Merging/Compression start-up in ST40: Analysis of first experimental results

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Tokamak Energy Ltd. has recently successfully completed the first program of operations. This initial program has concentrated on optimising the Merging/Compression start-up technique. During this program there have been $\sim$ 700 plasma pulses, with many parameters varying, such as: gas timing and level of gas injected; strength of vertical field; toroidal field; and M/C coil current. In this paper we compare the plasma current to the M/C coil current, and derive an experimental scaling law.

Introduction

Merging/Compression is an inductive start-up method which involves forming two plasma rings around two internal poloidal field coils [1, 2, 3, 4]. Then, through magnetic reconnection some of the poloidal flux is converted into thermal energy. Figure 1 shows the different stages of the Merging/Compression start-up technique for pulse #5157. From left to right the stages are: (1) First breakdown, if the gas puff is appropriately timed then this stage can be avoided, however we found the first breakdown to be a good pre-ionisation for the next stage. (2) Second breakdown, in this stage the plasma current is induced in the same direction as the M/C coil current and two plasma's surround the two M/C coils. (3) Start of merging and magnetic reconnection. (4) Merging and drop in plasma inductance. (5) Flat top period, the plasma is limited on the center post and shrinks in size. (6) Disruption, this stage occurs when $q^* \approx q_{\text{cyl}} \approx 2$. Figure 2 compares the a magnetic reconstruction to images from a fast visible camera, times indicated in figure 1.

It has been shown on a wide variety of tokamaks and merging experiments that the thermal energy released during magnetic reconnection scales like B_{rec}^2 [5]. ST40 will test this scaling with higher reconnecting fields. The reconnecting field is proportional to the plasma current. It is therefore desirable for us to know how plasma current scales with the M/C coil current, to aid us in designing our next Merging/Compression scenarios at higher reconnecting fields [7].

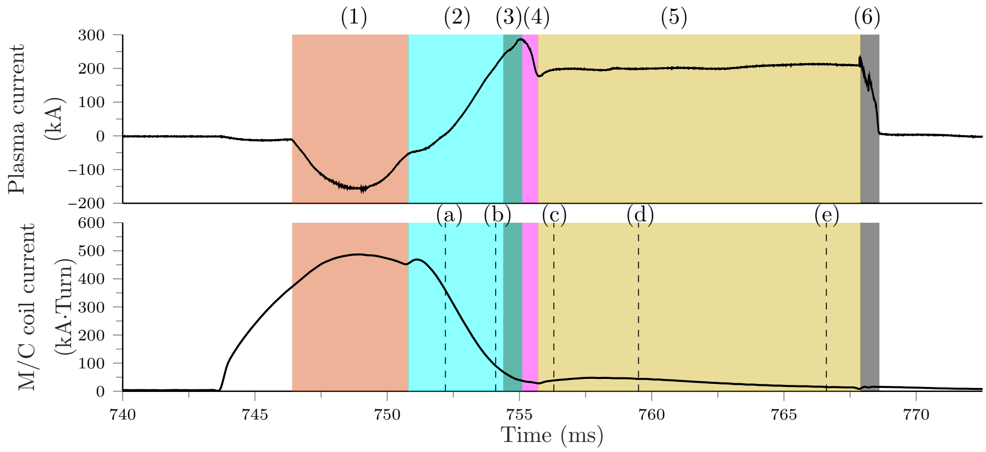

Figure 1: *Shows the different stages (1-6) during Merging/Compression start up in ST40 (pulse #5157). The upper plot shows the plasma current waveform and the lower plot shows the M/C coil waveform. Also indicated (a-e) are the times when magnetic reconstruction is compared to the visible camera images in figure 2.*

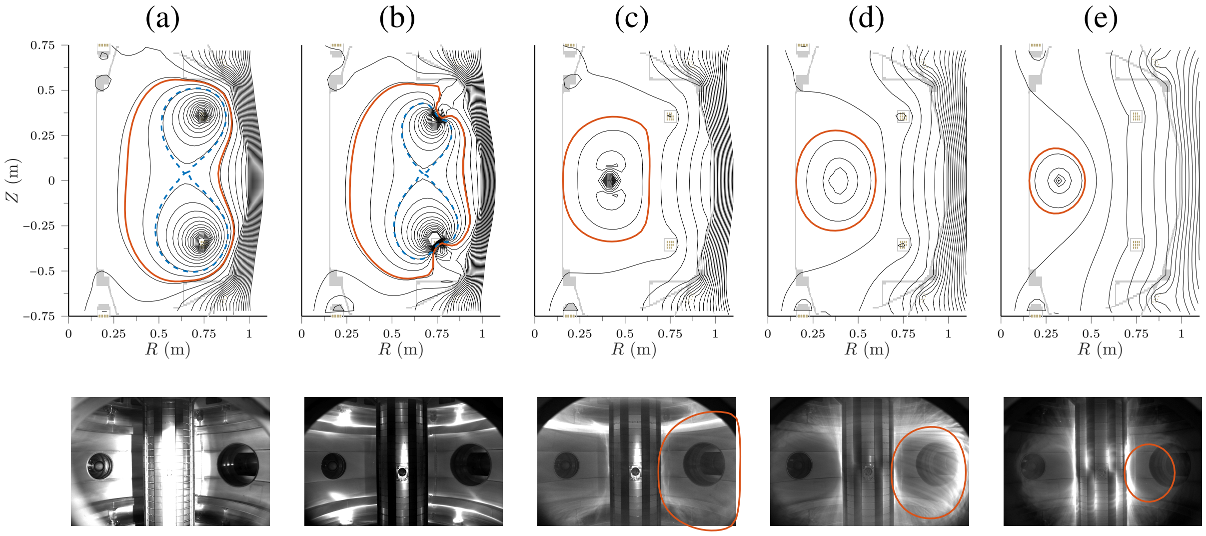

Figure 2: *Compares the magnetic reconstruction to visible camera images for the times (a-e) indicated in figure 1.*

