Test of current diffusion modelling in MAST current ramp-up

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1. Introduction

Tokamaks typically use the current ramp-up to tailor the q-profile for the main heating phase of advanced tokamak scenarios. This is achieved with a combination of actuators including the I_P ramp-rate, externally applied heating, plasma density and plasma shaping that affect current diffusion. The capability to predict the q-profile evolution throughout the current ramp-up phase in response to these actuators is crucial for the design of new plasma scenarios and specification of poloidal field, heating and current drive systems for future devices.

Previous current diffusion results on MAST[1] and JET[2] have shown consistency with neoclassical resistivity[3, 4] when approaching stationary conditions but inconsistency in the early current ramp-up phase[5, 6]. Particularly it was found that the modelled current diffusion was more rapid than experimental measurements suggested. This result prompted an experiment to measure the q-profile evolution throughout the current ramp-up and flat-top phase of a plasma with no additional heating with the aim of removing experimental uncertainties in the apparently contradictory aforementioned results. This was achieved by making use of high resolution Thompson scattering (TS) [7], Motional Stark Effect (MSE)[8] and Z_{eff}[9] measurements available on MAST.

2. Experimental method

A plasma with no neutral beam (NB) heating has the advantages that no NB generated fast-ions (FI) are present, eliminating uncertainties associated with FI transport and FI induced MHD, and the magnitude of neoclassical bootstrap current is minimised. However, MSE measurements, which allow the current profile (j_ϕ) to be accurately determined, require NB injection. To resolve these mutually exclusive requirements, the NB start-time was varied in a series of otherwise identical pulses producing a sequence of MSE measurements that can be combined to construct the complete time evolution of the q-profile in an equivalent ohmic plasma. The MSE measurement in the first 2ms after the beam switches on is taken to be representative of the j_ϕ profile of the ohmically heated plasma at that time. This assumption is valid as the MSE diagnostic takes measurements on a much faster timescale than the slowing-down time of the NB fast-ions in the plasma, which is typically 10 to 15 ms during the I_P

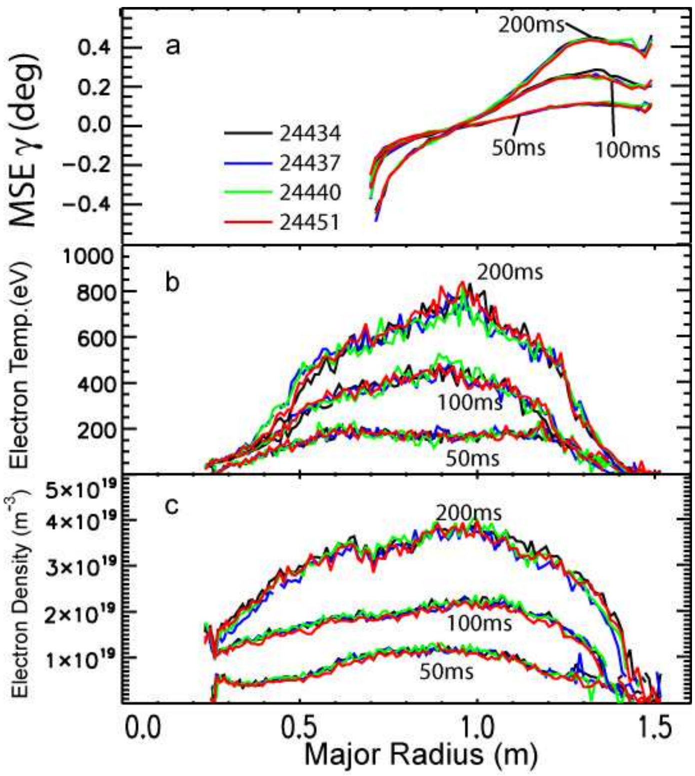

Figure 1.**a)** MSE, **b)** TS electron temperature and **c)** TS electron density measurements from consistency-check shots. Profiles from 4 similar shots are overlaid at 3 different times demonstrating excellent shot-to-shot reproducibility.

ramp-up phase, hence the measurement is taken before the FI population is established and before the beam has heated the plasma significantly. These MSE "snapshot" measurements are then used as a constraint in the EFIT equilibrium solver[10] to determine the q and j_ϕ profiles.

