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The effect of E_r on MSE measurements of q, a new technique for measuring E_r, and a test of the neoclassical electric field.

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Abstract

Previous analysis of motional-Stark Effect (MSE) data to measure the q-profile ignored contributions from the plasma electric field. The MSE measurements are shown to be sensitive to the electric field and require significant corrections for plasmas with large rotation velocities or pressure gradients. MSE measurements from rotating plasmas on the Tokamak Fusion Test Reactor (TFTR) [Phys. Plasmas **2**, 2176 (1975)] confirm the significance of these corrections and verify their magnitude. Several attractive configurations are considered for future MSE-based diagnostics for measuring the plasma radial electric field. MSE data from TFTR is analyzed to determine the change in the radial electric field between two plasmas. The measured electric field quantitatively agrees with the predictions of neoclassical theory. These results confirm the utility of a MSE electric field measurement.

I. Introduction

The rotational transform of the magnetic field plays a fundamental role in determining the equilibrium and stability of plasma in toroidal magnetic confinement configurations. As a consequence, accurate measurement of the rotational transform profile or the safety factor q (its inverse) is crucial for the analysis and interpretation of experimental studies of plasma equilibrium, transport, MHD stability and micro-stability. The motional-Stark effect (MSE) diagnostic[1–4] was developed to measure the q-profile in tokamaks, and has become one of the preferred techniques due to its excellent spatial resolution, high accuracy, non-perturbative nature, and presumed ease of interpretation. This technique uses the Stark polarization and splitting of line radiation from hydrogenic atoms (either H^0 or D^0), injected as a beam at high velocity across the magnetic field, due to the induced electric field $\boldsymbol{E}_M = \boldsymbol{v}_b \times \boldsymbol{B}$, where $\boldsymbol{v}_b$ is the beam velocity and $\boldsymbol{B}$ is the magnetic field. By measuring the polarization angle of the Stark-split emission, the direction of the electric field is determined. Past analysis of MSE data assumed that $\boldsymbol{E}_M$ was the only electric field contributing to the Stark polarization, and thus that the direction of the magnetic field could be directly determined from the measured direction of the electric field. Determining the profile of the local direction or pitch of the magnetic field determines the q profile directly in tokamaks with circular cross section[5,6] or through numerical solution of the Grad-Shafranov equation.[7,8] Determination of the q profile is equivalent to determining the plasma current profile.

In a magnetically confined toroidal plasma, the radial electric field $\boldsymbol{E}_r$ is an important element of the force balance perpendicular to the flux surface

$$\nabla_r p_a = n_a e_a(\boldsymbol{E}_r + \boldsymbol{V}_a \times \boldsymbol{B}) \tag{1}$$

for each thermal plasma species a, where e_a, n_a, p_a, and $\boldsymbol{V}_a$ are the charge, density, pressure, and fluid velocity in the flux surface of the species, respectively. Thus, large electric fields are expected in plasmas with large pressure gradients or large velocities.

Previous analysis of MSE measurements ignored the plasma electric field. In Section II of this paper, we examine the sensitivity of MSE measurements of the q profile to the plasma E_r and find that significant corrections are expected in plasmas with large rotation velocities or large pressure gradients. In Section III, MSE measurements are analyzed for rotating plasmas on the Tokamak Fusion Test Reactor (TFTR),[9] experimentally confirming the significance of the E_r corrections and quantitatively verifying their magnitude.

Determining E_r is important for testing theories predicting the equilibrium flows for the different species. In axisymmetric toroidal configurations, like tokamaks, neoclassical theory[10] predicts that the poloidal velocity $V_{\theta a}$ of the ions should be viscously damped, and that the dominant terms of the ion radial force balance are from $\nabla_r p_a$, E_r and $V_{\phi a} B_P$, where $V_{\phi a}$ is the fluid velocity in the toroidal direction and B_P is the poloidal component of $\boldsymbol{B}$. In addition, recent theoretical and experimental studies indicate that E_r, and particularly the gradient or shear of E_r/B_P, is important for stabilizing turbulence[11] and MHD-instabilities.[12] Thus, measurements of E_r are crucial for understanding the stability and transport of magnetically confined plasmas.

It is very difficult to measure E_r in a hot dense plasma. The most direct technique measures the change in energy of a heavy-ion beam probe (HIBP) as it passes through the plasma and is incrementally ionized.[13] Very high beam energies are required for the heavy-ion beam to cross the magnetic field to the core of the plasma and then to escape following ionization. Even moderate sized tokamaks utilize 2 MeV thallium beams, and the required energies for large tokamaks are prohibative. HIBP measurements of E_r were found to agree qualitatively with neoclassical predictions in neutral beam-heated[14] and ohmic[15] plasmas. In other cases, the plasma electric field has been calculated using Eq. 1 and localized measurements of $\nabla_r p_a$, $V_{\phi a}$ and $V_{\theta a}$ for one of the species (typically an impurity).[16] In cases where $V_{\theta a}$ measurements were not available, the neoclassical transport theory prediction is often used.

In Section IV, we consider the use of MSE measurements as a diagnostic for measuring E_r in toroidal plasmas. Several attractive configurations are explored, including their expected uncertainties. MSE measurements from TFTR are analyzed to determine the change in E_r between two plasmas. The inferred change in E_r is then compared with various models of flow equilibrium. The measured E_r is in good agreement with the neoclassical prediction, confirming its utility in the absence of direct measurements, and confirming the utility of a MSE E_r measurement. Section V discusses some of the implications of these results and summarizes the work.

