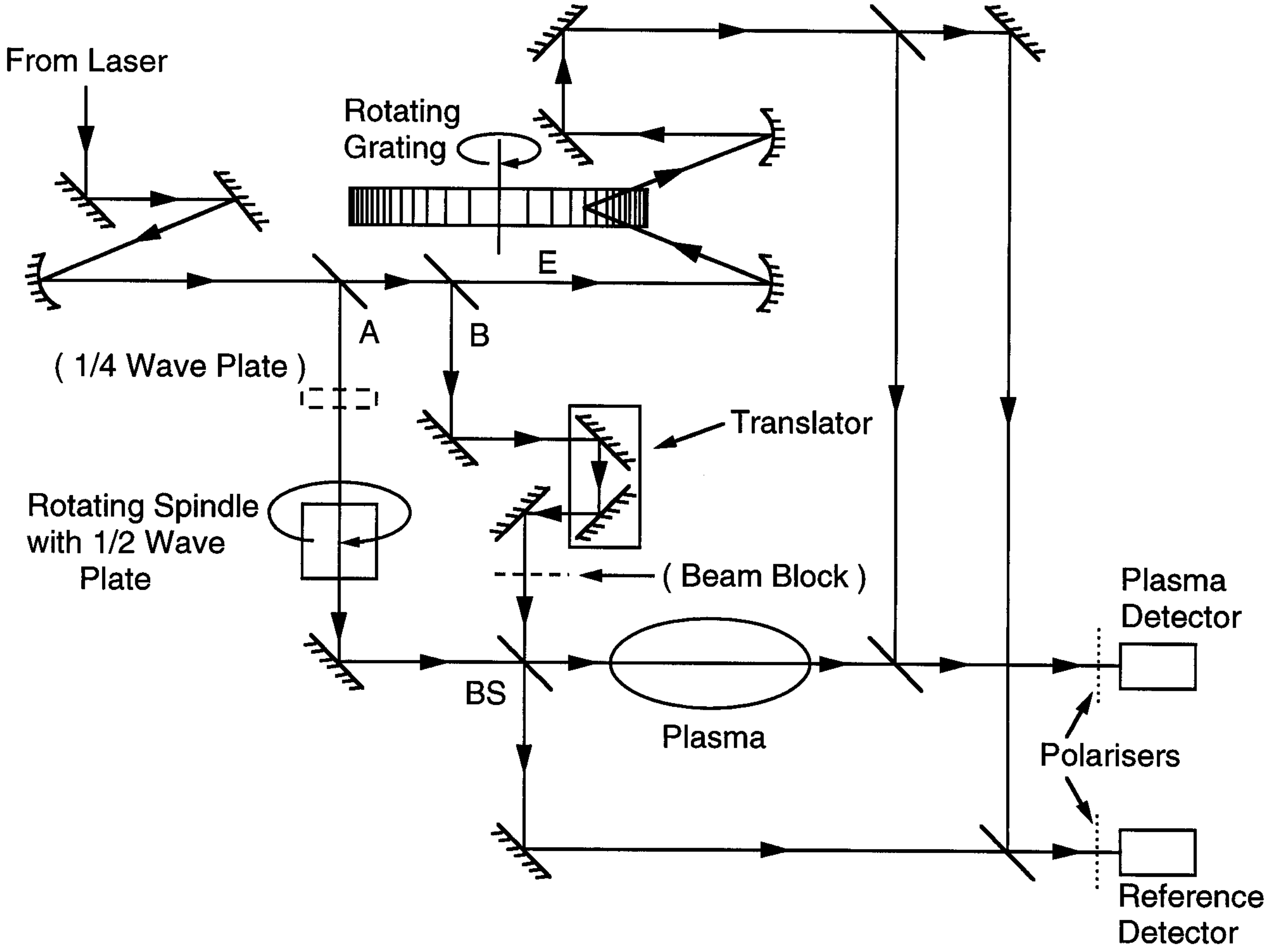
From Laser
Rotating
Grating
E
A
B
(1/4 Wave Plate)
Translator
Rotating Spindle
with 1/2 Wave
Plate
(Beam Block)
Plasma
Detector
BS
Plasma
Polarisers
Reference
Detector

