

## Motional Stark Effect $q$ -Profile Measurements on JET

N. C. Hawkes<sup>1</sup>, B. C. Stratton<sup>2</sup>, C. D. Challis, E. Joffrin<sup>3</sup>, B. Rice<sup>4</sup>,  
R. DeAngelis<sup>5</sup>, W. Zwingmann<sup>3</sup>

JET Joint Undertaking, Abingdon, Oxon, OX14 3EA, U.K.

<sup>1</sup>Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK

<sup>2</sup>Princeton Plasma Physics Laboratory, PO Box 451, Princeton, NJ 08543, USA

<sup>3</sup>Association Euratom-CEA, CEA-Cadarache, F-13108, St. Paul lez Durance, France

<sup>4</sup>Lawrence Livermore National Laboratory, PO Box 808, Livermore, CA 94550, USA

<sup>5</sup>Association Euratom-ENEA sulla Fusione, CRE Frascati, 00044, Frascati, Roma, Italy

### Introduction

The profile of the safety factor,  $q(\psi)$ , of tokamak plasmas plays a crucial role in the physics of reactor-relevant high performance operating regimes, such as the enhanced reverse shear regime. Accurate measurement of the  $q$ -profile has therefore become critical to the understanding and control of these plasmas.

The  $q$ -profile is obtained from a constrained solution of the Grad-Shafranov equation (using the EFIT code[1]), where the constraints include the set of external magnetic (coil) measurements augmented by internal measurements of the magnetic field pitch angle. An accurate internal measurement of the pitch angle can be obtained from measurement of the polarisation of the Stark split  $D_\alpha$  emission from deuterium atoms injected by the heating neutral beams[2, 3]. A motional Stark effect (MSE) diagnostic[4, 5] has been deployed on JET during the first 1999 campaign in order to make this measurement. This diagnostic technique has been used on other tokamaks for a number of years but the complexities of the available access and the neutral beam injection geometries on JET are particularly challenging.

The JET system is comprised of 25 spatial channels covering the full outboard minor radius of the plasma. Each channel incorporates a fast tunable narrow-band filter and avalanche photodiode detector. The light from all channels passes through a double photoelastic modulator (PEM) that encodes the polarisation direction of the plasma light as an amplitude modulation of the detector signals at harmonics of the PEM modulation frequencies. The data are digitised and signal processing is performed in software to extract the required harmonic amplitudes. A survey spectrometer observes the beam emission spectrum at four spatial points to aid in tuning of the interference filters.

A significant challenge in the operation of the system is the analysis of the data when all the injector sources (PINIs) are operating. The complication arises from the different beam-

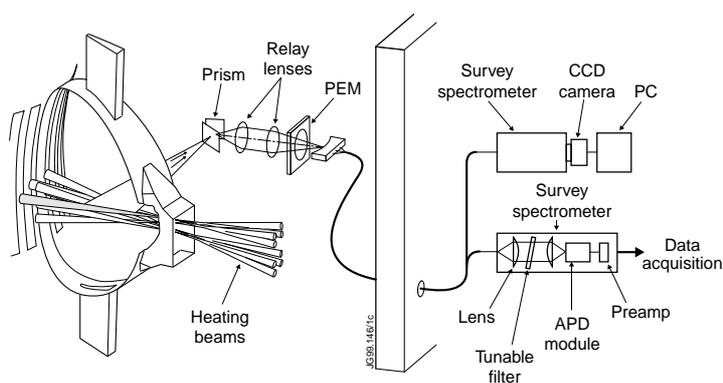


Figure 1: Schematic of the layout of the JET MSE system showing the directions of the eight PINIs of the octant 4 heating beams.

sightline intersection angles for beams from different sources, which each give a different polarisation angle for the same sightline. The signal from a single PINI gives rise to a measured polarisation angle,  $\gamma_i$ , where,

$$\tan \gamma_i = \frac{E_H}{E_V} = \frac{B_V A_0 + B_R A_1 + B_T A_2}{B_V A_3 + B_R A_4 + B_T A_5}, \quad (1)$$

and the six coefficients,  $A_n$ , describe the PINI and sightline geometries. The Stokes vectors of the polarised light signals from the eight PINIs sum to an overall measured polarisation,  $\gamma_m$ , according to

$$\tan 2\gamma_m = \frac{E_{H,total}}{E_{V,total}} = \frac{\sum_i w_i \sin(2\gamma_i)}{\sum_i w_i \cos(2\gamma_i)} \quad (2)$$

### Calibration

To select signals from only one bank of heating beams the longest wavelength feature ( $\pi_3$ ) of the  $D_\alpha$  Stark spectrum is used for the polarisation measurement. This wavelength changes with changing toroidal field and hence the filter spectrometers must be tuned for each field used. This is done in a single discharge by sweeping the filter tilt angle during a neutral beam pulse. In practice only two settings have been found necessary, one for  $B_\phi \leq 2T$  and one for  $B_\phi \geq 2T$ .

