Measurements of the edge current during MAST H-modes using MSE

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Understanding ELMs is important for current and future fusion devices. ELMs are thought to be the result of peeling-ballooning modes that have a stability region determined in terms of the pressure gradient ∇p and the edge current density j_ϕ . Whereas several high resolution diagnostics exist to measure the pressure profile, j_ϕ is usually calculated using neoclassical theory. Measurements of j_ϕ would test these calculations, but are challenging in conventional tokamaks.

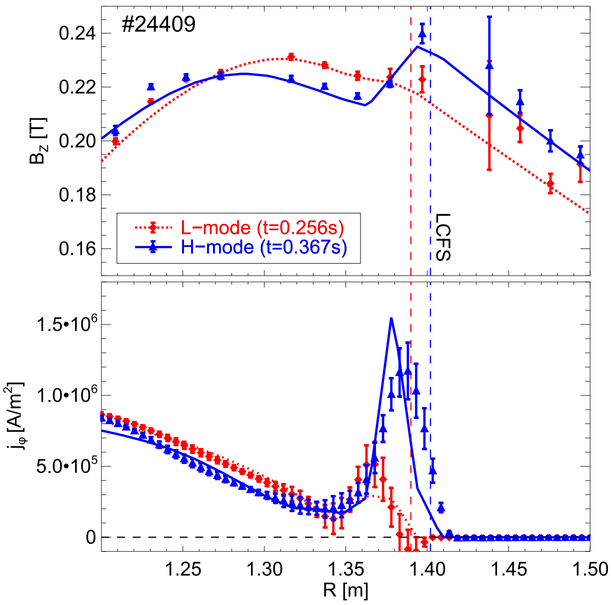

Figure 1: B_Z profiles and corresponding j_ϕ for a MAST plasma in L- and H-mode directly from the MSE measurements – error bars – and from MSE constrained EFIT – lines.

Motional Stark Effect diagnostics (MSE) – the most commonly used technique to derive j_ϕ in tokamaks – measure the magnetic pitch angle profile $\gamma_m = \arctan(B_\theta/B_\phi)$ which depends on the integrated current. Consequently, a change of j_ϕ in the edge will result in only a small change in γ_m, as it has to compete with the total plasma current. Moreover, MSE is dependent on the local electric field E_r as well, which can be significant in the pedestal region during H-mode. In spherical tokamaks, however, the low B_ϕ and similar B_θ, compared to conventional tokamaks, leads to a larger γ_m and also to a larger change in γ_m for any given change in j_ϕ. E.g. for a typical $B_\theta = 0.2$ T, a change $\Delta B_\theta = 0.02$ T due to an edge j_ϕ, would yield $\Delta\gamma_m = 2.8^\circ$ in a spherical tokamak with $B_\phi = 0.25$ T; whereas in a conventional tokamak with $B_\phi = 2.5$ T the change in pitch angle is only $\Delta\gamma_m = 0.46^\circ$. With a time resolution of 2 ms, the MAST MSE system (35 channels, $\sim \Delta R = 0.02m$) can operate with a statistical error of $\sim 0.5^\circ$ in the plasma edge; enough to resolve the expected changes in γ_m [1, 2].

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In MAST the MSE angle γ is measured in the mid plane ($B_R = 0$, $B_\theta = B_Z$) resulting in:

$$\tan(\gamma) = \frac{-\cos(\beta)B_z - (E_r/v)\cos(\alpha+\beta)}{\sin(\alpha)B_\phi} \quad (1)$$

with β the angle between the neutral beam and the line of sight, α the angle between the toroidal direction and the neutral beam and v the beam velocity. Equation (1) is used within EFIT to constrain the equilibrium reconstruction [3]. It can, however, also be used to calculate B_Z directly from the MSE angle γ. In that case the values of B_ϕ, E_r and v are found from an initial EFIT reconstruction, the known beam energy and active Doppler spectroscopy on He^+ respectively [4]. Figure 1 shows B_Z and the corresponding j_ϕ – as derived from EFIT and directly from the MSE measurements – for L- and H-mode. The effect of E_r is reasonably small in MAST: $\sim 2\%$ in B_Z and $\sim 10\%$ in j_ϕ.

Once the B_Z profile is known, Ampère's law is used to derive j_ϕ:

$$\mu_0 j_\phi = \frac{\partial B_R}{\partial Z} - \frac{\partial B_Z}{\partial R}, \quad (2)$$

where the first term can be found from the initial EFIT reconstruction under the assumption that the flux surface shape is only weakly dependent on the local j_ϕ.

Figure 2 shows the evolution of j_ϕ, $\max(|\nabla p_e|)$ and D_α during a MAST H-mode discharge (#24409). After the L-H transition (at $t = 0.263$ s) high frequency, type III ELMs appear followed (at $t = 0.302$ s) by two long ELM free periods separated by a type I ELM at $t = 0.345$ s. A final ELM at $t = 0.392$ s terminates the H-mode. The periods around the ELMs are blocked by grey areas in figure 2 because no reliable MSE measurement exists at those times. The high frequency of the type III ELMs and the 2 ms time resolution of the MSE diagnostic meant that only a few j_ϕ profiles could be obtained during that period.

