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STARK EFFECT MEASUREMENTS OF THE  
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PLASMAS**

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<sup>†</sup>Lawrence Livermore National Laboratory

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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\*

B.W. Rice,<sup>‡</sup> L.L. Lao, K.H. Burrell, C.M. Greenfield, Y.R. Lin-Liu  
General Atomics, P.O. Box 85608, San Diego, CA 92138-5608

### 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  $\mathbf{E} \times \mathbf{B}$  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 discriminate 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- $\alpha$  line into orthogonally polarized components ( $\sigma, \pi$ ) as a result of a strong electric field in the rest frame of the neutral deuterium atoms. When viewed in a direction perpendicular to  $\mathbf{E}$ , the Stark components  $\sigma$  and  $\pi$  are polarized perpendicular and parallel to  $\mathbf{E}$ , 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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<sup>‡</sup>Lawrence Livermore National Laboratory, Livermore, CA 94551 U.S.A.

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

$$A_1 = -\cos(\alpha + \Omega)$$

$$A_2 = \sin \alpha \cos \theta$$

$$A_3 = \cos \alpha \cos \theta$$

$$A_4 = \sin(\alpha + \Omega) \sin \theta$$

$$A_5 = -\cos \Omega / v_b$$

$$A_6 = -\cos \theta / v_b$$

$$A_7 = \sin \theta \sin \Omega / v_b$$

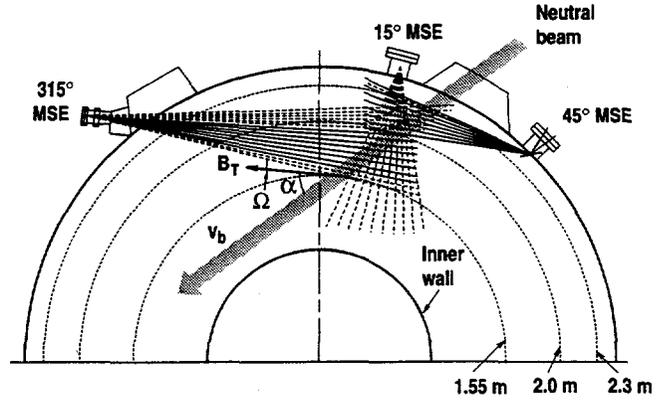


Fig. 1. Viewing geometry for 35 channel MSE system on DIII-D. The dashed lines indicate the line-of-sight of the new channels added to determine  $E_r$ .

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

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

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  $B_\phi=2.1$  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  $R \sim 2$  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  $R \sim 2$  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  $\sim 7$  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  $\beta$  from 2.5–3 s. During this time 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.

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  $\Phi$  is possible. Figure 4 shows the equilibrium reconstruction (including polynomial fit to  $E_r$ ) of

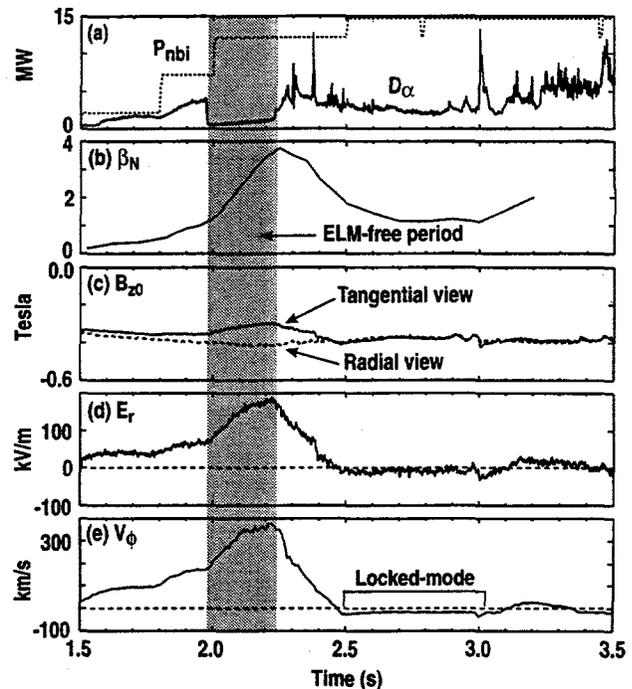


Fig. 2. Temporal evolution of discharge 92043: (a) neutral beam power and  $D_{\alpha}$  emission, (b) normalized beta, (c) MSE  $B_{z0}$  measurement, (d) local value of  $E_r$  at  $R=2.1$  m calculated from Eq. (2), (e) CER toroidal rotation.