II. Effect of E_r on MSE measurements of q

A typical MSE instrument for measuring the q profile in a tokamak consists of an array of polarimeters viewing an injected hydrogenic neutral atom beam at different depths in the plasma.[3,7] The geometry of a single sightline is illustrated in Fig. 1. The horizontal angle between the sightline and the magnetic field Ω is usually minimized in order to maximize the radial localization of the measurement. The horizontal angle between the the atom beam's velocity and the magnetic field α must be $\neq 0$ in order that $\boldsymbol{E}_M$ be sensitive to both the poloidal and toroidal components of the magnetic field. In addition, the angle between the sightline and the beam's velocity $\alpha + \Omega$ is chosen to be $\neq \pi/2$ so that the line-emission from the beam atoms is Doppler shifted and is not contaminated by emission from the plasma edge.

The standard analysis of the measured polarization assumes that the motional electric field E_M is the only electric field affecting the Stark polarization of the light emitted from the beam atoms. In this case, the measured polarization angle γ_m is given by

$$\begin{aligned} \tan\gamma_m &= \frac{v_b B_P \cos(\alpha+\Omega)}{v_b B_T \sin\alpha}, \\ &\equiv \tan\gamma_s \frac{\cos(\alpha+\Omega)}{\sin\alpha} \end{aligned} \tag{2}$$

where B_T is the toroidal component of $\boldsymbol{B}$. For simplicity, we assume that the sightline-beam intersection is located so that there is no component of the magnetic field in the major-radial direction. Generalization to more complicated geometries is straight forward.[7] In the standard analysis, the local pitch of the magnetic field $B_P/B_T = \tan\gamma_s$ is then determined by a geometrical correction to γ_m. For flux surfaces with circular cross-section, the rotational transform is geometrically related to the local magnetic field pitch,[5,6] and $q \propto 1/\tan\gamma_s$. For non-circular cross section surfaces, q is still approximately proportional to $1/\tan\gamma_s$, however the proportionallity factor must be determined from a self-consistent numerical solution for the plasma equilibrium.

In a plasma with a radial electric field, the measured polarization angle is

$$\tan\gamma_m = \frac{v_b B_P \cos(\alpha+\Omega) + E_r \cos\Omega}{v_b B_T \sin\alpha}. \quad (3)$$

Thus, the only measurement geometry which is not sensitive to E_r has $\Omega = \pi/2$, i.e. a radial sightline, as was used in the original PBX-M implementation.[1] In such a configuration, the width of the beam must be minimized to allow radial localization of the measurement. Expanding E_r and $(\boldsymbol{V}_a \times \boldsymbol{B})_r = V_{\phi a} B_P - V_{\theta a} B_T$ gives

$$\tan\gamma_m = \frac{v_b B_P \cos(\alpha+\Omega) + \left(\frac{\nabla_r p_a}{n_a e_a} - V_{\phi a} B_P + V_{\theta a} B_T\right)\cos\Omega}{v_b B_T \sin\alpha}. \quad (4)$$

Therefore, determination of $\tan\gamma = B_P/B_T$ and q from γ_m not only requires knowledge of the equilibrium geometry but also the plasma E_r, or equivalently the plasma pressures and flows.

The correction factor between the new (including E_r) and old (neglecting E_r) interpretations of the MSE measurements is

$$F \equiv \frac{\tan\gamma}{\tan\gamma_s} = 1 + \left(\frac{V_{\phi a}}{v_b} - \frac{V_{\theta a}}{v_b}\frac{B_T}{B_P} - \frac{\nabla_r p_a}{n_a e_a v_b B_P}\right)\frac{\cos\Omega}{\cos(\alpha+\Omega)}. \quad (5)$$

The corrected q values will be approximately given by $q = q_s/F$, where q_s is from the old interpretation. At the magnetic axis, the correction factor can be further simplified as ∇p_a and $V_{\theta a}$ must vanish. The corrected axial q is given by

$$q(0) = q_s(0)\left(1 + \frac{V_{\phi a}}{v_b}\frac{\cos\Omega}{\cos(\alpha+\Omega)}\right)^{-1}. \quad (6)$$

From these expressions, significant corrections to the inferred q and plasma current profile should be expected for plasmas with large rotation velocities, such as observed with unidirectional beam injection, or large pressure gradients, such as observed with transport barriers.[17–19] Central toroidal rotation velocities as high as 1.3×10^6 m/sec have been experimentally observed[20] with unidirectional neutral-beam injection in the same direction as the plasma current. For a typical MSE system with $\Omega \approx 0$ and $\cos\alpha \approx 0.75$ observing a 90 keV deuterium beam, $v_b = 2.9 \times 10^6$ m/sec, the correct $q(0)$ is only 0.63 of the value given by the standard MSE interpretation. In plasmas with significant $\nabla_r p_a$ or V_{θ_a}, a non-linear analysis is required to interpret the MSE measurements using Eq. 5 because the correction terms involve the magnetic field components. Alternatively, the effects of $\nabla_r p_a$ or V_{θ_a} can be treated as an offset in Eq. 4.

III. Experimental Observations

TFTR is heated by tangential deuterium or tritium neutral beams, with half the beams directed co-parallel to the plasma current and half directed anti-parallel. This allows the preparation of nearly identical plasmas but with toroidal rotation velocities of opposite sign. Charge-exchange recombination spectroscopy[21] of fully ionized carbon is used to measure the carbon toroidal rotation, density, and temperature profiles simultaneously. The energy dependence of the charge-exchange cross section requires a significant correction[22] to the apparent $V_{\phi C}$, which must be included in the analysis. The carbon density profile is normalized to match the measured visible bremstrahlung emission on a single chord tangentially passing through the center of the plasma, using the electron density n_e profile measured by an array of infrared interferometers[23,24] and the electron temperature T_e profile measured by electron cyclotron emission.[25,26]

Fig. 2 shows the time evolution of two plasmas where opposite neutral beam torque was applied to identical target plasmas. These plasmas have a major radius of 2.58 m, minor radius of 0.94 m, average B_T = 4.6 T, initial plasma current of 0.9 MA, and were initially heated by $P_b \sim 9.6$ MW of neutral beam power. The two plasmas shown were selected from a set of six discharges taken in succession, three of each type, showing the same behaviour. During the beam heating, the central T_e increases from ~ 5 to ~ 6 keV. After 0.5 sec of neutral beam heating the plasma current was increased to 1.8 MA to modify the current profile in the outer part of the plasma. For one of the plasmas, all of the neutral beams inject co-parallel to the plasma current. For the other, initially 77% of the beam power is injected anti-parallel to the plasma current. After 1.2 seconds of injection, the beam power and input-torque were modified in the two plasmas to produce the same central rotation velocity, as seen in Fig. 2(c).

