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Motional Stark Effect Measurements of q-Profiles in JET Optimised Shear Plasmas

B. C. Stratton[1], N. C. Hawkes[2], C. D. Challis, E. Joffrin[3], B. Rice[4], R. DeAngelis[5], W. Zwingmann[3]

JET Joint Undertaking, Abingdon, Oxon., OX14 3EA, U K
[1]Princeton Plasma Physics Laboratory, PO Box 451, Princeton, NJ, 08543, USA
[2]Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxon., OX14 3DB, UK
[3]Association Euratom-CEA, CEA-Cadarache, F-13108, St. Paul lez Durance, France
[4]Lawrence Livermore National Laboratory, PO Box 808, Livermore, CA 94550, USA
[5]Association Euratom-ENEA sulla Fusione, CRE Frascati, 00044, Frascati, Roma, Italy

INTRODUCTION

Measurements of the profile of the safety factor, q, play an important role in understanding the physics of high-performance tokamak operating regimes, such as JET's Optimised Shear regime. The Motional Stark Effect (MSE) provides a way of measuring the magnetic field pitch angle in the plasma interior, and these measurements are used to constrain an EFIT magnetic equilibrium reconstruction of the plasma, which yields the q-profile. An MSE diagnostic has been implemented on JET and is now in routine use. In this poster, the diagnostic instrumentation and calibration techniques are briefly described, followed by measurements of the q-profile in JET Optimised Shear plasmas.

JET MSE DIAGNOSTIC

D_α emission from neutral beam atoms is split into Stark components by the electric field seen by the atoms due to their motion through the magnetic field of the tokamak. The σ and π lines of the Stark spectrum are polarized perpendicular and parallel, respectively, to the local electric field, which is perpendicular to the magnetic field. In MSE polarimetry, the magnetic field pitch angle is deduced from measurement of the polarization angle of a spectrally-resolved region of the Stark spectrum which has a high polarization fraction.

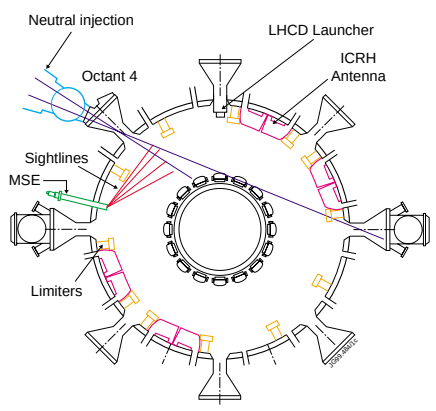

Fig.1:

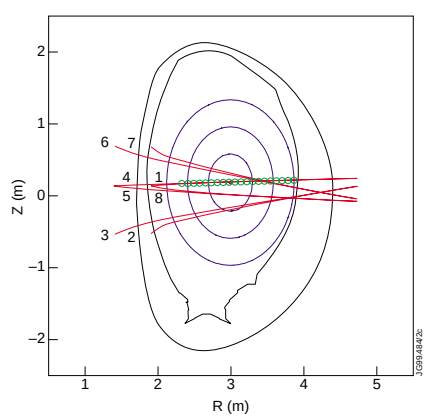

Fig.2:

MSE polarimetry on JET is complicated by the geometry of the neutral beam trajectories. JET has two neutral beam boxes, located at Octants 4 and 8. Each beam box consists of eight injectors arranged in two banks of four injectors each, normal and tangential. To avoid overlap of the σ and π lines, the MSE diagnostic views the π^+ emission from the Octant 4 tangential beams, which operated in deuterium at an energy of 80 keV for the measurements described here. This emission is largely discriminated from the emission from the normal beams due to its larger Doppler shift.

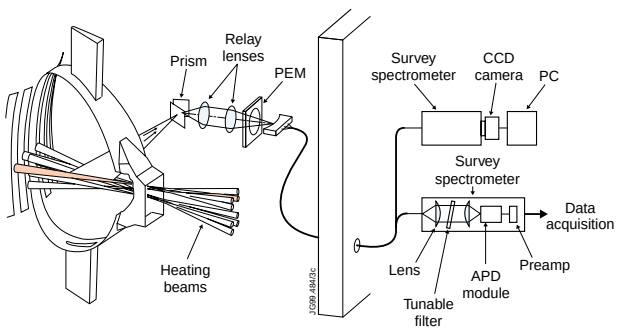

Fig.3:

Light emitted by the Octant 4 neutral beams is collected by optics which transport the plasma image outside the vacuum vessel and through a pair of photoelastic modulators (PEMs) and a linear polarizer. The light is fiber-optically coupled to interference filter spectrometers, which incorporate a remotely-controlled filter tilting mechanism. This allows the center wavelength of the filter bandpass to be tuned over a range sufficient for observation of the σ and π lines of the Stark spectrum emitted by the full- and half-energy components of the beams. The detectors are low-noise avalanche photodiode modules. The data are digitized at 250 kHz. Digital signal processing techniques are used to extract the Fourier components of the signal at the PEM first- and second-harmonic frequencies as well as the DC component of the signal. These extracted signals are integrated over times in the 10-50 ms range to improve the signal-to-noise ratio of the measurements. The system has 25 spatial channels covering the outer half of a JET plasma with spatial resolution of 0.03-0.07 m per channel with ~0.05 m channel-to-channel separation.

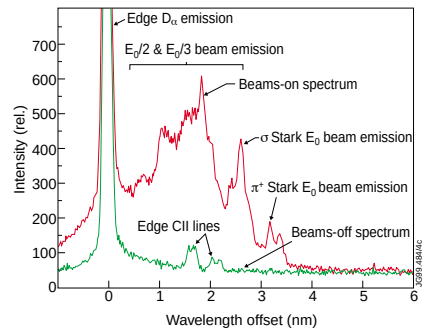

Fig.4:

A survey spectrometer connected to four of the sightlines is used to monitor the beam emission spectrum as an aid to tuning the filters. The spectrum shows that the π^+ emission from the full-energy (E_0) component of the beams is resolved from the σ emission from the E_0 beam component and emission from the $E_0/2$ and $E_0/3$ beam components.

CALIBRATION

The calibration has two aspects: 1) determining the system response to input light of known linear polarization; and 2) measuring the relative contributions of the emission from the different beams in the field of view to the measured pitch angle:

1. The system response to changes in the polarization angle of the input light was measured by a laboratory calibration in which the diagnostic viewed light polarized by a rotating linear polarizer. These measurements alone did not allow the zero pitch angle response to be accurately measured. The zero angle response was deduced from data obtained with beam injection into the torus filled with gas only. To quantify the effects of Faraday rotation on the input optics, the toroidal field was applied in both the normal operational direction and the opposite direction.

2. For a given sightline, the beam-sightline intersection angle is different for the various beams in the field of view. The sightlines are aimed at the beam from PINI 1, but the signal from the PINI 7 beam is approximately equal. The signals from the other PINIs are smaller but are not negligible in all cases. The relative contributions of all eight Octant 4 beams to the total signal were measured by injecting short pulses from each beam into a steady-state sawtoothing discharge. These data were used to derive weights which relate the measured pitch angle to the magnetic field pitch angle in a model which has been incorporated into EFIT.

q-PROFILE IN SAWTOOTHING DISCHARGE

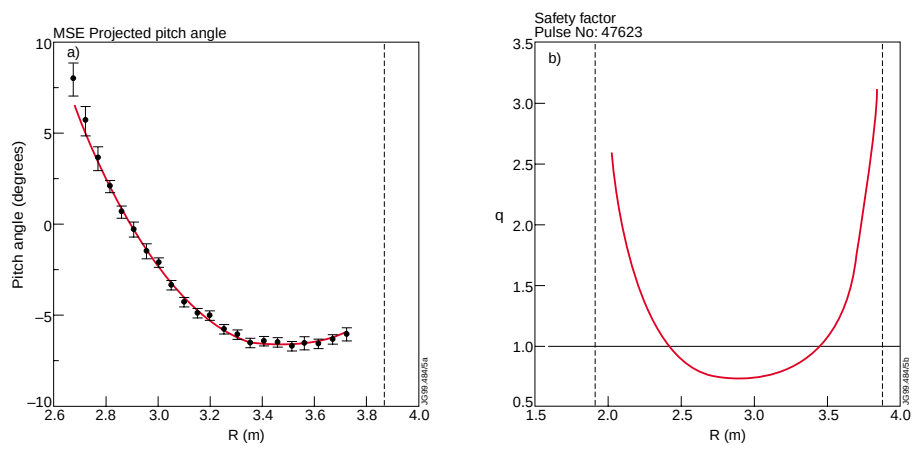

Fig.5:

Measurements in a sawtoothing discharge provide a test of the calibration. Shown are the measured and EFIT calculations of the pitch angle and the deduced q-profile for injection of PINI 1 only into a sawtoothing discharge. Note the good fit to the measured pitch angle. In this case and those shown below, EFIT was run with the external magnetics measurements and MSE pitch angle as constraints. The polynomial representation of the ff' and p' functions in the Grad-Shafranov equation was used, with four degrees of freedom for ff' and three degrees of freedom for p'. No smoothing or edge constraints were applied to ff' and p'.