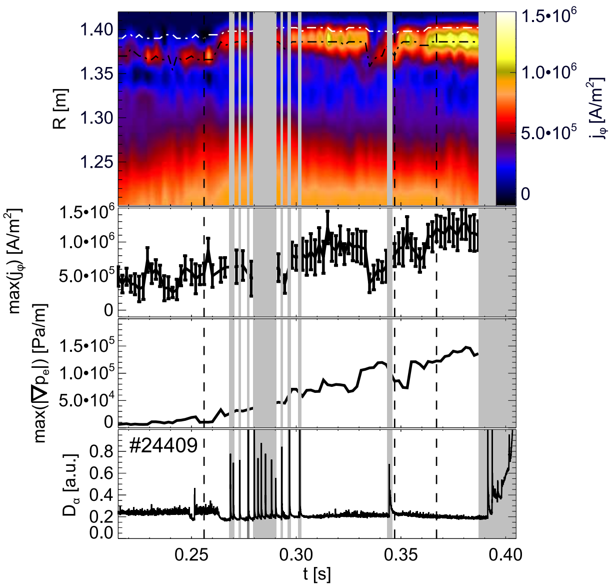

Figure 2: The evolution of j_ϕ, $\max(|\nabla p_e|)$ and D_α.

As expected one observes strong edge currents during the long ELM-free periods. The data, however, shows 2 interesting features:

(a) Just after the ELM at $t = 0.345$ s, $\max(|\nabla p_e|)$ drops significantly, whereas $\max(j_\phi)$ keeps increasing. A possible explanation might be that current can only distribute through diffusion and hence has no time to react to the ELM.

(b)A transient decrease of $\max(j_\phi)$ is observed when $\max(|\nabla p_e|)$ increases (at $t = 0.332$ s and $t = 0.355$ s). A possible explanation here is that the increased collisionality (as the increase in $|\nabla p_e|$ is mainly due to an increase in n_e) reduces the bootstrap fraction of the edge current [5].

A more detailed comparison between the pressure driven current and j_ϕ measured by MSE is shown in figure 3. It shows j_ϕ based on the neoclassical calculation of the bootstrap current [6, 7]. Profiles are shown just after the ELM ($t = 0.347$ s), when the MSE measured j_ϕ is still high, and late in the ELM-free period when both the measured j_ϕ and $|\nabla p_e|$ have recovered ($t = 0.367$ s). It is clear that in both cases the neoclassical calculation yields a lower and more narrow peak in j_ϕ than that measured by MSE. This could be due to the assumptions made for the neoclassical calculation ($T_i = T_e$, $n_i = n_e$), the spatial resolution of the MSE diagnostic, ... However, it could also be possible neoclassical theory is no longer valid in the plasma edge during H-mode because $\rho_\theta \sim L_n$ (with ρ_θ the poloidal gyroradius and L_n the density gradient length).

Finally $\max(j_\phi)$ was plotted as a function of $\max(|\nabla p_e|)$, as is usually done for a stability plot (figure 4). To determine the stability boundary ELITE calculations were performed for 2 time points just before the first ($t = 0.343$ s) and last ($t = 0.383$ s) ELMs [8, 9]. This resulted in the 2 dashed lines on figure 4, indicating the ballooning boundary of the stability region. A peeling boundary was not found for these time points. To guide the eye a dotted line is added to the figure in the location were the peeling boundary is expected. It is observed that during the type III ELMy phase of the discharge $\max(j_\phi)$ and $\max(|\nabla p_e|)$ are located in the area where the peeling boundary is expected (crosses). In the first long ELM free period $\max(j_\phi)$ and $\max(|\nabla p_e|)$ start near the peeling boundary, but then move towards the ballooning boundary: increasing $\max(|\nabla p_e|)$ and decreasing j_ϕ. At the ELM crash $\max(|\nabla p_e|)$ drops while $\max(j_\phi)$ keeps on rising, consequently getting close to the peeling boundary again. $\max(|\nabla p_e|)$ then quickly starts to increase, while $\max(j_\phi)$ drops, moving towards the ballooning boundary again. $\max(|\nabla p_e|)$ and $\max(j_\phi)$ subsequently increase, more or less following the ballooning boundary.

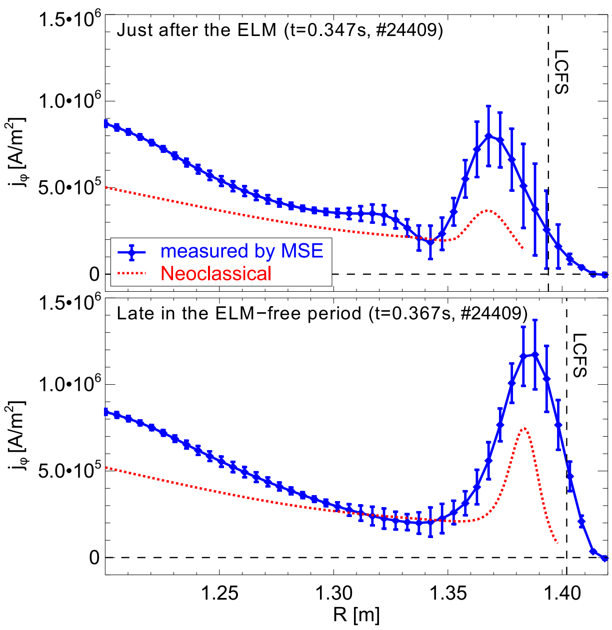

Figure 3: Comparison of j_ϕ measured by MSE and that based on the neoclassical bootstrap current.