Fig. 3(a) shows the measured evolution of $q(0)$ during neutral-beam heating from the standard MSE analysis[27] for both plasmas. Note that the apparent $q(0)$ values rapidly separate on a timescale similar to the measured evolution of the central plasma rotation. This nominal evolution of $q(0)$ is much faster than expected from resistive diffusion at these high temperatures. Also note that after 4.2 sec, when the measured central rotation velocities are equal, the standard-analysis $q(0)$ values agree, indicating little systematic evolution of $q(0)$. After correction for E_r, using Eq. 6 and the measured $V_{\phi C}$, there is good agreement between the measured evolution of $q(0)$ for these plasmas, see Fig. 3(b). This agreement should be expected on these short time-scales.

Fig. 4(a) shows the magnetic pitch profile $\tan \gamma_s$ from the standard MSE analysis after 0.8 seconds of injection. The pitch profiles are different in the core even though the plasmas should not have had time to evolve significantly. This difference in the measured pitch profiles is well developed after only 0.15 seconds of beam injection and persists for the duration of injection. The analysis time was selected to minimize the difference in the Shafranov shift profiles of the two plasmas to simplify the analysis. Fig. 5 shows the calculated E_r profiles for each plasma using the carbon radial force-balance, Eq. 1, and the charge-exchange recombination measurements of $\nabla_r p_C$ and $V_{\phi C}$. TFTR does not have a direct measurement of $V_{\theta C}$ yet , so it has been calculated from neoclassical theory using a multi-species numerical solution valid at all aspect ratios and collisionalities.[28] The radial electric field in both cases is dominated by the contributions from $V_{\phi C}$, with only minor contributions from $\nabla_r p_C$ and the calculated $V_{\theta C}$. These modeled electric field profiles have been used to correct the magnetic pitch profiles, using Eq. 5. The corrected profiles are in excellent agreement, as shown in Fig. 4(b), except near the outside of the plasma where the plasma is cooler and the q profile appears to be evolving differently in the two cases.

These experimental results confirm the importance of the plasma electric field E_r in the interpretation of MSE measurements of q and the magnetic pitch.

IV. Measurements of E_r and comparison with theory

The sensitivity of the MSE measurements to E_r offers a new spectroscopic technique for measuring E_r in large hot plasmas. If exploited, such a measurement would be fundamentally important for diagnosing and understanding the flow equilibrium in tokamaks and for testing theories[29,30] of turbulence suppression by $\boldsymbol{E}_r \times \boldsymbol{B}$ flow shear. A direct measurement of E_r would also allow more direct comparison with theoretical predictions than available with heavy-ion beam probes, as they measure the electric potential and require an extra differentiation. Finally, a measurement of E_r, in combination with measurements of $\nabla_r p_a$, $V_{\phi a}$, and $V_{\theta a}$ for a single species, could also be used to test for contributions to the radial force balance equation from the stress tensor.

From Eq. 3, separation of the contributions from B_P/B_T and E_r requires two measurements at the same location but using different values of the v_b, α, or Ω. The choice of $\alpha + \Omega = \pi/2$ would give a single measurement only sensitive to E_r, but would preclude use of the beam Doppler shift to separate the beam emission from emission at the plasma edge. A conceptually simple arrangement is separate symmetric measurements on two separate beams, one co-parallel to the plasma current and one anti-parallel. The different beam angles would change the sign of the first term in Eq. 3, and separation of the terms would be done by simply subtracting and averaging the two measurements. Another possibility would be to combine a tangential view, as in Fig. 1, with a vertical view which would only be sensitive to E_r and B_P. The general disadvantage of dual measurements using different values of α or Ω is that they require two completely separate spectroscopic instruments.

An alternative arrangement is to measure the polarization using two different values of v_b, using both the full and half-energy components of a hydrogenic beam. These components are well distinguished in the MSE spectrum,[31] and the half-energy measurement would be *more* sensitive to E_r than the full-energy measurement. This configuration has the advantage that the viewing geometry and many of the optical components would be common to the two measurements. However, its applicability may be limited by the penetration of the half-energy component into dense plasmas.

The uncertainty in a dual MSE measurement of E_r is given by

$$\sigma(E_r) = v_{b1} v_{b2} B_T \frac{[\sigma_1^2 \cos^2(\alpha_2 + \Omega_2)\, \sin^2 \alpha_1 \; + \; \sigma_2^2 \cos^2(\alpha_1 + \Omega_1)\, \sin^2 \alpha_2]^{1/2}}{v_{b1} \cos(\alpha_1 + \Omega_1)\, \cos \Omega_2 \; - \; v_{b2} \cos(\alpha_2 + \Omega_2)\, \cos \Omega_1}, \tag{7}$$

