Merging Compression start-up prediction for ST40

P.F. Buxton[1], O. Asunta[1], M.P. Gryaznevich[1], S. McNamara[1], Tokamak Energy Ltd. team

[1] *Tokamak Energy Ltd, 120A Olympic Avenue, Milton Park, Oxfordshire, OX14 4SA, United Kingdom*

Tokamak Energy Ltd. is currently constructing ST40 (steady-state parameters: $R_{\text{Geo}} \sim 0.4\,\text{m}$, $B_T \sim 3\,\text{T}$, $I_p \sim 2\,\text{MA}$, $T_i \sim 8\,\text{keV}$), see [1] for construction and commissioning progress.

Introduction

The size of a reactor (or Pilot Plant), particularly those based on the spherical tokamak, is predominately set by the radius of the central column [2]. This can easily be shown by noting that the plasma's geometric centre (R_{Geo}) is related to the radius of the central column (r_c), the gap between central column and plasma (g), and the plasma's aspect ratio (A) via: $R_{\text{Geo}} = A\,(r_c + g)\,/\,(A-1)$. As an example, consider increasing the central column radius from $r_c = 79\,\text{cm}$ to $r_c = 89\,\text{cm}$ (while keeping $A = 1.8$ and $g = 1\,\text{cm}$ fixed) this results in an increases of the plasma's geometric centre from $R_{\text{Geo}} = 180\,\text{cm}$ to $R_{\text{Geo}} = 200\,\text{cm}$. Therefore, to minimise the central column radius we consider not having a solenoid (or only a very narrow solenoid) highly desirable.

Before heating and current drive systems such as NBI or ECH can be used a tokamak plasma with a fairly high plasma current and density must be established, this is the challenge of plasma start-up.

Merging Compression (MC)is an extremely reliable and proven solenoid free start-up method, which on MAST has produce plasma's with $\sim 0.5\,\text{MA}$ of plasma current, temperatures $\sim 1.2\,\text{keV}$ and densities $\sim 10^{19}\,\text{m}^{-3}$ [3]. MC involves forming two plasmas around two in-vessel poloidal field coils and then merging the two plasmas. During the merging, magnetic field line breaking and reconnection converts some poloidal magnetic flux into thermal energy. The disadvantage of Merging Compression is that the in-vessel poloidal field coils increase the size of the vacuum vessel.

A related start-up technique, which also involves magnetic reconnection, is Double Null Merging (DNM). DNM uses external poloidal field coils to create two tokamak plasmas which are then merged. Because the poloidal field coils are external this technique should not significantly increase the overall size of the tokamak, because of these reasons DNM start-up is Tokamak Energy's preferred method of plasma start-up.

2 Merging Compression predictions for ST40

A lot of work has been done on the theoretical understanding of the magnetic reconnection process [4], however there is not yet a complete theoretical understanding. Therefore, to predict the performance on ST40 we rely on experimentally derived scalings [3]. One of ST40's missions is to demonstrate magnetic reconnection at higher reconnection fields in the vicinity of a relatively thick conducting wall. Both of these will demonstrate magnetic reconnection in more reactor (or Pilot Plant) relevant conditions.

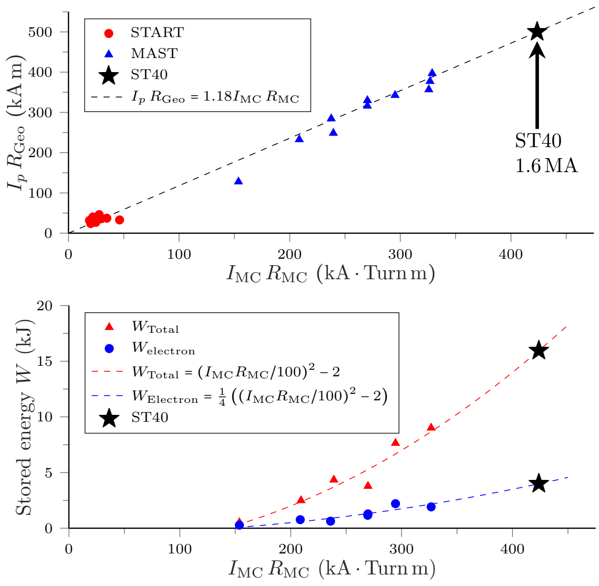

Figure 1: *Extrapolation from START and MAST experimental data to ST40 conditions [3, 5]*