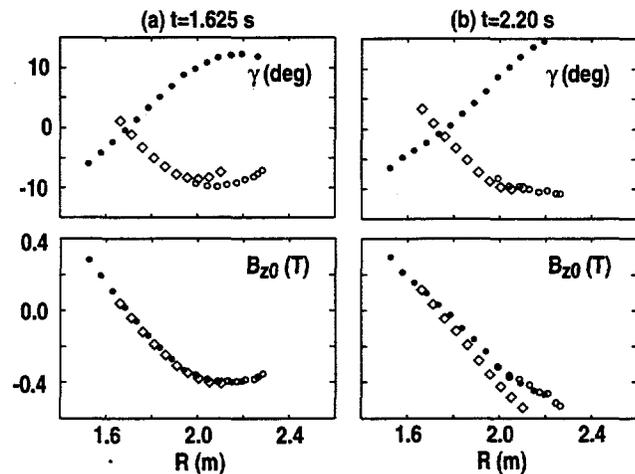


Fig. 3. Profiles MSE pitch angle and  $B_{z0}$  measurements for two phases of discharge 92043: (a) Low-power L-mode phase with low plasma rotation and  $E_r$  field; (b) High-performance phase with peak  $E_r \sim 170$  kV/m.

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.

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  $\sim 2$ – $3$  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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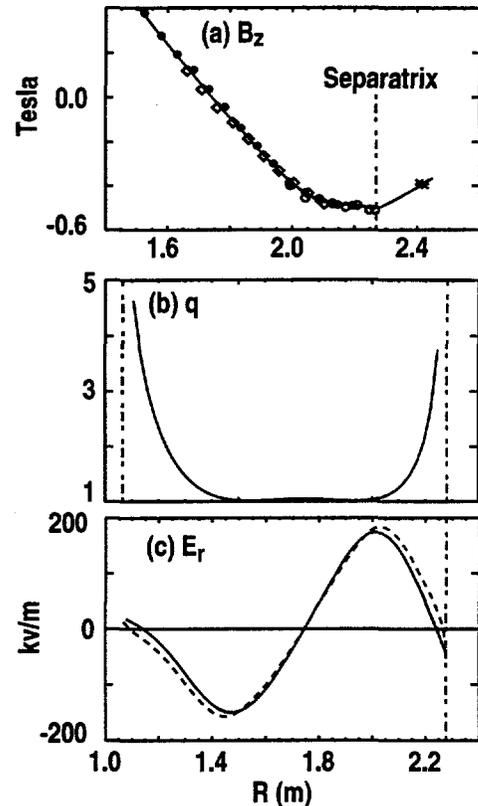


Fig. 4. EFIT equilibrium reconstruction including  $E_r$  at 2.2 s: (a) MSE  $B_z$  data; (b)  $q$  profile; (c)  $E_r$  determined from EFIT (solid line) and CER analysis of carbon impurities (dashed line).

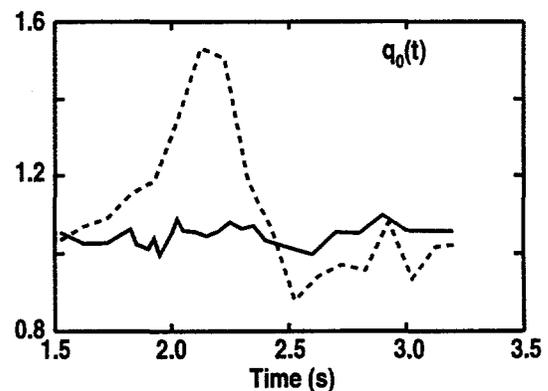


Fig. 5. Time evolution of  $q(0)$  determined by EFIT using full MSE system including  $E_r$  (solid line) versus that obtained using only the tangential channels and no  $E_r$  (dashed line).