The above results show the capability of MSE as tool for measuring the evolution of the edge j_ϕ in spherical tokamaks. This thanks to the large pitch angle and the fact that the E_r correction is small. The evolution of j_ϕ shows interesting behaviour that does not always seem to correlate with $|\nabla p_e|$. Neoclassical calculations of the bootstrap current typically result in lower values for edge j_ϕ than measured with MSE. Further and more detailed analysis on a wider variety of discharges will allow to evaluate the agreements and disagreements between the measured data, neoclassical calculations and stability codes. Also a new EBW (Electron Bernstein Waves) emission diagnostic is being constructed at MAST, designed specifically to measure the pitch angle in the edge and hence complement the MSE data[10].

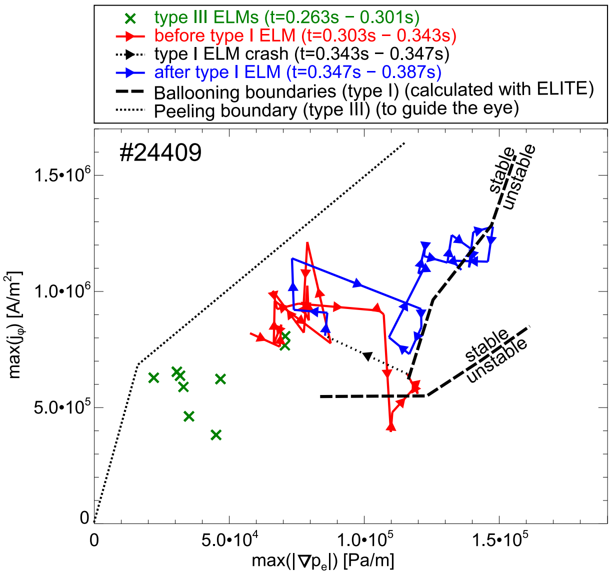

Figure 4: $\max(j_\phi)$ plotted versus $\max(|\nabla p_e|)$. This shows the evolution within the stable region.

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References

[1] M. F. M. de Bock, N. J. Conway, M. J. Walsh *et al* , "Ab initio modeling of the Motional Stark Effect on MAST", *Review of Scientific Instruments*, vol. 79, no. 10, p. 10F524, 2008.

[2] N. J. Conway, M. F. M. De Bock, C. A. Michael *et al* , "The MAST motional Stark effect diagnostic", *Review of Scientific Instruments*, vol. To be published: proceedings 18th conference on High-Temperature Plasma Diagnostics, May 2010, 2010.

[3] L. C. Appel, G. T. A. Huysmans, L. L. Lao *et al* , "A Unified Approach to Equilibrium Reconstruction", in *33rd EPS Conference on Controlled Fusion and Plasma Physics* (ECA, ed.), vol. 30C, pp. P–2.184, EPS, 2006.

[4] H. Meyer, C. Bunting, P. G. Carolan *et al* , "The structure, evolution and role of the radial edge electric field in H-mode and L-mode on MAST", *Journal of Physics: Conference Series*, vol. 123, p. 012005, 2008.

[5] D. M. Thomas, A. W. Leonard, T. H. Osborne *et al* , "The effect of plasma collisionality on pedestal current density formation in DIII-D", *Plasma Physics an*, vol. 48, pp. A183–A191, 2006.

[6] O. Sauter, C. Angioni, and Y. R. Lin-Liu, "Neoclassical conductivity and bootstrap current formulas for general axisymmetric equilibria and arbitrary collisionality regime", *Physics of Plasmas*, vol. 6, no. 7, p. 2834, 1999.

[7] O. Sauter, C. Angioni, and Y. R. Lin-Liu, "Erratum: ŞNeoclassical conductivity and bootstrap current formulas for general axisymmetric equilibria and arbitrary collisionality regimeŤ [Phys. Plasmas 6, 2834 (1999)]", *Physics of Plasmas*, vol. 9, no. 12, p. 5140, 1999.

[8] H. Wilson, P. Snyder, G. Huysmans *et al Physics of Plasmas*, vol. 9, p. 1277, 2002.

[9] P. Snyder, H. Wilson, and et al. *Physics of Plasmas*, vol. 9, p. 2037, 2002.

[10] V. F. Shevchenko, M. F. M. D. Bock, S. Freethy *et al* , "2D EBW studies in MAST", in *16th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, Sanya, China*, 2010.