q-PROFILES IN OPTIMISED SHEAR TARGET PLASMAS

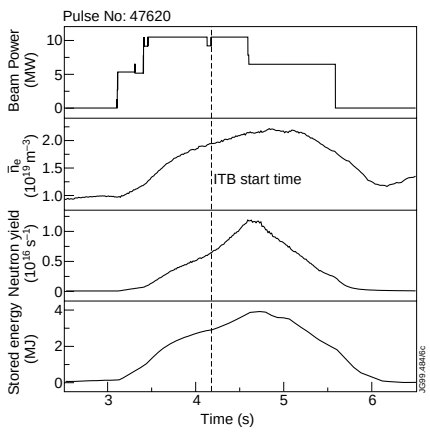

Fig.6:

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JET Optimised Shear discharges are produced by injection of high-power heating (NB and ICRF) into a target plasma with q_0 greater than one. The target plasma is obtained by lower-power ICRF heating in the I_p ramp-up period of the discharge, which raises T_e and slows current diffusion into the plasma core. The value of q_0 in the target plasma may have a significant effect on formation of an Internal Transport Barrier (ITB) and thus the peak neutron yield and stored energy reached during the high-power heating phase [1]. To study this, target plasma q-profiles were obtained from EFIT constrained by MSE data in a series of discharges at B_T=2.6 T and I_p=2.6 MA, with 10.5 MW NB power and 4.5 ICRF power during the high power phase. The target plasma had 5 MW NB power, with PINI 7 off to allow reliable interpretation of the MSE data.

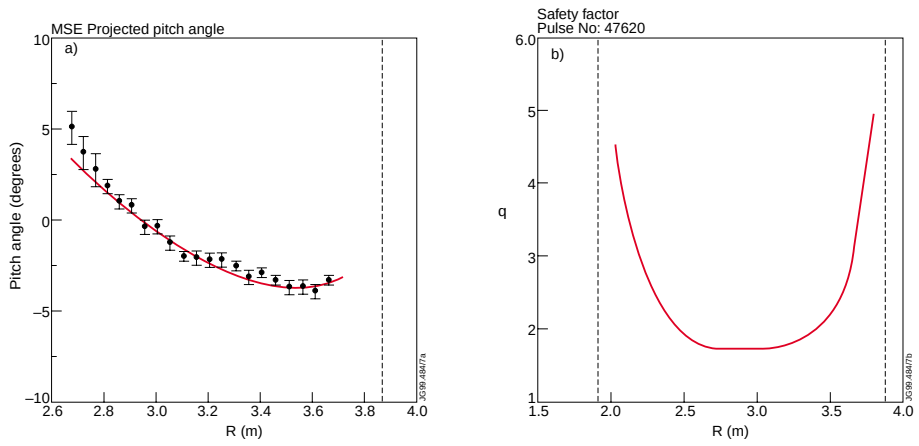

Fig.7:

Shown are measured and calculated pitch angles and the q-profile in the target phase of a discharge (0.05 s before the start of high-power heating) which had an ITB during the high-power phase. The q-profile is flat in the core region with q_0=1.7. A flat or mildly reversed core q-profile is typical of JET Optimised Shear target plasmas.

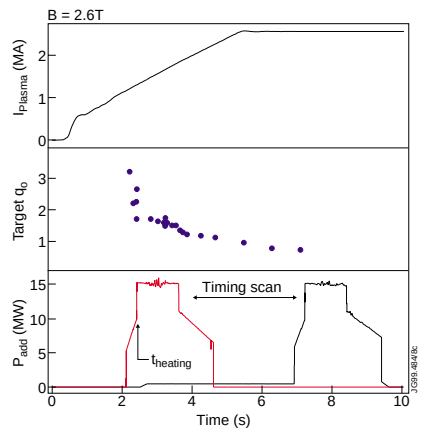

Fig.8:

The value of q_0 in the target plasma was varied by changing the time of NB and ICRF heating from early in the I_p ramp-up to later times early in the I_p flat top. The values of q_0 obtained from MSE measurements 0.05 s before the start of high-power heating are shown along with the I_p time evolution and the range of start times for NB plus ICRF heating. As expected, the target q_0 decreases as the heating start time is moved later.