where $\sigma_{1,2}$ are the uncertainties in the measurements of $\tan \gamma_m$ and the subscripts 1,2 denote the parameters for the two MSE measurements. The smallest uncertainty in E_r with good spatial resolution is obtained with symmetric measurements of co-parallel and anti-parallel beams, giving $\sigma(E_r) = \sigma\, v_b B_T \, \sin \alpha / \sqrt{2}$, where $\Omega = 0$ has been assumed for simplicity. For a system using full- and half-energy components, the uncertainty would be $3.41\, \sigma v_b B_T \, \sin \alpha$. For TFTR, with $B_T = 5$ T and 90 keV D neutral beams, the typical statistical uncertainty in the MSE measurement[3,27] of $\tan \gamma_s$ is $\sim 1.7 \times 10^{-3}$ (95% confidence). Presuming that any systematic uncertainties can be calibrated out in a dual measurement system, the uncertainty for these two configurations would be ~ 12 kV/m and ~ 57 kV/m, respectively. In TFTR, E_r values as high as ~ 100 kV/m have been calculated in conjunction with internal transport barriers. Thus, a parallel/anti-parallel MSE measurement of E_r would have adequate resolution, but a useful half-/full-energy measurement would require reduction of the intrinsic MSE uncertainty.

While a dual MSE measurement of E_r is not available at this time, the data in Fig. 4(a) can be analyzed for the the change in E_r between the two plasmas, assuming that the magnetic pitch or q has not changed. In this case, using Eq. 3, the change in E_r is given by $\delta E_r = v_b B_T \sin\alpha\,(\tan\gamma_{m1} - \tan\gamma_{m2})$, and is shown in Fig. 6. Also shown are the neoclassical prediction, from Fig. 5, and the predicted profile assuming that the bulk plasma motion is purely parallel. In the later case, the expected change in E_r is small due to the similar pressure gradients observed in the two plasmas. Good agreement is observed with the neoclassical prediction, demonstrating the theoretically predicted electrostatic charging of the plasma due to injected momentum.[10,32] This validates the use of the neoclassical force-balance in situations where E_r measurements are unavailable, and illustrates the utility of a MSE E_r diagnostic.

V. Discussion

Previous studies have used MSE measurments to investigate small changes in q due to sawtooth instabilities.[2,27,33] These data may need re-evaluation, as the changes observed may be affected by changes in E_r due to changes in the plasma pressure profile or rotation. Similarly, studies of MHD stability which depend sensitively on the precise values of q, such as sawtooth stability, or magnetic shear[12,34] from MSE measurements in strongly rotating plasmas may need re-evaluation. For example, the value of $q(0)$ measured after a sawteeth crash in Figure 7 of Ref.27 increases to ~ 0.9 after correction. Accurate and authoritative determination of q from MSE measurements requires accurate measurements or knowledge of E_r.

In summary, motional Stark effect measurements are sensitive to the plasma radial electric field E_r as well as the pitch of the magnetic field. Analysis of TFTR MSE measurements for nominally identical plasmas where E_r is varied by changing the toroidal rotation velocity agree with the predicted sensitivity to E_r. This sensitivity offers the potential for a direct spectroscopic measurement of E_r with a dual MSE system observing different beam velocities or at different angles. Such a system could simultaneously measure the magnetic pitch. The change in E_r between two plasmas with the same magnetic pitch, but varying toroidal rotation velocities, has been obtained from the MSE measurements. The measured change in E_r is in good agreement with neoclassical predictions and disagrees with that expected if the bulk plasma motion was parallel to the magnetic field.

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Figures

FIG. 1. Plan view of typical MSE diagnostic layout, showing the intersection of a viewing sightline with the injected atom beam at a toroidal flux surface in the plasma.

FIG. 2. Time evolution of (a) beam power P_b, (b) injected beam torque, and (c) central carbon toroidal velocity $V_{\phi C}$ for two plasmas produced by injecting oppositely oriented neutral beams into identical target plasmas.

FIG. 3. Time evolution of $q(0)$ for the two plasmas shown in Fig. 2: (a) from the standard MSE analysis ignoring E_r, and (b) after correction using Eq. 6 and the measured $V_{\phi C}$. The plasma with positive neutral beam torque is indicated with solid lines, and the negative torque with dashed lines. The error bars represent typical 95% confidence intervals.

FIG. 4. Radial profile of the magnetic pitch $B_P/B_T = \tan\gamma$ for the two plasmas of Fig. 2 at 3.3 seconds: (a) from the standard MSE analysis ignoring E_r, and (b) after correction for E_r using Eq. 5 with measured $\nabla_r p_C$ and $V_{\phi C}$ profiles and a neoclassical calculation of $V_{\theta C}$. The plasma with positive neutral beam torque is indicated with solid lines, and the negative torque with dashed lines. The error bars represent typical 95% confidence intervals.

FIG. 5. Radial profiles of the E_r from Eq. 1, showing the contributions from the terms proportional to the measured $\nabla_r p_C$ and $V_{\phi C}$, and the neoclassically calculated $V_{\theta C}$, for the plasmas of Fig. 2 at 3.3 seconds with (a) with positive neutral beam torque, and (b) negative torque.

FIG. 6. Radial profile of change of E_r between the plasmas of Fig. 2 at 3.3 seconds, assuming that the q profile is the same: (a) from the change in MSE pitch, (b) neoclassical prediction using kinetic measurements, and (c) assuming that the bulk plasma motion is parallel flow. The error bar represents the typical 95% confidence interval.

