

Tailoring the q-profile on MAST for scenario optimisation

D. Keeling, R. Akers, C.D. Challis, G. Cunningham, H. Meyer and the MAST team

EURATOM/UKAEA Fusion Association, Culham Science Centre,

Abingdon, Oxon, OX14 3DB, UK

1. Introduction

The high neoclassical resistivity and peaked conductivity profile observed in spherical tokamaks, with a consequent higher current penetration rate, results in rapid approach to low values of core safety factor (q) at the start of the discharge. This provides specific challenges for initiating $q>1$ regimes, desirable for long pulse or steady-state spherical devices. Experiments were therefore carried out to determine the extent to which the q -profile on MAST may be modified during the plasma current (I_p) ramp-up phase with the aim of developing a start-up regime that can later be used to access advanced modes of operation such as the hybrid or improved H-mode [1].

2. Experiment

Twelve pulses were carried out in all to investigate separately the effect of the current ramp-rate, density ramp-rate and neutral beam (NB) start-time. Four pulses used a slow current ramp (3.5MA/s) and slow density ramp ($4.9 \times 10^{20}/\text{m}^3 \cdot \text{s}$) with NB start times of 0s, 70ms, 140ms and 200ms. Four pulses used a fast current ramp (7MA/s) and slow density ramp with NB start times of 0s, 35ms, 70ms and 105ms. And four pulses used a fast current ramp and fast density ramp ($8.8 \times 10^{20}/\text{m}^3 \cdot \text{s}$) with NB start times of 0s, 35ms, 70ms and 105ms. Other plasma parameters such as shape, position and current flat-top were kept constant. NB start times were chosen such that they were at comparable stages of the current ramp for the fast and slow ramp cases i.e. $I_p=0$, $I_p=1/3 \times I_{p,\text{max}}$, $I_p=2/3 \times I_{p,\text{max}}$, $I_p=I_{p,\text{max}}$.

3. Analysis

Analysis was carried out using the TRANSP code [2] which was used to perform an interpretive analysis, taking plasma profiles and solving the poloidal field diffusion equation (PFDE) self-consistently with the neoclassical resistivity and calculated non-inductive current drive. For each pulse, TRANSP analysis was started at the earliest time an acceptable EFIT equilibrium could be produced. Validation and benchmarking of the analysis was performed by comparison with Alfvén cascades [3] in the MHD analysis of some shots and observation of sawtooth precursor modes in the soft X-ray measurements [4]. In this way, values of q_{min} at certain times could be determined along with arrival time of $q=1$, enabling the TRANSP simulation setup to be adjusted so as to achieve the best match to the available MHD data. An EFIT equilibrium reconstruction [5], constrained only by external magnetic

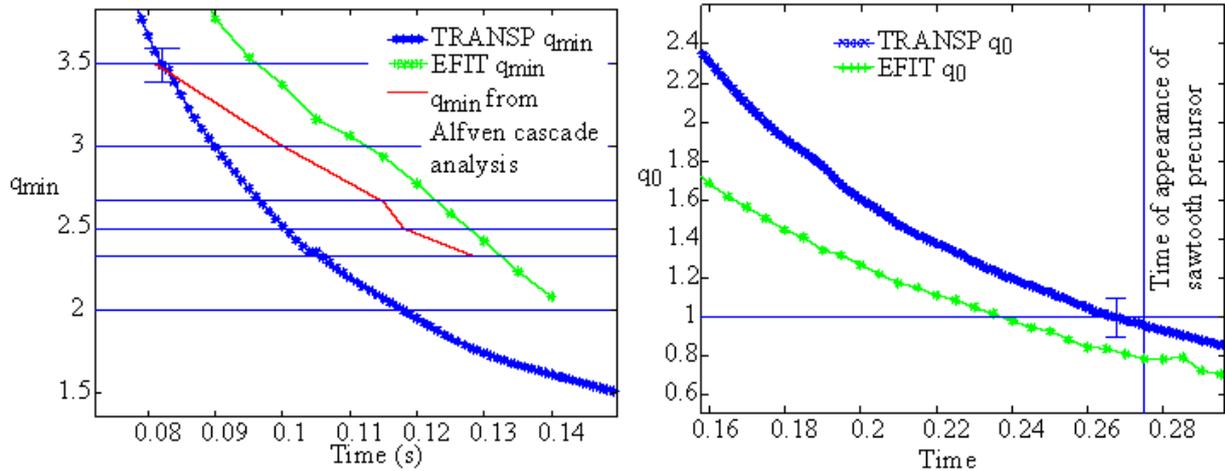


Figure 1: q_{\min} (left) and q_0 (right) values from EFIT and TRANSP, compared with Alfvén cascade and sawtooth precursor mode analysis. Error bars show extent of q -profile variation produced by TRANSP when input profiles are varied by their maximum error estimates.

