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Current profile and E_r results with MSE measurements in JET Optimised Shear Plasmas

N. C. Hawkes[1], B. C. Stratton[2], B. Alper[1], B. Budny[2], C. D. Challis[1], S. Reyes-Cortes[3], V. Drozdov[1], K. Günther[1], D. Mazon[4], T. C. Hender[1], D. Testa[5], K-D. Zastrow[1], W. Zwingmann[4]

JET Joint Undertaking, Abingdon, Oxon, OX14 3EA, U.K.
[1]*Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK*
[2]*Princeton Plasma Physics Laboratory, PO Box 451, Princeton, NJ 08543, USA*
[3]*Euratom/IST, Av. Rovisco Pais, Lisboa, Portugal*
[4]*Association Euratom-CEA, CEA-Cadarache, F-13108, St. Paul lez Durance, France*
[5]*Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridege, USA*

The magnetic safety factor (q), and its shear $r/q(\partial q/\partial r)$, play a critical role in allowing the plasma to access regions of higher performance characterised by the appearance of an internal transport barrier (ITB). A motional Stark effect (MSE) diagnostic has been built on JET in order to measure the q-profile and reveal the interrelationship between this and transport improvements in these optimised shear plasmas.

The MSE technique (which uses the polarisation of visible light emission to measure the direction of the Lorentz electric field of atoms in high velocity heating beams) is perturbed by the existence of the plasma intrinsic radial electric field. It is possible to measure the plasma E_r and compensate for its effect on the MSE measurements. The MSE data also yield more detail about the profile of plasma E_r than other available diagnostics, in particular its time evolution and spatial scale lengths. Such information is relevant to theories of turbulence stabilisation by $\omega_{\mathbf{E}\times\mathbf{B}}$ flow shear.

Details of q(r) measurements

The neutral heating beams of JET are arranged as multiple intersecting beamlets (PINIs). The different poloidal angles of the various PINIs yield very different polarisation angles, which means that certain of the PINIs cannot be used during an experiment if MSE measurements are required. We use the EFIT equilibrium code to solve the Grad-Shafranov equation subject to the additional contraints of the MSE polarisation measurements. The code is modified to model the overall polarisation direction of the light emission from the various JET injectors.

As with other MSE diagnostics, the largest uncertainty in the analysis occurs in the measurement of the zero point of the polarisation angle. In JET, several techniques have been used, but the most reliable one is that of injecting a beam into a gas-filled torus with a purely toroidal magnetic field.

The response of the diagnostic to variations in the angle of input polarised light is obtained from 'bench' calibration measurements, backed up by measurements of the polarisations in different parts of the MSE spectrum.

The response of the polarimeter optics and detectors is described using Müller matricies. A numeric inversion of the overall system response matrix allows the analysis of the signals, yield-

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ing the full Stokes vector of the input light. This reveals that a fraction of the MSE emission is circular polarised (due to the combined electric and magnetic fields in the rest frame of the emitting atoms).

q-Profile Results

q-profiles have been determined from a number of JET ITB experiments. In most cases the q-profiles obtained are close to flat over the central part of the plasma, figure 1, however, in a few cases (discharges with LHCD during the current rise and ICRH pre-heat) there is clear evidence of shear reversal. Confirmation of the MSE q-profile in these cases comes from MHD tearing modes (which locate the inner q=3 rational surface and define it as being in a region of negative magnetic shear), the observation of energetic particle modes (as "chirps" in the magnetics spectrograms) and the analysis of the TAE spectrum. (The measurements from infra-red polarimetry conflict with these results, for reasons that are not understood.) It is suggested that shear reversal is achieved in these discharges due to the current profile modification brought about by LHCD heating and current drive early in the discharge where MHD activity that otherwise would redistribute the current is stabilised by the application of ICRH.

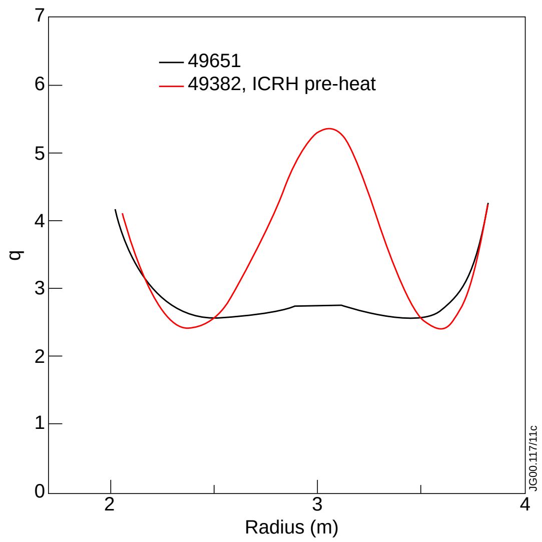

Figure 1: *q-profiles obtained from EFIT with MSE data in optimised shear discharges with LHCD pre-heating. In the case with the strongly reversed q-profile, ICRH was also applied, with the effect of preventing MHD collapses of the current profile during the early penetration phase[1].*

MSE measurements have also been analysed for a discharge series in which the timing of the main heating pulse was varied in a systematic fashion[2]. In these experiments the MSE calibration was derived from specific discharges where MHD observations (2/1 core modes at $q(0)$=2 in one case, and sawteeth at $q(0)$=1 in the other) served to benchmark the measurements.