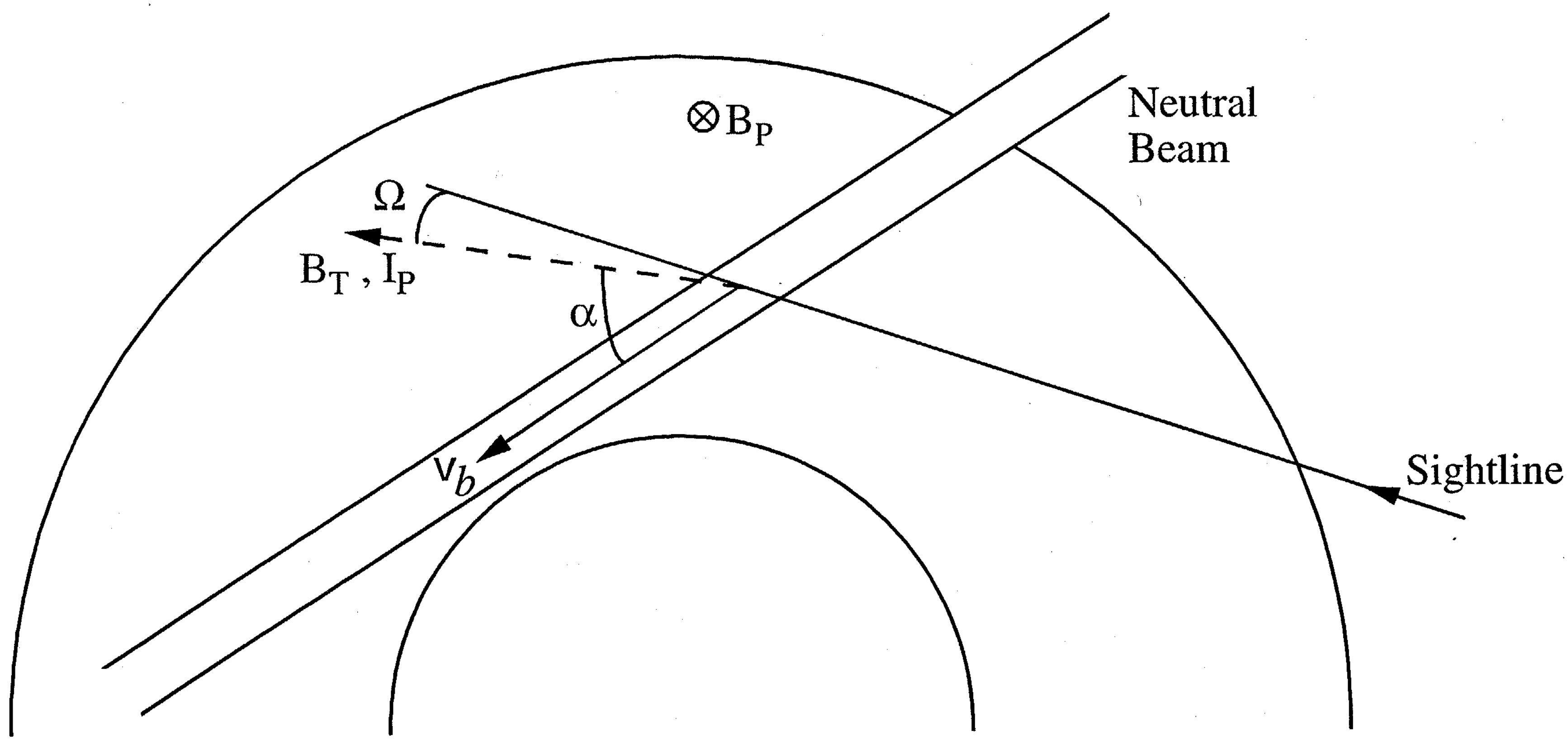


Fig. 1

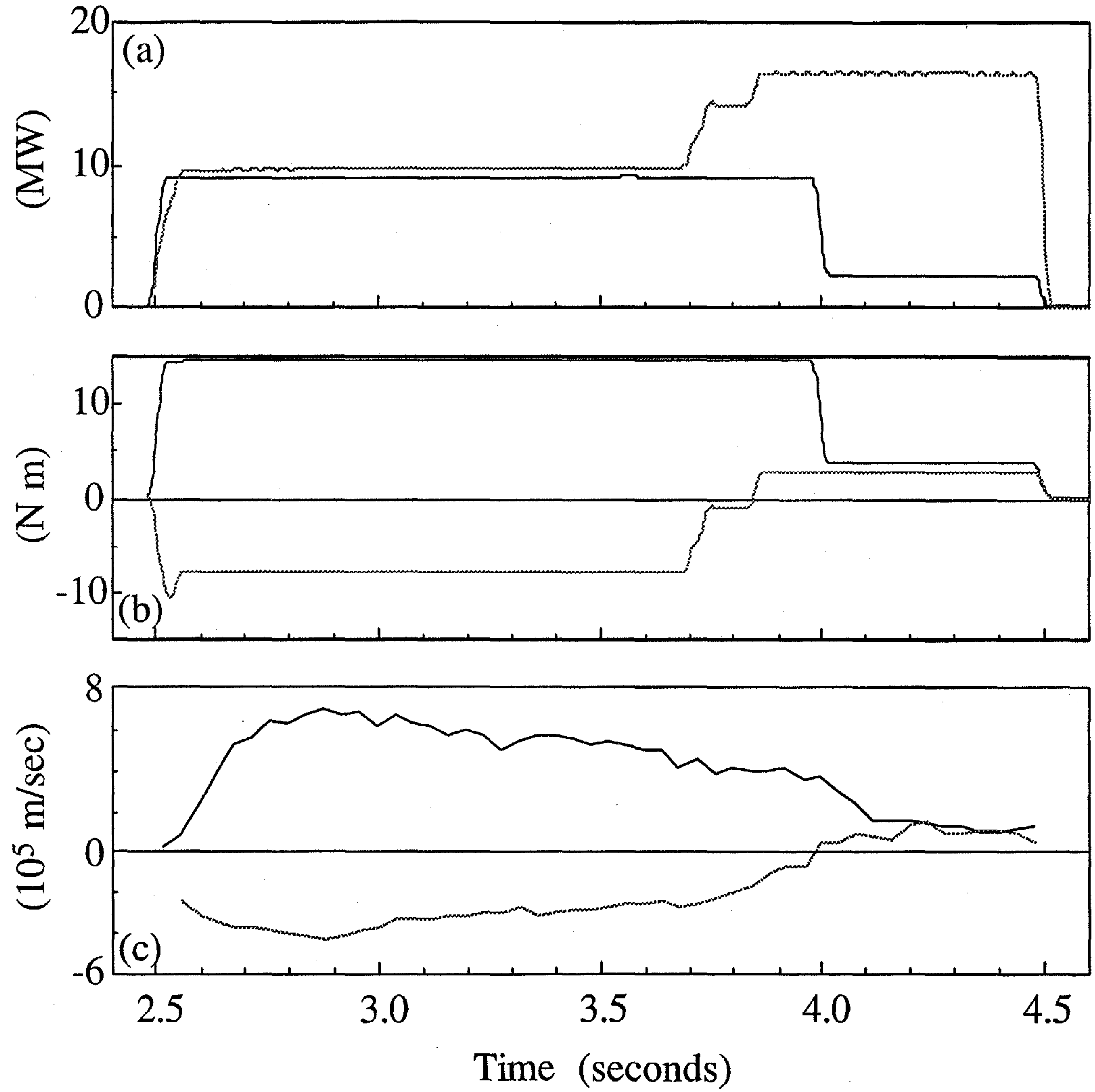