A further requirement is that good shot-to-shot reproducibility is achieved throughout the experiment; variation of plasma conditions would invalidate the assumption that the q-profile evolution in repeated plasmas is identical so that measurements can be combined. To ensure this condition, every fourth plasma pulse during the session was an identical consistency-check, with NB start=10ms. Figures 1a-c demonstrate the required repeatability.

Two plasmas were run with no additional heating in the current ramp-up and flat-top phases. EFIT was used to provide equilibrium reconstructions of these plasmas using magnetic measurements, TS and optically determined boundary position data as input, with the MSE "snapshots" as an additional fitting constraint. Varying the options in EFIT (e.g. polynomial or spline representation, order of the basis functions and relative weighting assigned to the constraints) resulted in only a small variation in the calculated q-profile. The difference in the resulting q-profiles is indicated by the error bars in figure 2c. Other experimental data (including I_P, B_T, T_e, n_e and Z_{eff}) is prepared using an integrated analysis chain for input to the TRANSP[11] code, which is used to model the current diffusion assuming neoclassical resistivity. The simulation is initialised at 75ms, half way through the I_P ramp phase. It is required that the calculated q-profile in the simulation matches the one derived from the MSE constrained EFIT at that time. After initialisation, the current profile is evolved in time using the poloidal field diffusion equation to see if the modelled q-profile evolution is consistent with the MSE measurement at later times.

3. Discussion

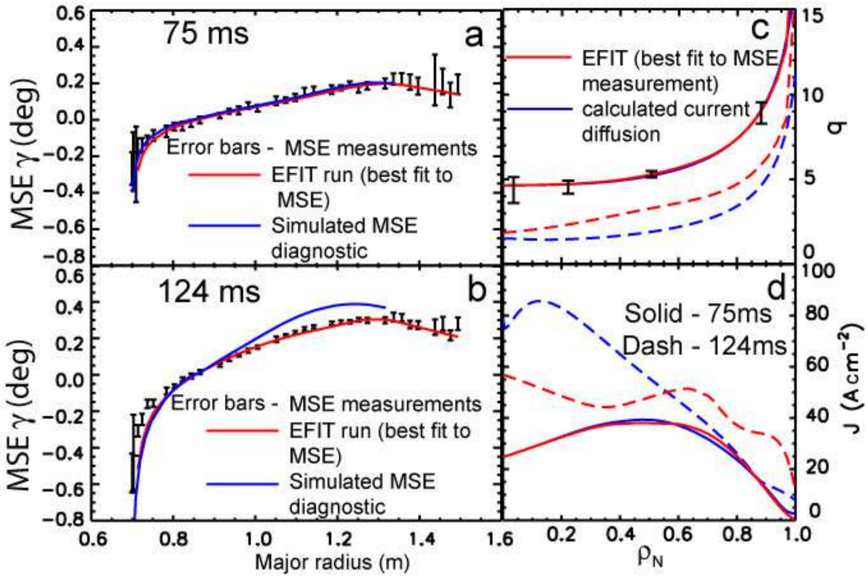

Figure 2 a, b MSE measurements, EFIT fit and simulated MSE diagnostic output at 74ms and 124ms respectively. **c, d** q- and j_ϕ-profiles respectively at 74 and 124ms. These results show that, after 50ms of simulated current diffusion, the simulated current profile no longer matches the experimental measurements or EFIT interpretation of the q-profile.

TRANSP provides a synthetic MSE diagnostic which produces expected values that may be directly compared with the experimental measurements; these are shown in figures 2a-b. Despite a good match to measurements at run initialisation, after 50ms the simulated MSE data lies well outside the region bounded by the experimental error bars; figures 2c-d show the corresponding q and j_ϕ profiles respectively. Fig. 2d shows that the simulated current profile is much more peaked than the MSE constrained EFIT profile, indicating that current diffusion is much more rapid in the simulation than the measurements suggest. The q-profile from the simulation at 124ms is correspondingly lower than that from the MSE constrained EFIT. This inconsistency between simulation and experiment can also be seen in figure 3. Figure 3 shows (a) times in the experiment where MSE "snapshots" were taken and (b and c) the resulting value of q produced from MSE constrained EFIT and from the simulation at, respectively, the magnetic axis and the half radius. The discrepancy between measurements and simulation is particularly pronounced at the half radius during the current ramp and early flat-top. The discrepancy becomes significant at the axis in the latter stages of the I_P flat-top. Note that no MHD is observable in these plasmas before 250ms at which time a sawtooth precursor n=1 mode appears.