The values of $q(0)$ obtained during the scan are close to the values obtained from EFIT using just magnetics data, but without the usual regularisation constraints of the intershot EFIT runs, figure 2.

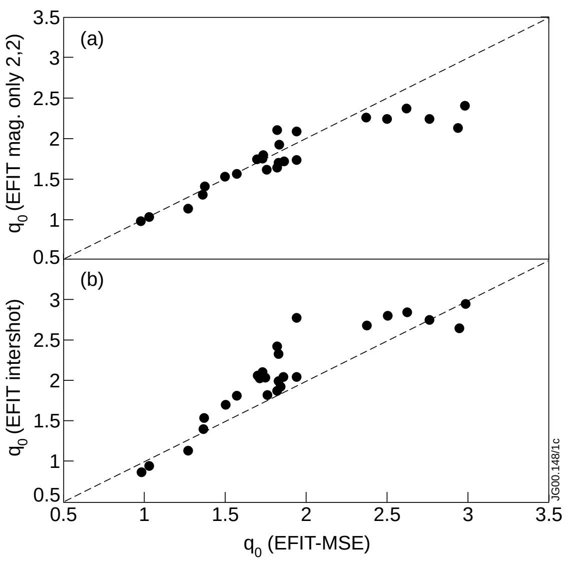

Figure 2: *Comparison of values of $q0$ from 'intershot' EFIT runs (low order ff' and p' polynomials using just magnetic data) with MSE constrained results. In (b) there is additional regularisation of the polynomials, in (a) this is turned off and agreement with the MSE values is better.*

E_r Effects on Measurements

The plasma radial electric field influences the MSE measurements. Although only about 2% of the strength of the Lorentz field, its orientation is such that the MSE measurements are particularly sensitive to it. We can estimate the plasma E_r from measurements of toroidal flow and radial pressure gradient using the radial force balance equation, $E_r = \nabla p/neZ - v_\theta B_\phi + v_\phi B_\theta$. Although v_θ is not measured, the TRANSP code predicts that this term is small (10-20%), with E_r dominated by toroidal flow, figure 3.

The correction to the MSE measurements is derived from Ref. [4] using the expression, $\Delta \tan \gamma_m = \cos \Omega \Delta E_r / v_b B_\phi \sin \alpha$. When the plasma E_r effect is included in the analysis for this shot (a high performance internal barrier case), the modification to the q-profile is modest (6% on axis and <20% peak correction).

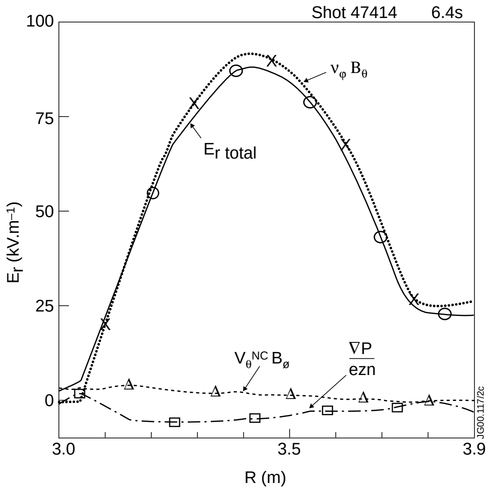

Figure 3: *Components of plasma E_r from the radial force balance equation, as calculated from the TRANSP outputs. The TRANSP run takes measurements of v_ϕ and p_z from charge exchange spectroscopy and calculates neoclassical v_θ.*

E_r Evolution in ITB Cases

In some cases the effect of plasma E_r on the MSE measurements is not small. In these cases the effect of E_r is seen as a slope change in the raw polarisation angle measurements that appears first on interior channels and then moves outwards as the transport barrier grows, figure 4. At times near the peak of the neutron rate a clear step is visible in the radial profile of MSE pitch angles, the appearance of the feature in the time plot is associated with the step crossing an individual channel and thus locates the 'foot point' of a step in E_r. The radial location of the step in the MSE profiles is coincident with a step in the profile of toroidal rotation. The magnitude of the E_r step obtained from the toroidal rotation term alone in the force balance equation, 90 kV.m^{-1}, is the same as that obtained from the change in the MSE signals.