Fig. 2

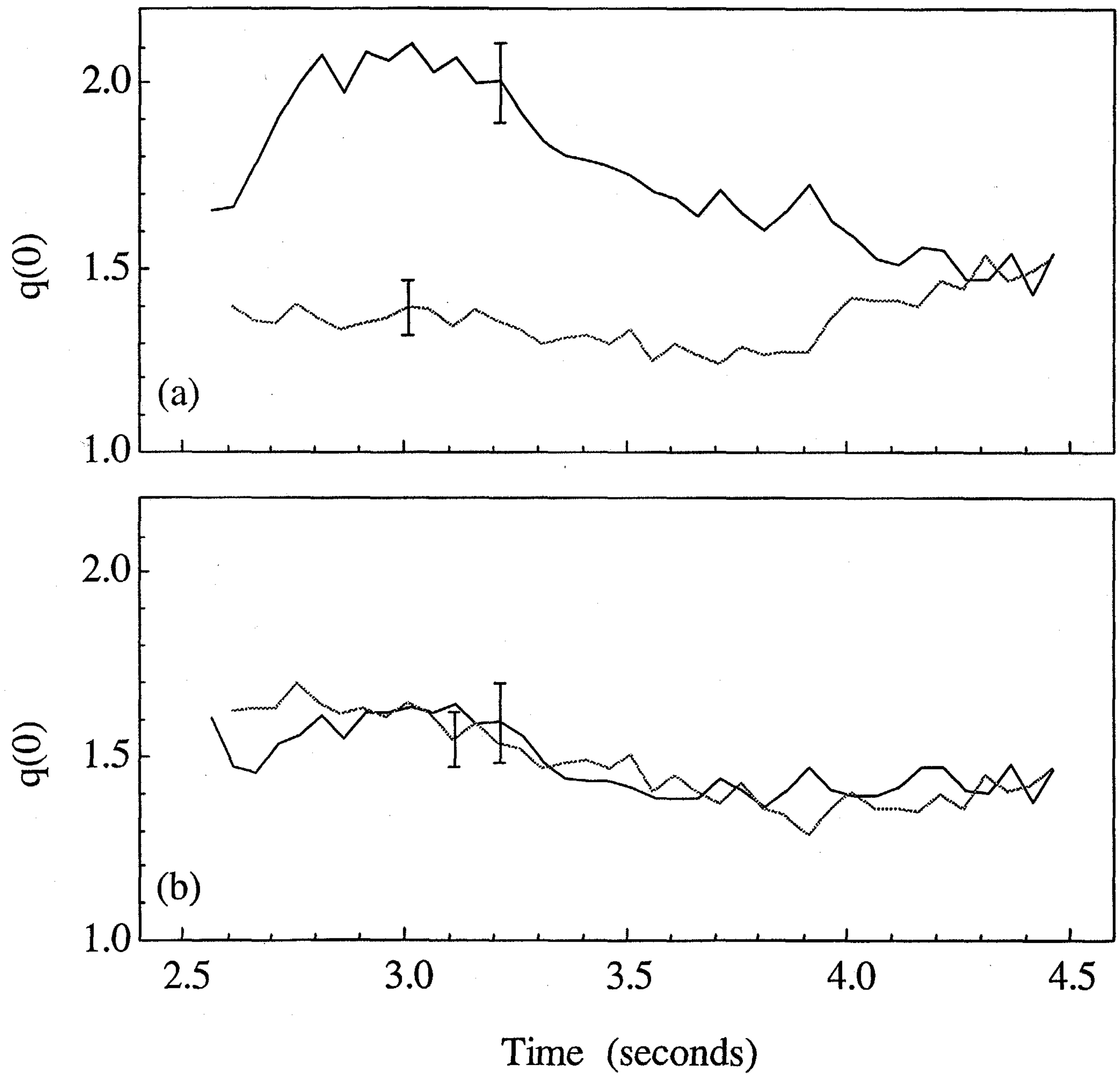