measurements, was used as the initial condition for TRANSP and the handover time from EFIT to the PFDE was the main parameter adjusted to achieve the match of the q -profile to the available MHD data. Results from pulse 16149 are shown in figure 1. This shows that in a single interpretive run, where TRANSP initial conditions are chosen to match the time and q_{\min} value of the first Alfvén cascade, both the early reversed magnetic shear and the time of $q_0=1$, from the first sawtooth precursor, are reproduced. Further refinement of analysis at this stage was not possible due to lack of current profile measurements on MAST.

4. Results

The q -profiles for each experiment were examined at the start of the current flat-top (200ms for the slow current ramp experiments, 105ms for the fast current ramp experiments). For each of the current/density ramp combinations this gives one ohmic and three NB heated experiments. The ohmic results show that increasing the density ramp rate increases magnetic shear ($s = (r/q)(dq/dr)$) in the outer half of the plasma, $0.5 \leq r/a \leq 1$ with only a very weak effect on the core. Increasing the current ramp rate decreases s in the outer half of the plasma, again with a very

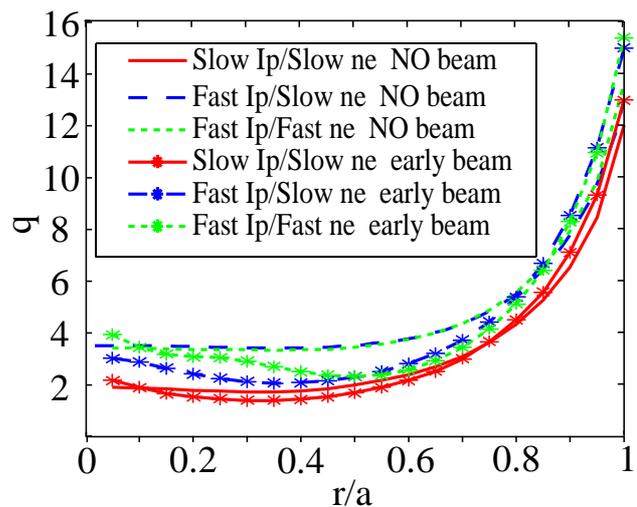


Figure 2: Comparison of q -profiles from experiments with no NB and with NB starting at 35ms (70ms for slow I_p ramp case).

weak effect on the core. Results with NB show negative values of s (i.e. reversed magnetic shear, a necessary condition for observation of Alfvén cascades) are obtained in all experiments with NB (See Figure 2). Earlier NB timing generally produces more negative values of s with the most pronounced results seen for fast current ramp cases. In all three cases, q_0 remains relatively unaffected.

5. Discussion

TRANSP shows the changes in the q -profile illustrated in figure 2 are due to changes in the ohmic current profile rather than the presence of beam driven current. The ohmic current accounts for 88-90% of I_p peaked off-axis ($r/a=0.4-0.5$) whereas the beam driven current is only 5-7% of I_p peaked closer to the plasma axis ($r/a=0.15-0.2$). The following process is suggested: on-axis beams heat the core lowering plasma resistivity and increasing current penetration time (evidence for electron temperature peaking due to NB heating is shown in figure 3.) As current diffuses toward the plasma core during the current ramp it ‘piles up’ off-axis due to the region of higher T_e at the core. Increased off-axis current density results in reversed magnetic shear. Examination of later times in the TRANSP runs shows that this is a dynamic effect and the plasma relaxes to a state with a monotonic q profile as the ohmic current slowly penetrates into the core.

6. Towards steady-state

Predictive simulations have been undertaken as part of a study to build a scientific case for a proposed upgrade to MAST. The main features of this proposed upgrade are: a longer pulse duration (up to 5s), cryopumped divertor, higher toroidal field and higher NB heating power. Amongst the intended aims of the project are: the demonstration of a stationary plasma in which $q_{\min} > 2$ with no inductive current drive. Simulations show that a large amount of extra off-axis neutral beam current drive (NBCD) will be necessary to achieve the stated aims because a stationary plasma requires the off-axis current to be maintained over a long time-