Fig. 1

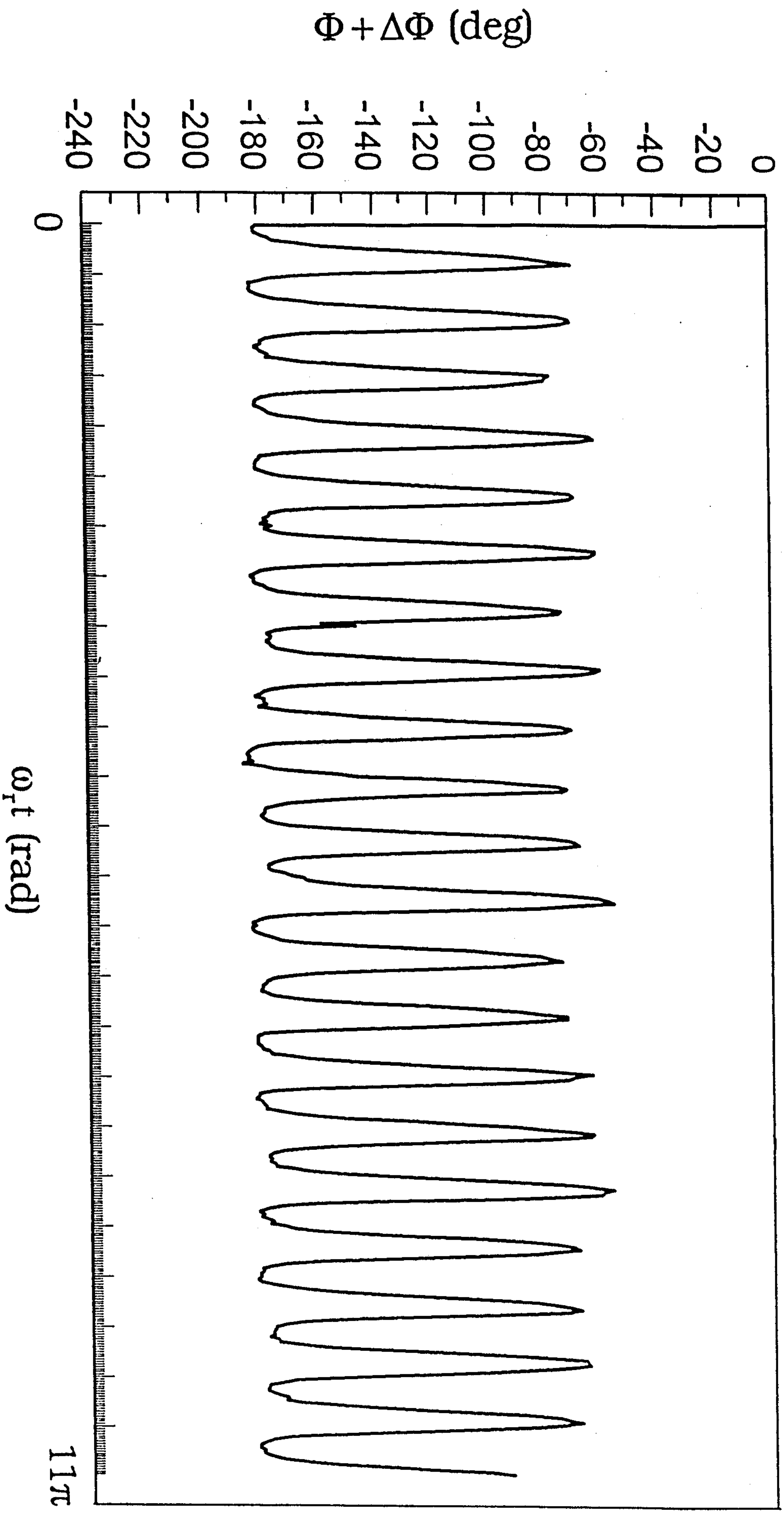

Fig. 2

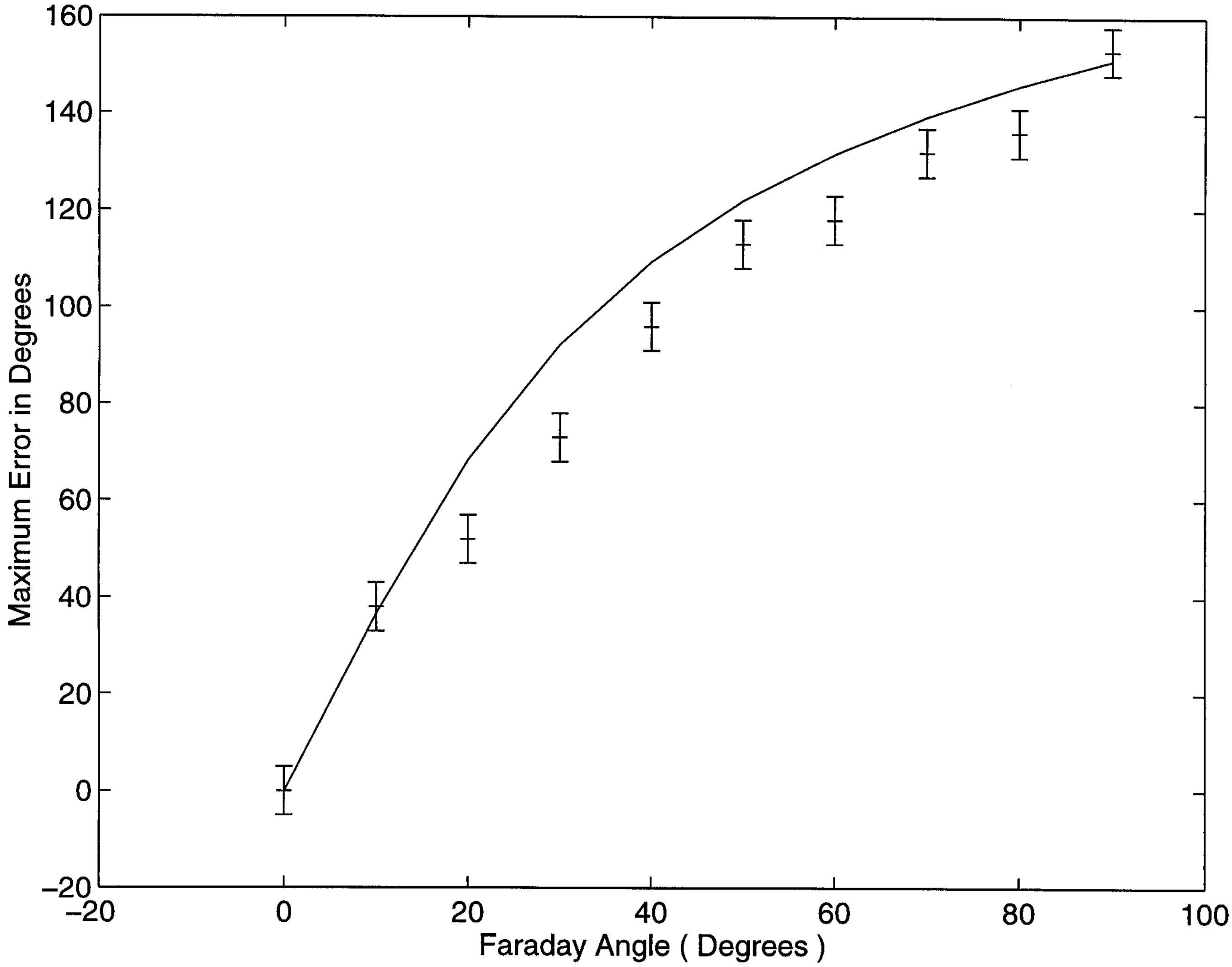
160
140
120
100
80
60
40
20
0
-20
Maximum Error in Degrees
-20
0
20
40
60
80
100
Faraday Angle (Degrees)