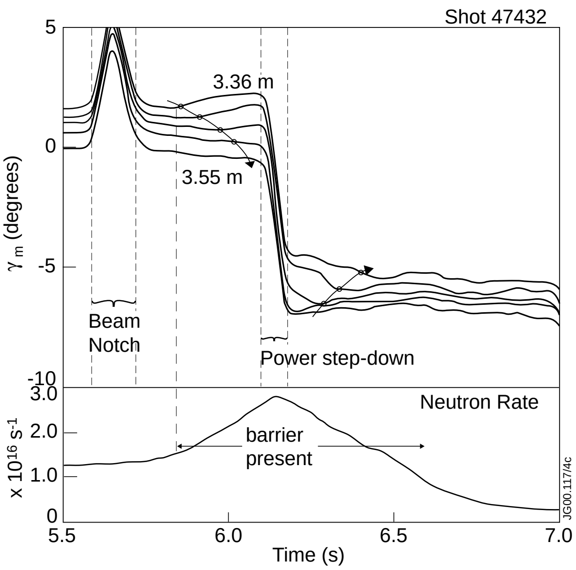

Figure 4: *Time evolution of raw MSE polarisation angle signals during a high performance optimised shear discharge. The large excursions in the signals are caused by changes in the neutral beam waveform, the slower deviations are due to the radius of strong E_r moving out and back across the MSE measurement chords.*

The full profile of plasma E_r can be obtained from a combination of the v_ϕ and MSE data. First the MSE data is corrected by the E_r profile obtained from the v_ϕ term in the force balance equation. The corrected MSE data are used to reconstruct the plasma equilibrium with

EFIT, ignoring channels in the vicinity of the step in E_r, where the space resolution of the v_ϕ measurements does not permit an accurate correction. Finally, the difference between the EFIT fitted MSE profiles and the uncorrected measurements is used to evaluate the full E_r profile, including the step. From this procedure, high resolution measurements of E_r and $\omega_{\mathbf{E}\times\mathbf{B}}$ shearing rate are possible, figure 5, using the expression for shearing rate[5],

$$\omega_{\mathbf{E}\times\mathbf{B}} = \left| \frac{RB_\theta}{B} \frac{d}{dR} \left(\frac{E_R}{RB_\theta} \right) \right|$$

While the measurements demonstrate that the scale length of velocity shear is smaller than the 10 cm chord separation of the charge exchange diagnostic, it is also possible that the scale length is smaller than the 5 cm chord spacing of the MSE measurements, since E_r changes within one channel width. Thus the shearing rates calculated are lower bounds for this parameter. This discharge displayed a ‘snake’[3] feature at 6.3 s at 3.5 m. This location is just at the foot of the ion temperature barrier, and in the low E_r shear region at the foot of the E_r step. However, the q-profile calculated with MSE data shows q approaching 1.0 at the snake location, not q=2 as the mode numbers of the snake would suggest.

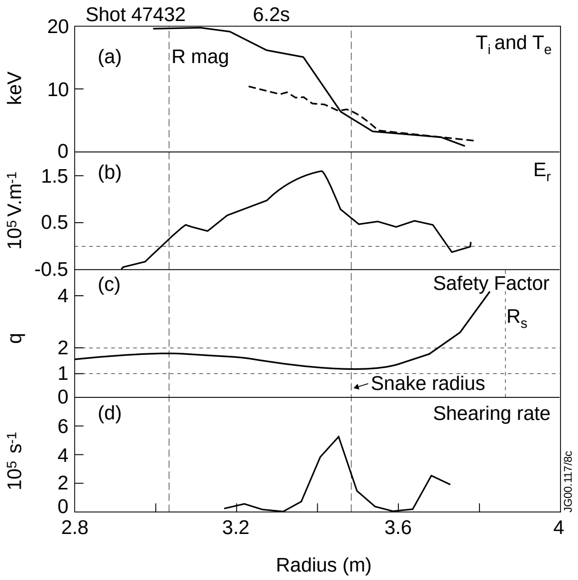

Figure 5: *Evaluation of $\omega_{\mathbf{E}\times\mathbf{B}}$ shearing rate obtained from the MSE measurements. CX measurements of v_ϕ have been used to correct most of the MSE profile, then the deviations of the uncorrected signals from the EFIT predictions for a smooth $q(r)$ profile used to derive E_r.*

The data shown in the above figure have been smoothed significantly in the time coordinate for the purposes of illustration, but examination of the unsmoothed data has yet to reveal evidence of a fast, large amplitude transient in E_r at the barrier formation, such as has been observed in TFTR[6], and this is an area of continuing study.

Conclusions

MSE measurements are providing useful insight into the role of the q-profile on transport barrier formation in JET. Effects of plasma E_r are generally rather small, but important in some cases when we can use MSE measurements, together with other diagnostics, to obtain an estimate of the $\omega_{\mathbf{E}\times\mathbf{B}}$ shearing rate, which is found to peak near the T_i barrier. The high space resolution obtained from the MSE measurement yields a more accurate estimate of the shearing rate.

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