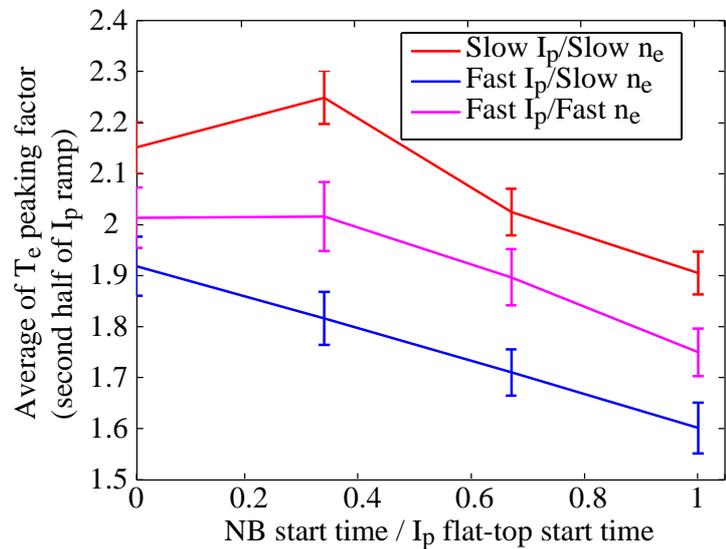


Figure 3: Electron Temperature (T_e) peaking factor, time averaged over the second half of the current ramp, plotted versus NB start time. NB heating decorrelates resistivity profile from ohmic heating giving access to different q -profile evolution.

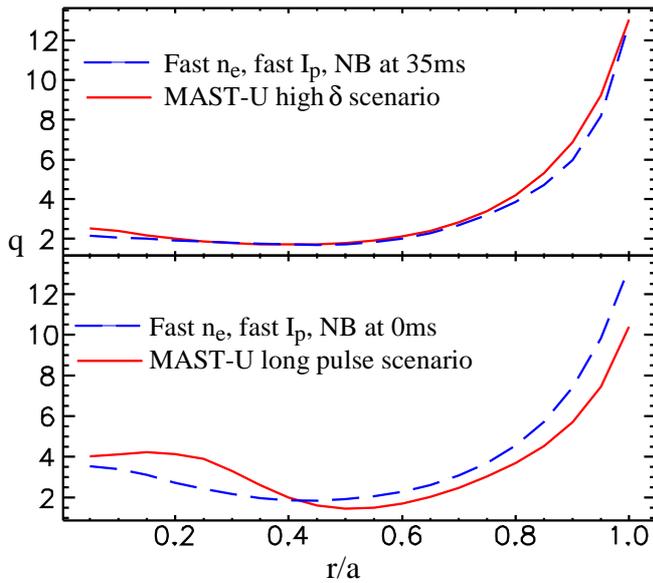


Figure 4: Fully relaxed q-profiles from two MAST-U fiducial scenarios compared with transiently obtained q-profiles from MAST experiments exhibiting the current pile-up effect.

current to relax into a stationary state in the MAST-U scenarios whereas a fully relaxed current profile may be achieved much more rapidly by making use of the current pile-up effect to pre-shape the q-profile before turning on the off-axis beams.

7. Conclusions

The technique of early core heating to slow current penetration represents a powerful tool for controlling and shaping the q-profile on MAST. This technique combined with off-axis NB [6], as envisaged for the proposed upgrade to MAST, will allow rapid formation of a steady-state compatible q-profile and maintenance of this profile to demonstrate potential steady-state operation.

8. References and Acknowledgements

[1]. A. Staebler et al., Nucl. Fusion **45** (2005) 617; [2]. R. J. Goldston et al., J. Comput. Phys. **43** (1981) 61; [3]. S.E. Sharapov et al., Phys. Plasmas **9** (2002) 2027; [4]. R.J. Buttery et al., Nucl. Fusion **44** (2004) 1027; [5]. L. Lao et al, Nucl. Fusion **30** (1990) 1035; [6] M. Turnyanskiy et al, This Conference.

This work was funded jointly by the United Kingdom Engineering and Physical Sciences Research Council and by the European Communities under the contract of Association between EURATOM and UKAEA. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

scale whereas the current pile-up effect described above is transient over several hundred milliseconds. The fully relaxed q-profiles of several MAST-U fiducial scenarios are similar to the dynamically obtained q-profiles obtained with the current pile-up effect (see figure 4). This not only demonstrates the need for off-axis NBCD in MAST-U to maintain the off-axis current, but also suggests the current pile-up effect may be useful in starting up such scenarios. Simulations show that it takes approximately 1.8 - 2 seconds for the