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THE IMPORTANCE OF THE RADIAL ELECTRIC FIELD (E_r) ON INTERPRETATION OF MOTIONAL STARK EFFECT MEASUREMENTS OF THE q PROFILE IN DIII–D HIGH-PERFORMANCE PLASMAS*

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1. Introduction

The development of enhanced confinement regimes such as negative central magnetic shear (NCS) [1,2] and VH–mode [3] illustrates the importance of the *q* profile and **E**×**B** velocity shear [4] in improving stability and confinement in tokamak plasmas. Recently, it was realized that the large values of radial electric field observed in these high performance plasmas, up to 200 kV/m in DIII–D, have an effect on the interpretation of motional Stark effect (MSE) measurements of the q profile [5,6]. It has also been shown that, with additional MSE measurements, one can extract a direct measurement of E_r in addition to the usual poloidal field measurement. During a recent vent on DIII–D, 19 additional MSE channels with new viewing angles were added (for a total of 35 channels) in order to descriminate between the neutral beam $\mathbf{v_b} \times \mathbf{B}$ electric field and the plasma E_r field. In this paper, the system upgrade will be described and initial measurements demonstrating simultaneous measurement of the *q* and E_r profiles will be presented.

2. MSE Measurement Geometry

The MSE measurement relies upon the splitting of the neutral beam Balmer-α line into orthogonally polarized components (σ,π) as a result of a strong electric field in the rest frame of the neutral deuterium atoms. When viewed in a direction perpendicular to **E**, the Stark components σ and π are polarized perpendicular and parallel to **E**, respectively. The total electric field in the rest frame of the neutral beam atoms traveling with velocity v_b is the sum of the motional $\mathbf{E_b} = \mathbf{v_b} \times \mathbf{B}$ field and the plasma radial electric field given by $E_r = (Z_i e n_i)^{-1} \nabla_r p_i - v_{\theta i} B_\phi + v_{\phi i} B_\theta$ where Z_i is the ion species charge, n_i the ion density, p_i the ion pressure, e is the electronic charge, and $v_{\theta i}$ and $v_{\phi i}$ are the poloidal and toroidal rotation velocities, respectively. The derivation of the relationship between the polarization angle of the Stark components and the magnetic field and E_r components is presented elsewhere [5]. Using the viewing geometry shown in Fig. 1, the polarization angle of the electric field along the line-of-sight is given by

$$\tan\gamma = \frac{A_1 B_Z + A_5 E_R}{A_2 B_\phi + A_3 B_R + A_4 B_Z + A_6 E_Z + A_7 E_R} \approx \frac{A_1 B_Z + A_5 E_R}{A_2 B_\phi} \quad (1)$$

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where the *A* coefficients are viewing geometry dependent terms given by

$A_1 = -\cos(\alpha+\Omega)$
$A_2 = \sin\alpha\cos\theta$
$A_3 = \cos\alpha\cos\theta$
$A_4 = \sin(\alpha+\Omega)\sin\theta$
$A_5 = -\cos\Omega/v_b$
$A_6 = -\cos\theta/v_b$
$A_7 = \sin\theta\sin\Omega/v_b$

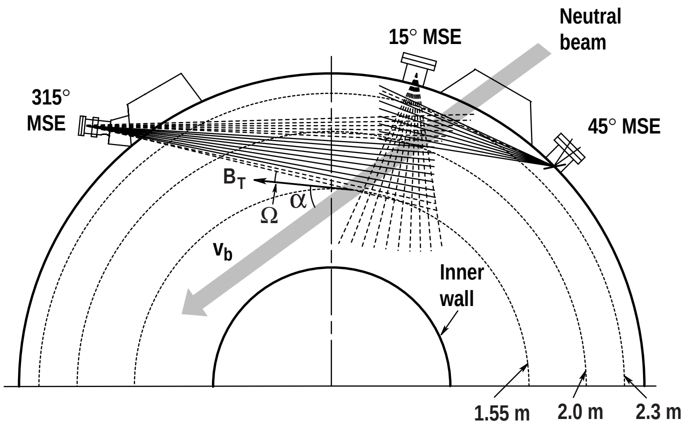

Fig. 1. Viewing geometry for 35 channel MSE system on DIII–D. The dashed lines indicate the line-of-sight of the new channels added to determine E_r.