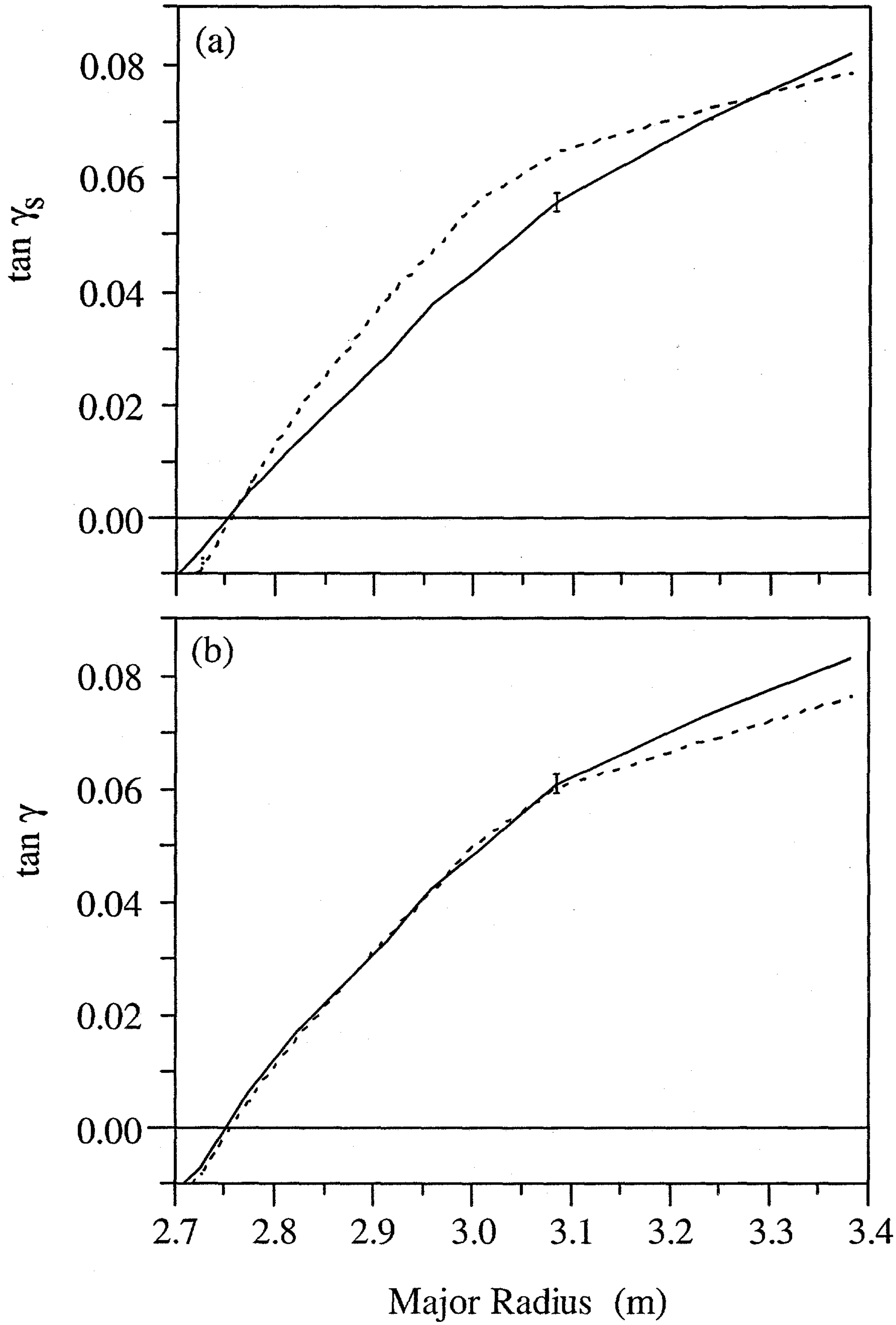
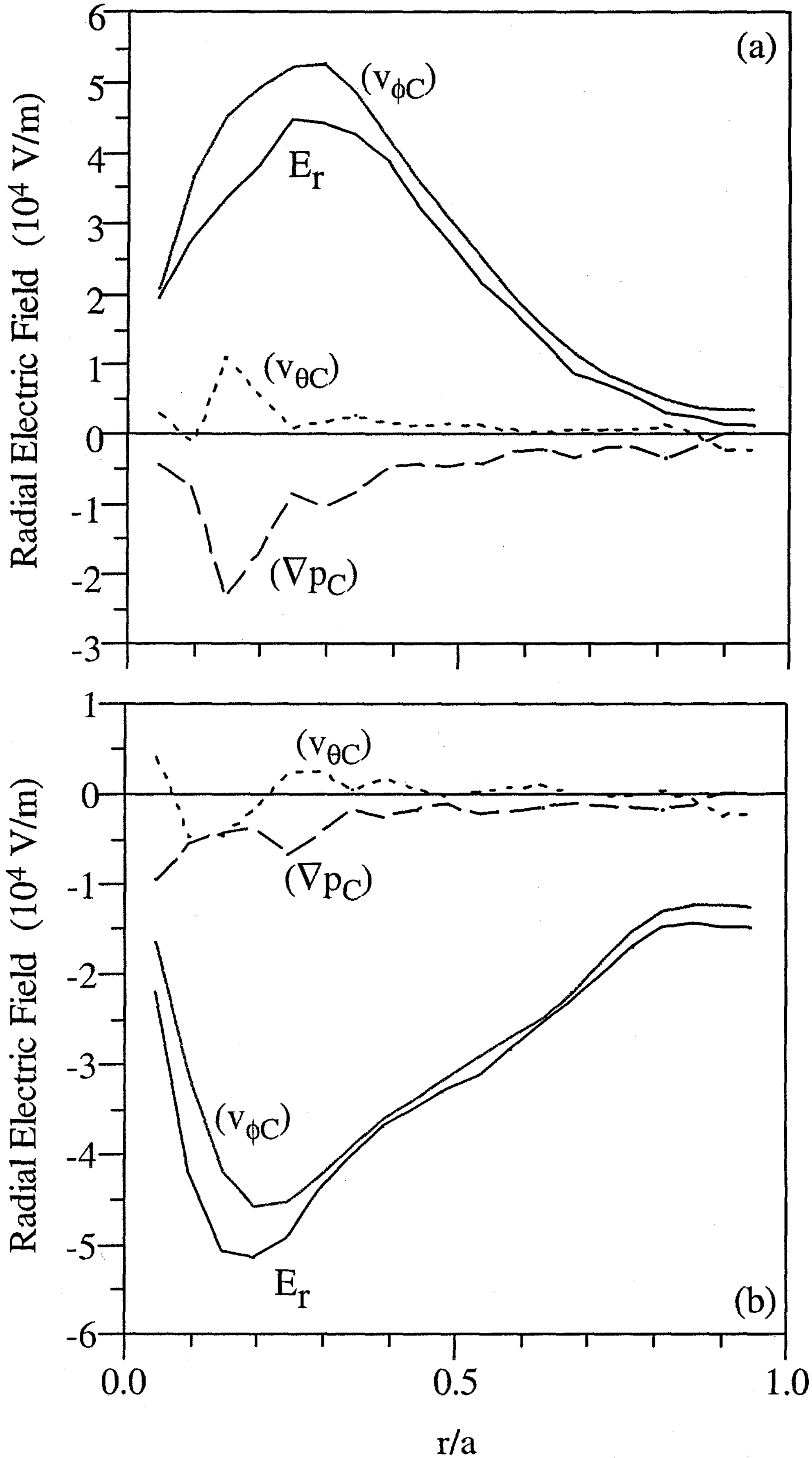