The relative contributions of different beams to the total signal amplitude (the  $w_i$  in equation 2) are measured by applying 250 ms pulses from each beam in turn into a plasma with otherwise constant conditions.

It has not, so far, been possible to conduct a full calibration of the polarimeter for every input angle and sightline. Instead, use has been made of the defined polarisation change occurring between the signals from different injectors in the switching shot: since different injectors cross the field of view in different directions, the polarisation angle of the light from the beams is rotated by a precise amount. This data is used to derive a ‘sensitivity’,  $f_m$ , for each sightline, with the expression  $2\gamma_m = \tan^{-1}(f_m R_\omega) + \tan^{-1}(g_m)$  (here  $R_\omega$  is the ratio of amplitudes of the first and second harmonics of the PEM frequency and  $g_m$  is the zero angle).

While the sensitivity parameter in the above expression does not depend on the assumed  $q$ -profile in the calibration discharge, this is not true of  $g_m$ . In this paper we have used the EFIT solution (using magnetics-only data with  $q_0$  held at 0.9) in a fully current-diffused sawtooth discharge as the equilibrium model, defining the zero offset. It is this estimate of the zero angle that is the main limitation in the present analysis.

A number of other techniques have been explored (including firing beams into a gas-filled torus and measuring the boundary  $q$  of a shrinking plasma, limited by the inner wall). In future, these methods combined with detailed laboratory measurements will be used to obtain a genuinely independent calibration.

### Results

Measurements during full-power heating are especially sensitive to the relative intensity calibration of the different PINIs and are not presented here. In figure 2,  $q$ -profiles are shown from the ‘target’ and ‘post-heat’ phases (before and after the main heating pulse) in a 2.6 T discharge optimised for high performance in the full-power phase[6].

The target  $q$ -profile obtained with the MSE data is significantly different from that obtained from just magnetics measurements (although this profile, from the intershot analysis chain, is somewhat over-constrained to ensure convergence—giving some loss of profile information), in particular the  $q$ -profile is broader and almost completely flat over the central 0.5 m. This demonstrates the effectiveness of the internal pitch angle measurements in constraining the equilibrium reconstruction.

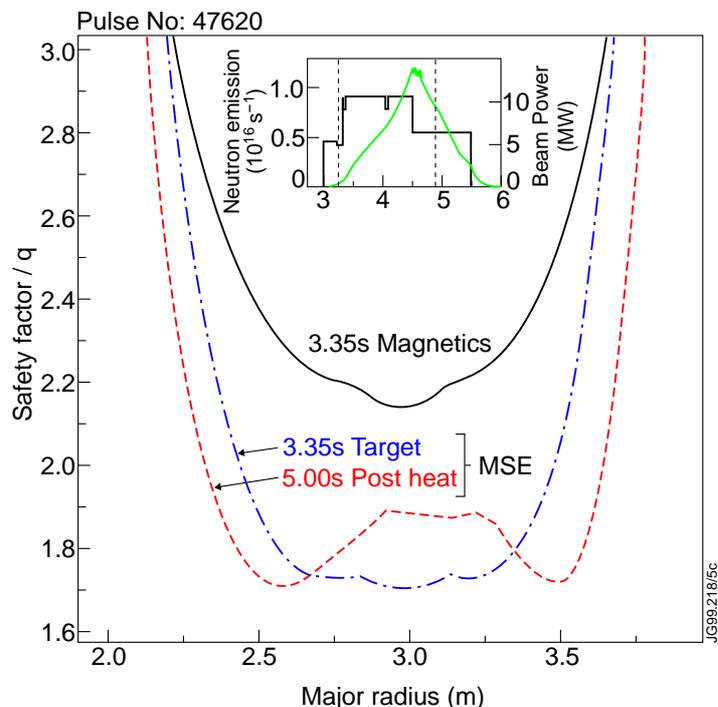


Figure 2:  $q$ -profiles obtained using MSE data during ‘pre-heat’ and following the main heating pulse in an optimised shear plasma as compared to the intershot magnetics-only analysis results.

disagree by 10 cm or more when no offset is used. The measurements from the FIR polarimeter are also consistent with the EFIT calculations at this offset value.