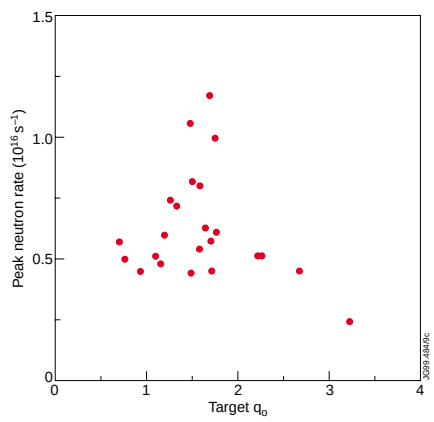

Fig.9:

The neutron yield plotted against target q_0 shows a peak at q_0≈1.6. The lower neutron yields of several of the shots with q_0 near this value is due to the development of n=1 MHD activity during the high-power phase. A previous analysis of the same data set based on target q_0 values from EFIT constrained only by magnetics data (0.3 s before the start of high-power heating) showed a peak in the neutron yield at q_0≈2.1 [1]. Much of the difference can be explained by the fact that the EFIT magnetics data-only analysis was done with the ff' and p' functions smoothed and with these functions forced to zero at the plasma edge, which tends to yield higher values of q_0.

TIME EVOLUTION OF Q-PROFILE IN OPTIMIZED SHEAR PLASMA

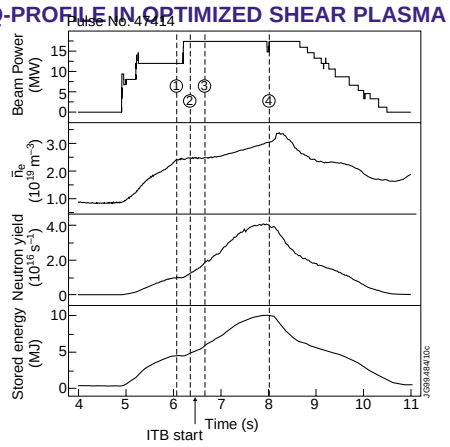

Fig.10:

The time evolution of the q-profile was measured in a high-power Optimised Shear discharge with B_T=3.45 T and I_p=3.4 MA. The total heating power was 27 MW (17 MW NBI and 10 MW ICRF). An ITB developed, starting at 46.4 s. PINI 7 was not injected, making this discharge well-suited to MSE measurements.

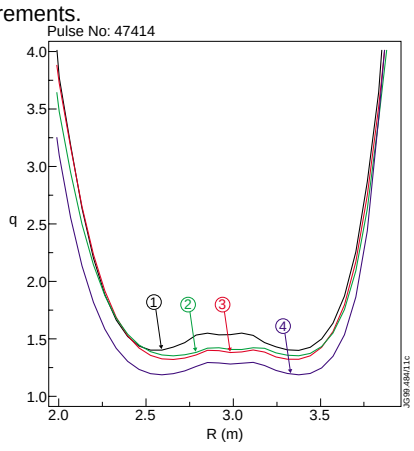

Fig.11:

The q-profile at four times is shown: 1) the target phase; 2) early in the high power phase; 3) after the formation of the ITB; and 4) at the time of peak neutron emission. The q-profile is approximately flat or mildly reversed at all of these times and it does not change shape significantly. q_0 decreases slowly with time.

CONSISTENCY WITH OTHER MEASUREMENTS

There is evidence that MSE values of q in the core region are systematically low. In a discharge with a snake MHD event associated with q=2 [2], EFIT constrained by MSE measurements shows q≈1.5 at the time and radius of the snake.

In the discharges from the Optimised Shear timing scan which had n=1 MHD activity (thought to be m=2 and thus associated with q=2), the MSE q values were ~1.5. However, EFIT modelling with q_0 fixed at 2.0 at the peak neutron yield discharge in the Optimised Shear timing scan yields a fit to the measured pitch angle profile that is almost indistinguishable from the q_0=1.6 case. Thus, it is possible that the observed peak in the neutron yield at q_0≈1.6 (as measured using MSE) in the timing scan is consistent with q_0≈2. Work to understand these differences is in progress.

CONCLUSIONS

- q-profiles in the target and high-power heating phases of JET Optimised Shear plasmas have been deduced from EFIT magnetic equilibrium reconstructions constrained by MSE measurements of the magnetic field pitch angle.
- q-profiles in Optimised Shear target plasmas are flat or mildly reversed in the core region.
- A peak in the neutron yield of Optimised Shear discharges is observed when q_0 is measured to be 1.6 in the target plasma.
- q-profiles during the high-power phase of an Optimised Shear plasma are similar to the target q-profile. Strong reversal is not seen in this case.

FUTURE WORK

- The MSE q-profile measurements presented here do not include the effect of the radial electric field, E_r, which has been shown to be important in tokamak discharges with low or reversed central shear. We will attempt to measure E_r in JET Optimised Shear plasmas.

ACKNOWLEDGEMENTS

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