4. Conclusions and future plans

A technique has been developed and used to obtain high quality MSE measurements of a plasma with no additional heating. Analysis using the neoclassical formulation for plasma resistivity shows that a standard treatment of the resulting data does not model the measured current diffusion; the modelled current diffusion is more rapid than the measurements suggest. Careful testing has ruled out simple explanations for the observed discrepancy including systematic errors in measurements principally affecting the resistivity calculation and possible errors in preparation and mapping of the simulation input data.

Previous studies on MAST and JET show consistency with neoclassical resistivity in near stationary conditions where collisionality is low and inconsistency in the early current ramp-up phase where collisionality is high. The present result, in which collisionality is high, is therefore also consistent with the previous results.

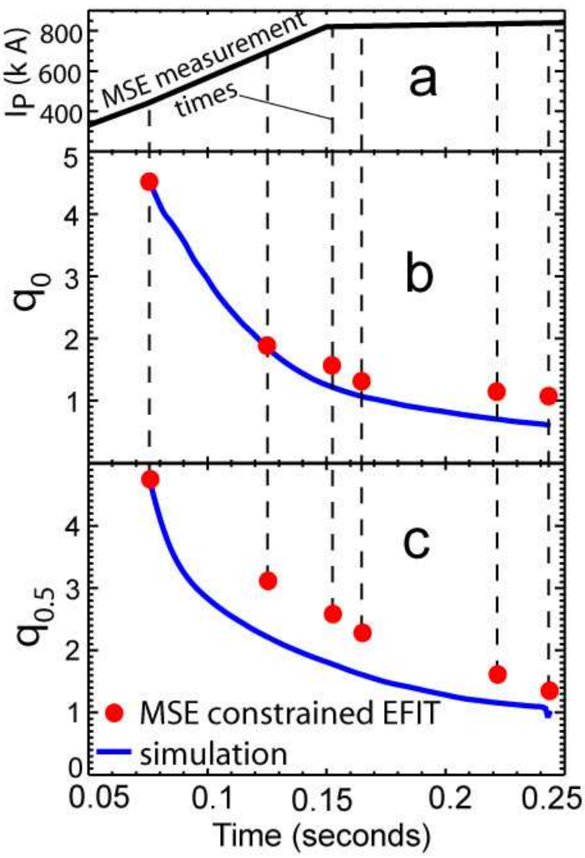

Figure 3 a I_P from experiment indicating where MSE data "snapshots" were taken. **b, c** q_0 and $q_{0.5}$ traces from MSE constrained EFIT and simulation based on NC current diffusion calculation.

It is unlikely that anomalous processes such as MHD can explain an anomalously slow current penetration into the plasma core as is seen in these experiments. Therefore further experiments are planned for the next MAST experimental campaign to investigate the sensitivity of the discrepancy between experiment and modelling at various values of collisionality.

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5. References

[1] B. Lloyd *et al.*, Plasma Phys. Control. Fusion **46** (2004) B477–B494

[2] D. Kelliher *et al.*, Plasma. Phys. Control. Fusion **47** (2005) p1459

[3] F.L. Hinton and R.D. Hazeltine, Rev. Mod. Physics, **48** (1976) 239-308

[4] O. Sauter *et al.*, Phys. Plasmas **6** (1999) p 2834 and O. Sauter *et al.*, Phys. Plasmas **9** (2002) p5140

[5] D. Keeling *et al.*, Proc 35th EPS Conf. 2008; M. Turnyanskiy *et al.*, Nucl. Fusion **49**(2009) 065002

[6] I. Jenkins *et al.*, Proc. 37th EPS Conf. 2010

[7] R. Scannell *et al.*, Rev. Sci. Instrum. 81, 10D520 (2010) doi:10.1063/1.3460628

[8] N.J. Conway *et al.*, Rev. Sci. Instrum. **81**, 10D738 (2010) doi:10.1063/1.3494254

[9] A. Patel *et al.*, Rev. Sci. Instrum. **75** (2004) p4944

[10] L.L. Lao *et al.*, Nucl. Fusion **25** (1985) p1421

[11] R.J. Goldston *et al.,* J. Comput. Phys. **43** (1981), 61