In past analysis of MSE data, it was assumed that the E_R component in Eq. (1) could be neglected. However, in recent high-performance plasmas, the E_R term in the numerator of Eq. (1) can be up to 25% of the B_Z term and therefore must be included in the analysis. Since coefficients A_1 and A_5 vary differently depending on viewing geometry and beam velocity, we see that with two MSE systems viewing the same radial location in the plasma from different angles (*A* coefficients), then both the poloidal field (B_Z) and the E_R field can be determined.

An upgrade to the DIII–D MSE system has recently been completed to provide this measurement. Nineteen additional channels were added as indicated by the dashed lines-of-sight in Fig. 1, providing two different viewing angles for each location in the plasma. The hardware design for the new channels essentially duplicates that of the original system [7]. All chords are tuned to the full-energy component of the neutral beam. For the radial viewing channels, the coefficient A_5 is approximately zero, while for the tangential viewing chords $A_5 \sim 1/v_b$. Defining an effective measured vertical field as $B_{Z0} = (A_2/A_1)B_\phi \tan\gamma$ (i.e. the measured vertical field assuming E_R=0), then the radial electric field at a radius *R* is given by

$$E_r \approx \frac{A_1 A_1'(B_{Z0} - B_{Z0}')}{A_5 A_1' - A_1 A_5'} \qquad (2)$$

where the prime refers to the second view at a given location.

3. Experimental Results

The simultaneous measurement of the *q* profile and E_r profile has been tested using a recent high-triangularity discharge obtained during commissioning of the new upper divertor hardware in DIII–D (see Fig. 2). This discharge has high confinement (H=3.5) and normalized beta associated with a large E_r field, similar to VH–mode or NCS plasmas, even though the ELM-free period is relatively short. The plasma fuel is deuterium with I_p=1.6 MA and B_ϕ=2.1 T. In Fig. 2(c), the effective vertical field (assuming E_r = 0) is plotted for a tangential chord (solid line) and a radial chord (dashed line) at a radius of *R*~2 m. If E_r were zero, then these two curves would track one another. The separation of the two curves during the ELM-free period from 2–2.25 s is an indication of the buildup of radial electric field. Using Eq. (2),

E_r at R~2 m is calculated directly from the MSE measurements as shown in Fig. 2(d). The temporal evolution of E_r follows closely the time evolution of the plasma toroidal rotation in Fig. 2(e) obtained from charge-exchange measurements of carbon impurities. The maximum time response of the MSE E_r measurement is 1 ms with an RMS noise resolution of ~7 kV/m. The curve in Fig. 2(c) was generated using a 5 ms sliding boxcar average giving somewhat better resolution. Possible systematic errors in E_r due to spatial averaging in the radial chords and calibration are a factor of 2–3 larger than uncertainties due to noise. An additional point-of-interest in this discharge is that a locked-mode develops after the collapse in β from 2.5–3 s. During this time the the impurity rotation shows a small negative rotation. In agreement with this observation, the MSE radial electric field measurement also reverses sign during mode-locking.