Fig. 1 shows an extrapolation from START and MAST experimental data to the ST40 regime. The top figure shows how $R_{Geo}I_p$ (final plasma geometric centre $\times$ final plasma current) scales with $R_{MC}I_{MC}$ (radial position of in vessel poloidal field coils $\times$ maximum current in coils). ST40 differs from MAST by a factor 1.5 increase in the compression ratio R_{MC}/R_{Geo} and a factor 2 increase in the coils current; together this leads to a factor 3 increase in plasma current to $I_p \sim 1.6$MA. To model the evolution of the plasma prior to and just after merging we have taken a typically shaped MAST plasma current waveform (I_p vs time [6, 7]) and scaled it up to match ST40's expected performance. Then, imposing this waveform we use a combination of Fiesta and RZIP codes [8, 9] to calculate the plasma equilibrium and induced eddy currents within the vessel. Fig. 2 shows the PF coil current waveform (calculated from a power supply model; the power supply architecture is a single trigger thyristor free wheel, with a fixed period of oscillation), the imposed plasma current and a biased vertical field waveform. We note that the maximum current within the internal PF coil is ~650 kA · Turn and this induces $\sim$ 800kA of current to flow within the passive vessel. Fig. 2 shows the proximity of the vessel to the internal PF coils. Consequently, the currents flowing within the vessel are not a small correction to the equilibrium, but instead strongly effect the shape of the equilibrium. This is important because we have optimised the biased vertical field (produced by the external BvL PF coil; see Fig. 2) so that the x-point between the two plasma rings prior to merging is inside the vessel.

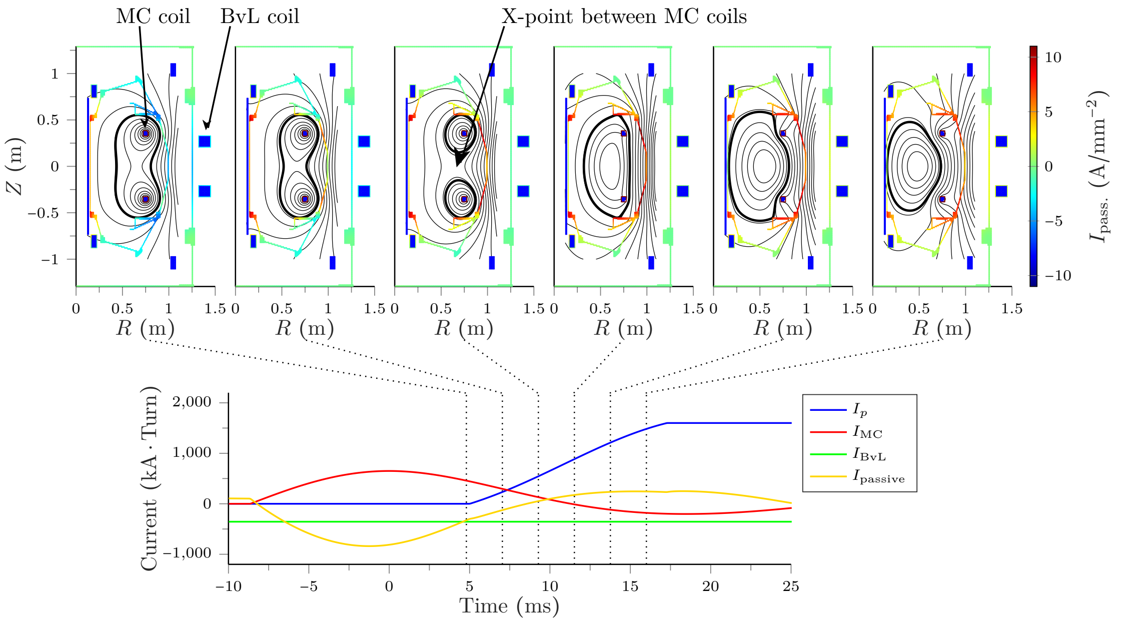

Figure 2: *Free boundary MHD solutions showing the plasma structure before and just after merging [5]; the plasma current waveform has been imposed from START and MAST experimental data.*

