

High elongation in the MAST Spherical Tokamak

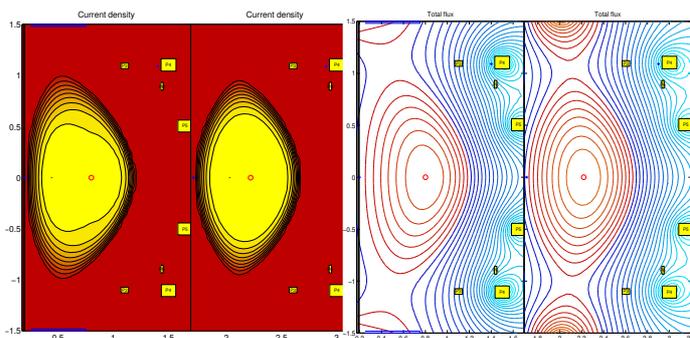
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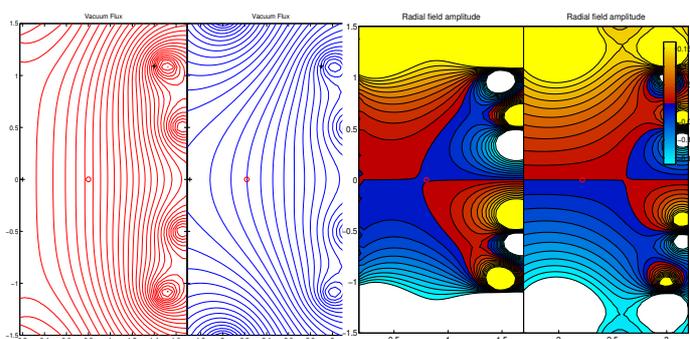
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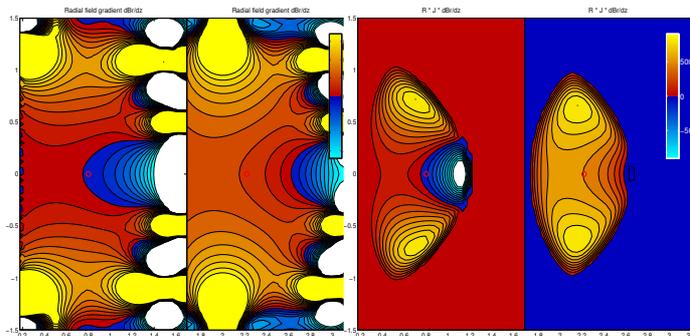
Many conceptual tokamak power plant designs, including the favoured Culham ST reactor, use high elongation as a route to high pressure and bootstrap current. This paper looks at the implications, with regard to vertical position control, when such models are to be tested on a tokamak with fixed coil geometry such as MAST. Several issues emerge, for example: the increasing quadrupole field has the effect of reducing the plasma cross section and edge q , and the bootstrap current is only increased significantly if the internal inductance is low. Also, the vertical stability of the plasma scales in rather unusual ways, for example *reduced* internal inductance leads to *reduced* stability, when the shaping field is constant. The model is compared with MAST experiments where elongation up to 2.5 has already been obtained.



1. Here we see two equilibria, with the same current density profile, calculated at low and high aspect ratio, $A=1.44$ and 4.56 respectively. The current density and flux plots are superficially similar.



2. However, the vacuum field (left) and its radial component (right), start to show significant differences.



3. As a result, the vertical derivative of the radial field (left) changes sign within the plasma volume, so that when this is crossed with the current density (right) the destabilising force gradient also changes sign within the plasma. In contrast, the large aspect ratio case is more intuitive.

Scaling of the vertical stability. The following plots show integral data where each point is calculated from a separate equilibrium. There are two major scans in the database, one at fixed current density profile but varying I_p and divertor current, the other at fixed currents but varying profile (l_i). In this case the destabilising force, which is the sum of the forces shown in figure 3, is compared with the stabilising force, calculated by RZIP[†] using the actual vessel geometry for MAST, for the low aspect ratio case.

[†]RZIP calculates the dynamic response of the plasma to currents in the equilibrium coils and induced currents in the vessel. It uses a rigid multi-filament representation of the plasma. The vessel-plasma coupling matrix is reduced to an adjustable extent by eigenvector extraction.

4. As expected, the destabilising force gradient increases rapidly with divertor current. The stabilising force falls initially, probably because the changing shape is moving the plasma away from the poloidal field coils, but then plateaus as most of the stabilisation is coming from the centre column.

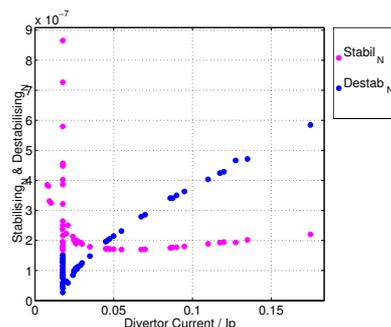


Fig. 204

5. As a result, f_s , the ratio of stabilising to destabilising force gradients, falls strongly with increasing divertor current, if the internal inductance (l_i) is held constant. It is notable that, if l_i is varied at fixed divertor current, then it is the higher l_i plasmas which are most stable, as they have most current near the centre of the machine where the quadrupole field is weak (of course their elongation is lower). This is directly opposite to the case of the conventional aspect ratio tokamak at moderate elongation.