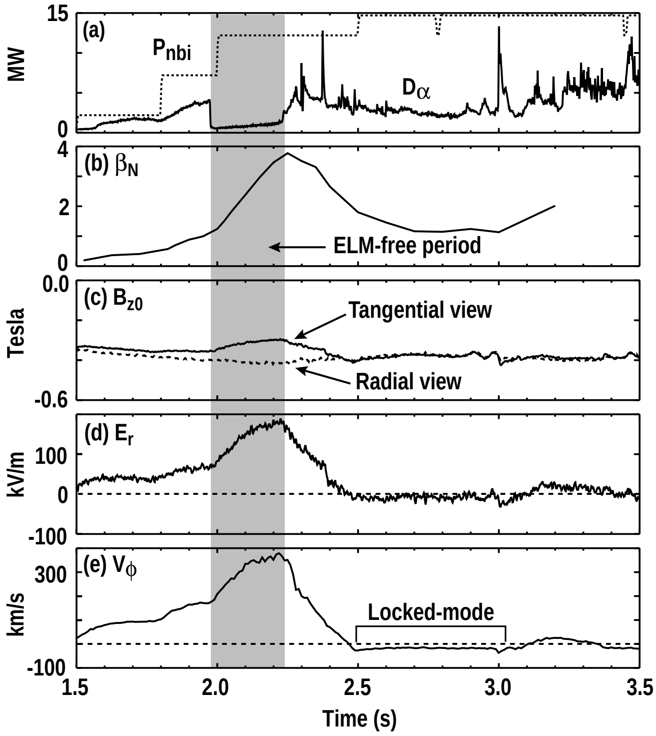

Fig. 2. Temporal evolution of discharge 92043: (a) neutral beam power and D_α emission, (b) normalized beta, (c) MSE Bz0 measurement, (d) local value of E_r at R=2.1 m calculated from Eq. (2), (e) CER toroidal rotation.

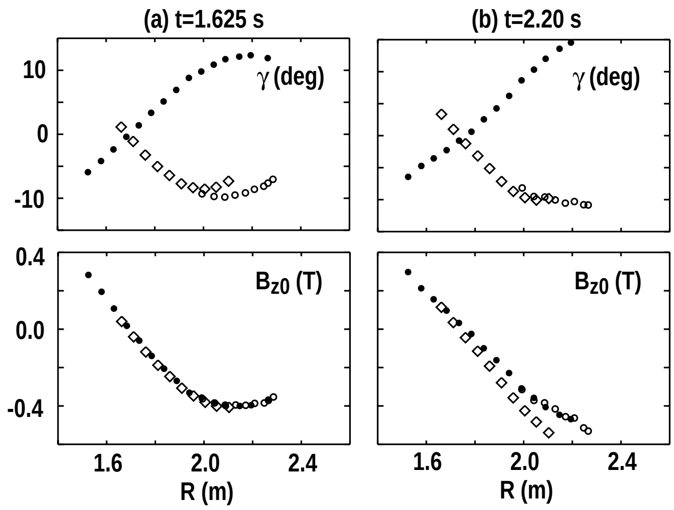

Fig. 3. Profiles MSE pitch angle and B_{Z0} measurements for two phases of discharge 92043: (a) Low-power L–mode phase with low plasma rotation and E_r field; (b) High-performance phase with peak E_r~170 kV/m.

To determine the profile of E_r, we first examine the profiles of pitch angle and B_{Z0} shown in Fig. 3. At 1.625 s, during the low-power L–mode portion of the discharge, the effective vertical field calculated from both the tangential (circles) and radial (diamonds) systems agree, indicating almost unmeasurable levels of E_r. However, by 2.2 s the tangential and radial profiles have significantly deviated from one another indicating large E_r. The EFIT equilibrium reconstruction code [8] has been modified to fit the radial electric field from the MSE measurements in addition to determining the usual equilibrium profiles of current and pressure. Since E_r is not a flux function, the EFIT code fits the gradient of the electrostatic potential $\partial\Phi/\partial\psi$, which is related to E_r through $E_r = -\partial\Phi/\partial\psi\nabla\psi = \Phi'(RB_Z\hat{R} - RB_R\hat{Z})$. Either a polynomial or spline representation of Φ' is possible. Figure 4 shows the equilibrium reconstruction (including polynomial fit to E_r) of the MSE profile data in Fig. 3 at 2.2 s. In Fig. 4(a), the B_Z data is calculated including the E_R, E_Z terms, and now shows good agreement between the tangential and radial views. The resulting q and E_r profiles are shown in Fig. 4(c) and 4(d) respectively. For comparison, the CER measurement of E_r obtained from Eq. (1) is also shown as the dashed line. The agreement between the two instruments is better than 20 kV/m over the entire plasma radius.