Fig. 3

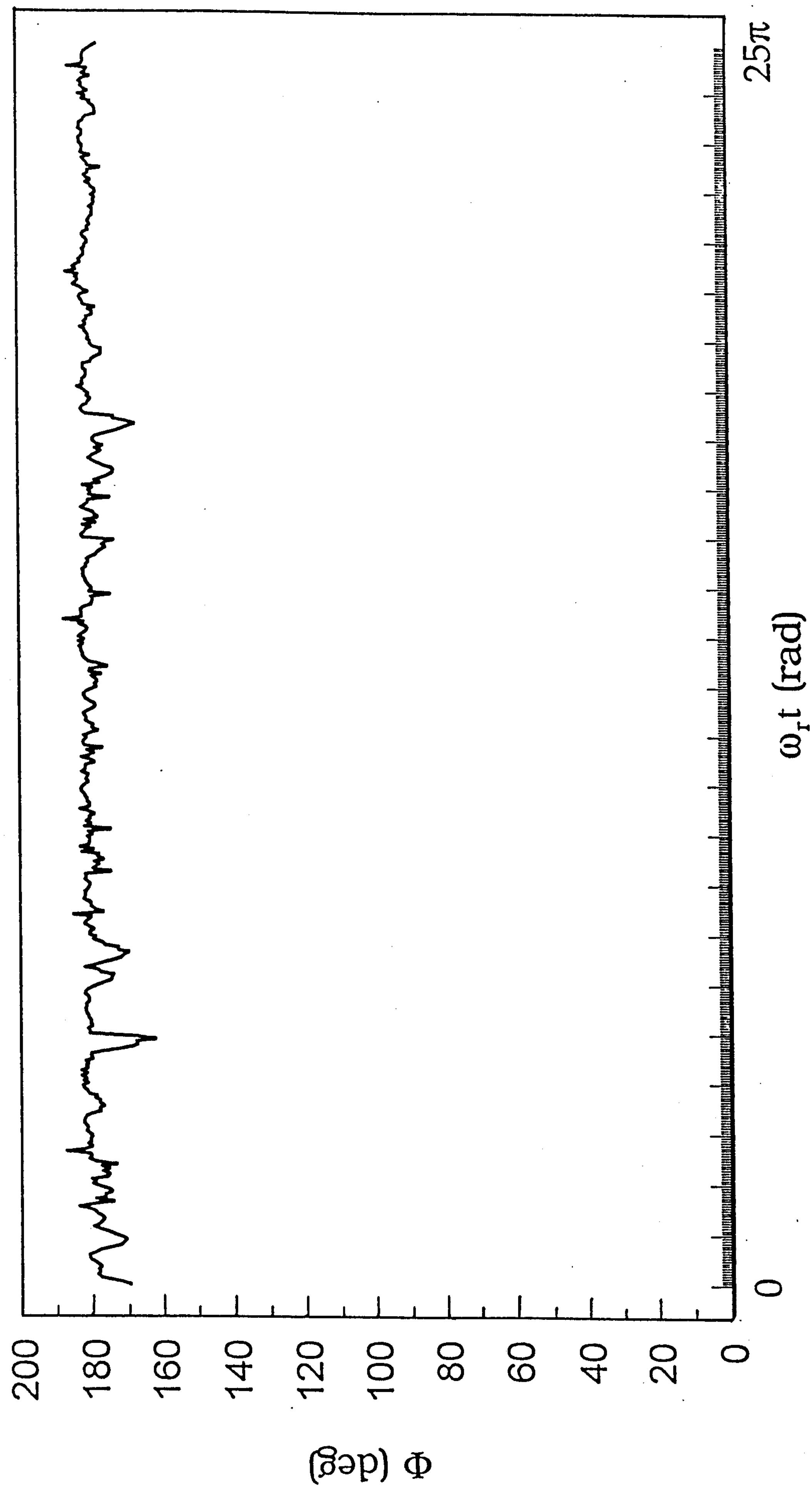

Fig. 4