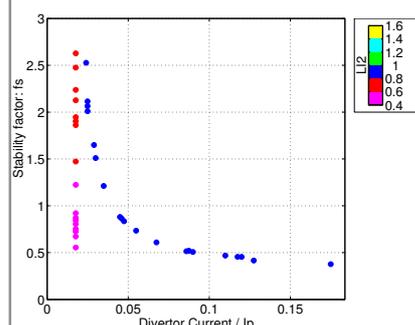
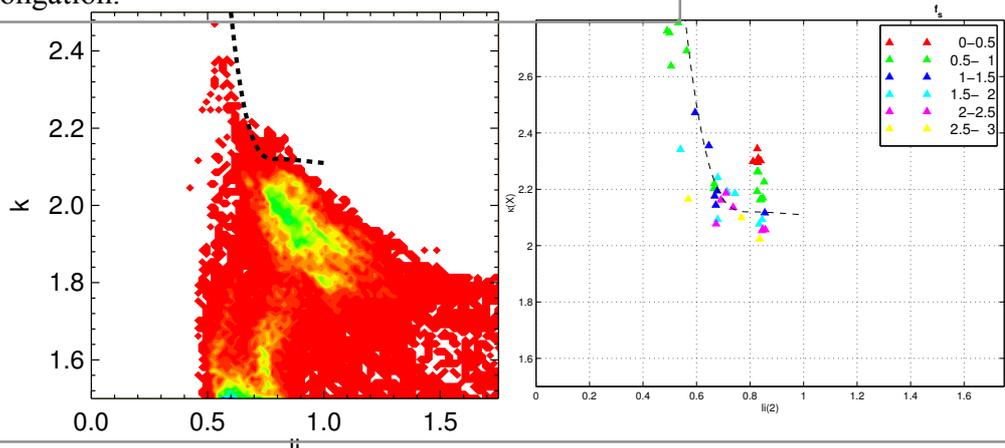
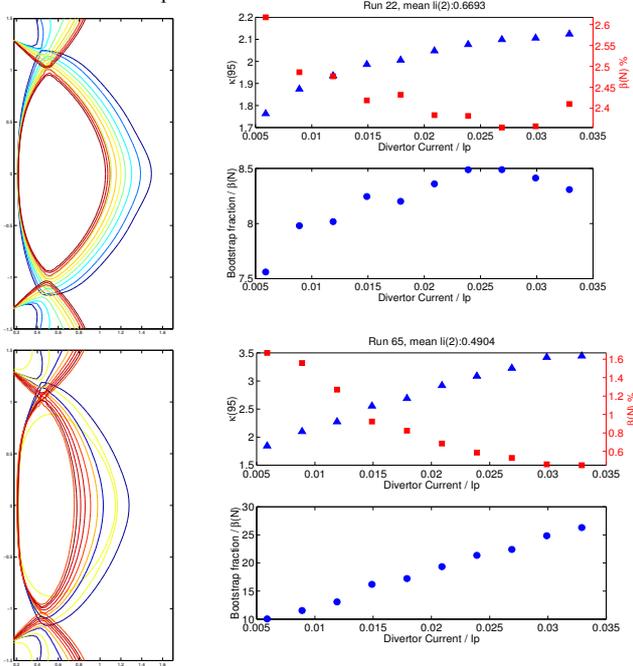


Fig. 203



6. These data can be re-plotted as κ vs. l_i as a function of the stability index (right). The dashed curve is an ‘eyeball fit’ to $f_s=1.5$, which is about the value which the MAST vertical position control system can achieve. If this same curve is over-laid on the distribution of κ vs. l_i for actual MAST plasmas (left) it coincides quite well with the high l_i , high κ edge of the distribution. The rather angular shape of this stability curve demonstrates clearly that it is very difficult to achieve high elongation when l_i is greater than 0.6 or so.