The value of  $q$  in the centre of the profile, at 1.7 is lower than that given by EFIT with magnetics data alone (2.1) and that with the FIR polarimeter data (1.9). In a similar discharge, at a later time, the appearance of an  $n = 1$  MHD mode correlated with a flattening of the  $T_e$  profile in the plasma centre indicates that  $q = 2$  near the axis. Since the plasma current is still increasing this evidence suggests that the value of  $q_0 = 1.7$  from the MSE measurements is an underestimate. This probably represents the limitations of the calibration method used here.

Figure 3 shows an example of the evolution of the  $q$ -profile obtained from MSE measurements during the high power heating phase of a 3.4 T discharge up until the end of the data acquisition at 7.5 s. (One of the eight PINIs was not operating in this discharge allowing the analysis of the MSE measurements to be extended with more confidence into the full-power phase.) No offset was required in the analysis of this case.

Again, and as is generally the case, the  $q$ -profile is far flatter over the central region than is obtained from the magnetics-only intershot analysis. During the high-power heating the  $q$ -

To obtain consistency between the magnetics measurements and the MSE data an offset of  $1.0^\circ$  has been subtracted from the MSE measurements. The origin of this offset is not clear; possibilities include Faraday rotation in the torus window, a misalignment of the diagnostic viewing direction or the limitations involved in the zero angle assumption built into the calibration procedure, although none of these explanations are obviously able to account for such a large offset. The exact value of the offset angle is obtained from minimising  $\chi^2$  from EFIT for the MSE measurements. With this offset value the calculated magnetic axis position (a sensitive function of offset) and that estimated from the soft X-ray (SXR) cameras agree to within about 1 cm while they disagree by 10 cm or more when no offset is used.

profile remains flat (possibly becoming very weakly reversed) with the value of  $q_0$  remaining almost constant right until the end of the data window.

In other discharges of this type a ‘snake’ MHD mode is sometimes seen at a radius of about 3.5 m after the main heating pulse. This phenomenon has 2/1 characteristic and is indicative of low shear, possibly a minimum in  $q$ , at this radius[7]. The MSE  $q$  profiles in these cases consistently show an off-axis minimum in  $q$  but the absolute values obtained are again slightly lower than predicted from the MHD.

### Conclusions

The MSE diagnostic has been commissioned and is taking data reliably. The  $q$ -profiles obtained using MSE data in EFIT magnetic reconstructions are broadly consistent with independent indicators of  $q$ . A large database of shots exists, of which, only a small part has so far been analysed. At present the diagnostic calibration is derived from magnetics-only  $q$ -profiles in fully-diffused sawtooth discharges but optical calibration is in progress to improve on this. In the future the accuracy of the analysis at full power will be improved by operating some of the beam lines at higher voltage.

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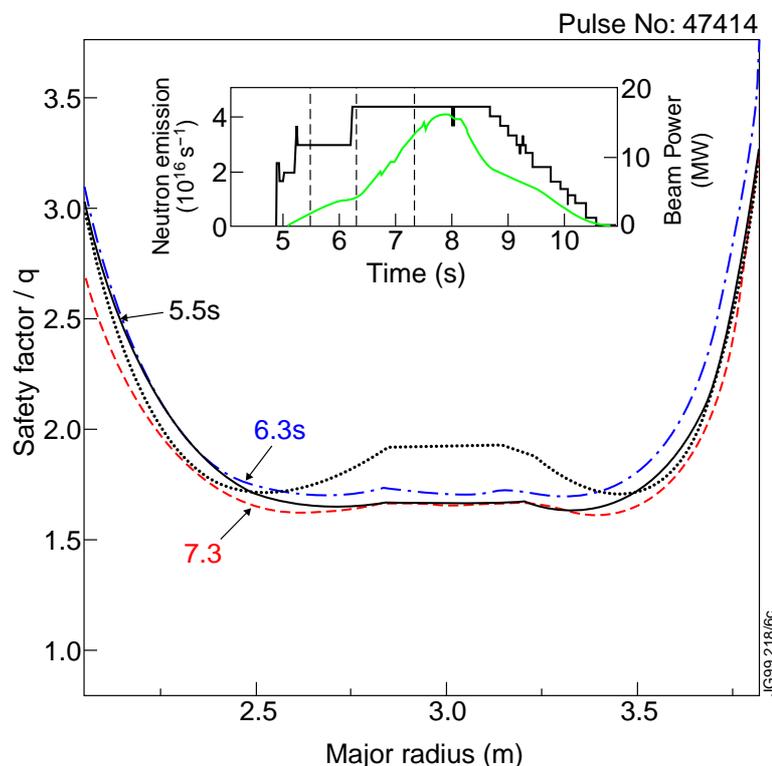


Figure 3: Evolution of the  $q$ -profile during the high power heating phase of an optimised shear plasma. The dotted curve is at 6.5 s and indicates the probable level of uncertainty during the high-power phase.