In addition to providing a direct local measurement of E_r, the new MSE measurements also allow the q profile to be calculated with improved accuracy. In Fig. 5, the temporal evolution of q_0 is shown, calculated from EFIT using the tangential chords only and no E_r (dashed line), versus that calculated using all MSE chords, thus including the E_r effect (solid line). The difference in q_0 is quite large, especially during the high-performance ELM-free period.

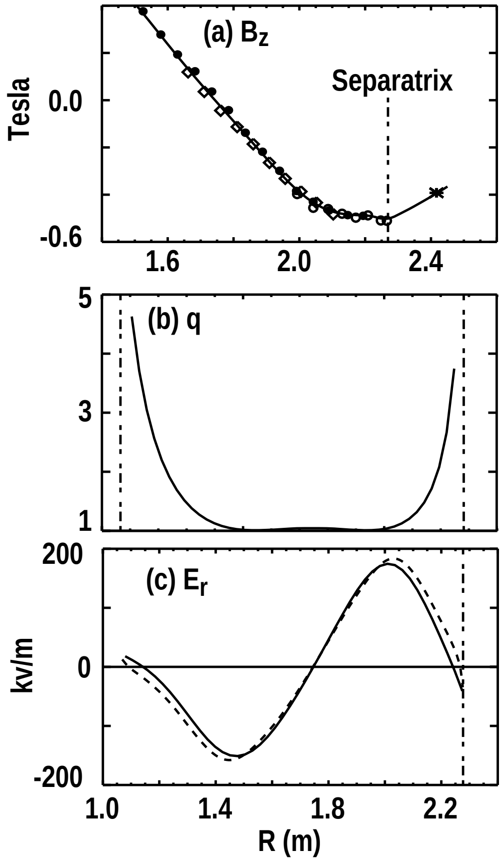

Fig. 4. EFIT equilibrium reconstruction including E_r at 2.2 s: (a) MSE B_Z data ; (b) q profile; (c) E_r determined from EFIT (solid line) and CER analysis of carbon impurities (dashed line).

In conclusion, we have demonstrated on DIII–D that the MSE diagnostic can provide simultaneous measurements of the q and E_r profiles. The uncertainty in E_r due to noise is 7 kV/m or less depending on averaging, while systematic errors are currently ~2–3 times this level. Given the importance of the effect of these profiles on plasma stability and confinement, this powerful measurement should continue to guide experimentalists in achieving improved performance in tokamaks.

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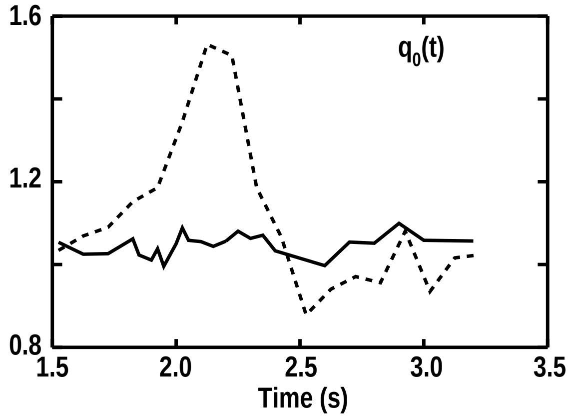

Fig. 5. Tme evolution of q (0) determined by EFIT using full MSE system including E_r (solid line) versus that obtained using only the tangential channels and no E_r (dashed line).