Fig. 3



(a)
0.08
0.06
0.04
0.02
0.00
tan γ_S
(b)
0.08
0.06
0.04
0.02
0.00
tan γ
2.7
2.8
2.9
3.0
3.1
3.2
3.3
3.4
Major Radius (m)

Fig. 4



(a)
$(v_{\phi C})$
E_r
$(v_{\theta C})$
(∇p_C)
Radial Electric Field (10^4 V/m)
6
5
4
3
2
1
0
-1
-2
-3
(b)
$(v_{\theta C})$
(∇p_C)
$(v_{\phi C})$
E_r
Radial Electric Field (10^4 V/m)
1
0
-1
-2
-3
-4
-5
-6
0.0
0.5
1.0
r/a

Fig. 5

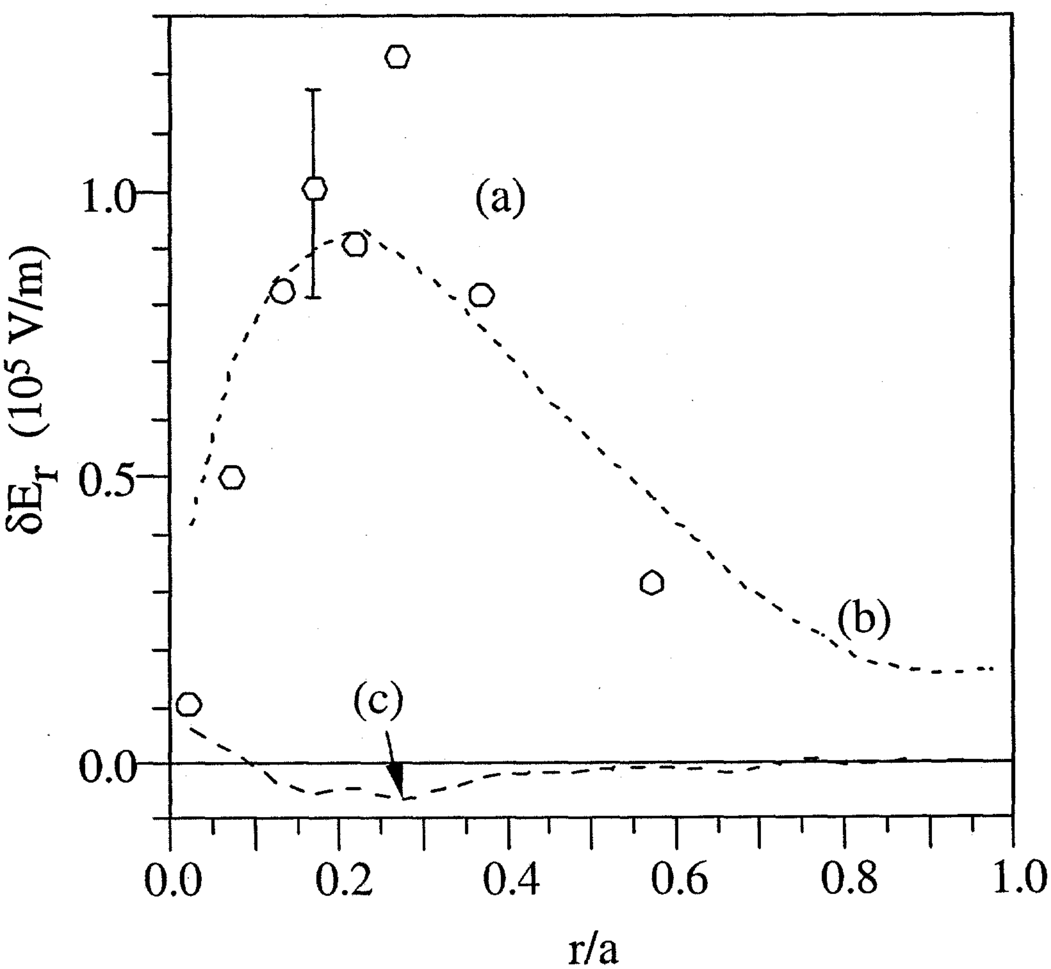


Fig. 6