ST40 first results; benchmarking the electromagnetic model

We have begun commissioning ST40 and have fired several hundred test pulses. The internal PF coils will have the highest voltage of all the coils $\sim 11\,\mathrm{kV}$ and so far we have tested up to $5.5\,\mathrm{kV}$ and $430\,\mathrm{kA}\cdot\mathrm{Turn}$. Using these plasma-less shots we have benchmarked the electromagnetic filamentary model. The model contains 486 filaments and was constructed directly from axisymmetric CAD drawings (checked to have the same mass) and using measured values for the stainless steel conductivity. ST40's vessel is unusual in that it is not a uniform thickness: most of the vessel is made from 8mm thick 316 stainless steel sheets, however there are also 8 thick flanges (4 top 4 bottom), and we note that approximately half the induced current flows within the sheets while the other half flows within the flanges. To test the electromagnetic model

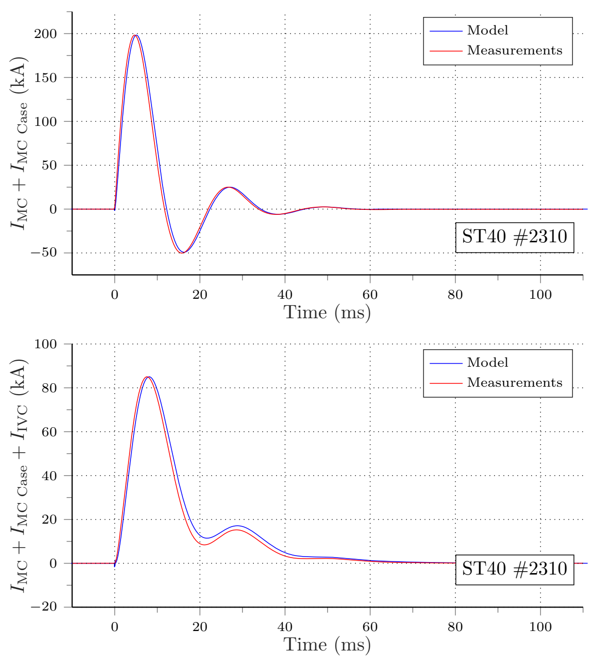

Figure 3: *Experimentally measured Rogowski signals compared to the vessel and coil filament model.*

we used the measured current within the PF coils as the input to our model (note: we slightly smoothed the waveform and downsampled). In these tests we fitted three Rogowski's: one arround each internal PF coils and another around the entire vessel. Fig. 3 shows a comparison between the experimentally measured Rogowski signal and the results from the model. These signals are in good agreement, although there is a ~ 0.5 ms phase difference between the signals, however this is well below the 16 ms wall time.

Planned work

We plan on fine-tuning the electromagnetic model by taking account of the average effect of ports and other non-axisymmetric manufacturing imperfections in the vessel.

ST40 will soon begin testing with a low Toroidal Field (TF). With a TF there will be helicity and we expect to be able to do low current merging experiments.

The ST25 tokamak is being upgraded to a "D" shaped vacuum vessel (ST25-D) and will investigate DNM in the presence of a relatively thick (~ 6 mm stainless steel) conducting wall.

Conclusions

We found that vessel eddy currents have a large impact on the MHD equilibrium and must be included when developing MC or DNM start-up scenarios. We have also demonstrated our ability to accurately calculate vessel eddy currents by comparison with experiments.

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