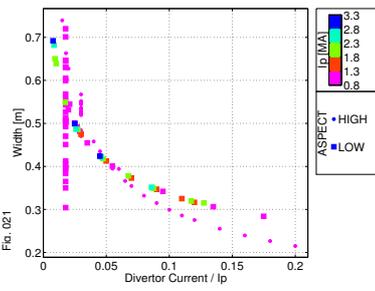
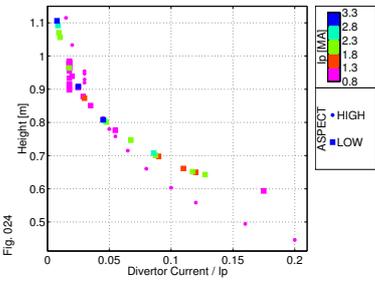
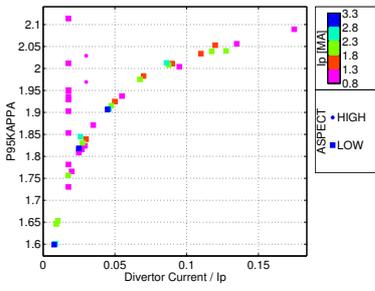
Scaling of the bootstrap current. The bootstrap current is an important issue for steady state tokamak operation. Here we see that the bootstrap current is increased at high elongation, assuming that the same β_N can be achieved, though low l_i is necessary to give a strong effect. Under optimal conditions, a scaling of $I_{boot} \propto I + \kappa^2$ can be obtained, for fixed β_N , A, I_p/I_{Tcrit}



7. On the left is shown the outline of a series of equilibria with the same current density profile but varying divertor current. Although the elongation changes significantly, the changing aspect ratio means that the effect on the bootstrap current is rather weak.

8. In this series of equilibria the l_i is lower, and the divertor current has a greater effect on the elongation. The effect is magnified by the bootstrap current depending more strongly on the elongation, with the result that the bootstrap current scales much more strongly with divertor current.

Scaling of the shape



9. As expected, the plasma elongation increases with divertor current, both for the low and high aspect ratio cases.

10. However, it is less obvious to see that the plasma height is actually reduced as the divertor current is increased, and this effect is slightly stronger for the high aspect ratio case.

11. The inevitable result is that the plasma width falls rapidly, and the safety factor decreases rapidly, with increasing divertor current. This is in spite of the decrease in major radius and resulting increase in the toroidal field on axis.

Scaling of the plasma performance

12. As a result of the shape changes described above, the net current carrying capacity, $(a^2+b^2)/R^2$, falls somewhat with increasing divertor current. This is consequence of using a single coil pair to change the elongation.

13. Ideally one would evaluate the maximum attainable β_N from a stability code, but for the present we simply use the Sykes-Troyon scaline for $\beta_{max} \propto I_p/aB$, and at first glance β_{max} appears to be increasing with divertor current. However, q_{95} is falling (colours); if the limit is followed at constant q_{95} , it is seen to fall slowly.

14. However, with the toroidal field on axis also increasing, the maximum pressure ($P_m = \beta_N \cdot B^2$) is increasing slowly, even at constant q_{95} .

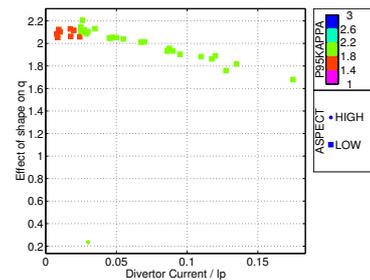


Fig. 023

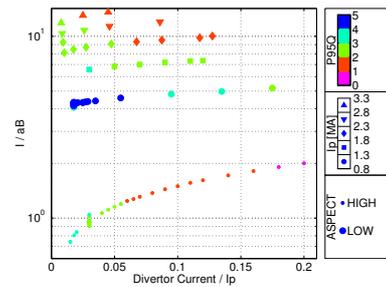


Fig. 025

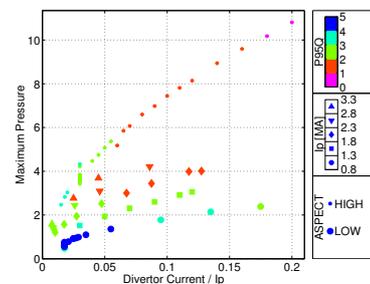


Fig. 026

Conclusion. A very wide range of plasma elongation and current profiles has been explored on MAST. These show that elongations up to 2.5 can be achieved provided the inductance is kept low. Extensive modelling in the full MAST coil and vessel geometry has now been performed, and this matches the experimental data very well.

As a result of this work it is becoming clear that there are significant differences between the way the way a conceptual tokamak design scales with elongation and the way a the performance of particular ST scales. In the former case the poloidal coils can be positioned at will so that the plasma cross section is maintained. In the latter case, when the coil positions are fixed, increasing the quadrupole field alone reduces the plasma cross section, so that to maintain an acceptable q_{95} , the current also has to be reduced. As a result the Sykes-Troyon limit for β actually falls somewhat as the elongation is increased.

Studies of the relation between the bootstrap current and elongation and inductance have shown how to optimise MAST plasmas to maximise the bootstrap fraction.

Some of the issues which will need to be taken into account in optimising the control system are also becoming apparent, in particular, inhomogeneity in the shaping field is inevitable at low aspect ratio, and causes the plasma stability against vertical displacement to vary strongly across the cross section. There is a similar inhomogeneity in the controlling field. These results will guide the development of the multi-variable digital plasma shape controller and the route to optimum performance of MAST.

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