Experimental scaling law for plasma current

To develop a scaling law we need to simplify and parameterize the M/C and plasma current waveforms, figure 3 shows the original waveforms in blue and simplified waveforms in red. Note, we are not interested in the first breakdown, only the second which results in merging and magnetic reconnection. We also indicate three times: t_0 when the gradient of the M/C coil current changes; t_{start} when the plasma current starts rising; and t_{peak} when the plasma current reaches it's peak. The delay $\Delta t = t_{\text{start}} - t_0$ is related to the plasma breakdown which requires a threshold loop voltage, which is delayed by eddy currents flowing within the vessel, and the avalanche which also has a time constant set by atomic physics. By adding pre-ionisation the threshold voltage can be reduced, on ST40 both a flash lamp and the first breakdown plasma are used as pre-ionisation. After breakdown the plasma current increases according to the circuit equations.

We have developed a scaling law which is both dimensionally correct and has a similar form to the circuit equations, when $t > t_{\text{start}}$ and $t < t_{\text{end}}$, the plasma current is:

$$I_{p,\,[\text{kA}]}\left(t\right) = -\int_{t'=t_{\text{start}}}^{t'=t} c_1 \left(\frac{dI_{\text{MC},\,[\text{kA}\cdot\text{Turn}]}}{dt_{[\text{ms}]}}\right) dt' \quad (1)$$

Here, c_1 is the scaling coefficient, and we also need to know t_{start}.

We have not yet found a dependence for the delay time Δt, and in figure 4a we simply plot against pulse number and note that the delay is between 0.5 ms and 1.5 ms. Considering the c_1 constant we find that there is a toroidal field dependence, as seen in figure 4b.

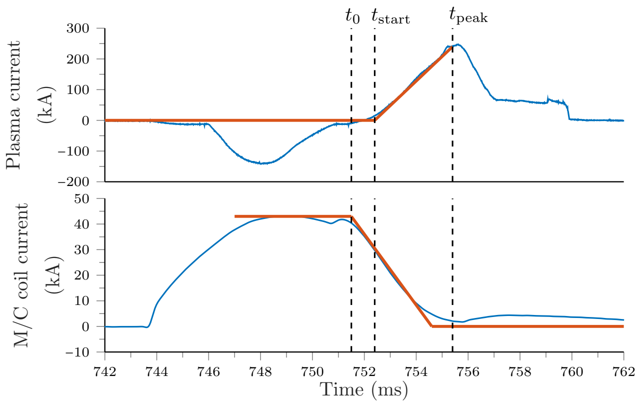

Figure 3: *Shows the plasma current and M/C coil current waveforms in blue. In red we show the simplification, which is used to fit the experimental scaling.*

When the two plasma rings are around the M/C coils the plasma's safety factor is significantly lower than is possible in a tokamak configuration, typically $q \sim 1/8$. This is possible because the rigid M/C coil provides stability, similar to a levitron. The ohmic current driven by a changing poloidal flux (loop voltage), in the toroidal direction is [6]:

$$\underline{J}_{\text{oh}} \cdot \underline{\hat{\phi}} = RB_\phi^2 \sigma_{\text{NC}} V_{\text{loop}} \frac{\left\langle 1/R^2 \right\rangle}{2\pi \left\langle B^2 \right\rangle} \quad (2)$$

In a typical tokamak configuration $B_\phi \gg B_p$, so $B_\phi^2 / \left\langle B^2 \right\rangle \approx 1$, and consequently the toroidal plasma current has virtually no dependence on toroidal field. In the opposite extreme where $B_p \gg B_\phi$ the toroidal plasma current would scale like $\sim B_\phi^2$. Fitting to the optimised pulses we observe a linear, not quadratic dependence of c_1 on the rod current, this suggests that this effect may already beginning to saturate.

We note that in ST40 the M/C coil ramp rate is between 120 and 165 kA ms^{-1}, taking the delaty time to be $\Delta t = 0.7$ and taking the cautious less optimistic extrapolation of $c_1 = 1.1$, allows us to simplify equation 1 to:

$$\max\left(I_{\mathrm{MC},\,[\mathrm{kA\cdot Turn}]}\right) = \frac{1}{1.1}\max\left(I_{p,\,[\mathrm{kA}]}\right) + 100 \tag{3}$$

The constant '100' is a result of the delay time and becomes less important as the plasma current increases.

Conclusions

In the next program of operations both the toroidal field and M/C coil current will be increased. In this paper we have derived an experimental scaling law which is dimensionally correct and has a physics basis to it's form. Using this scaling law we can extrapolate the performance of ST40 in the next program of operations.

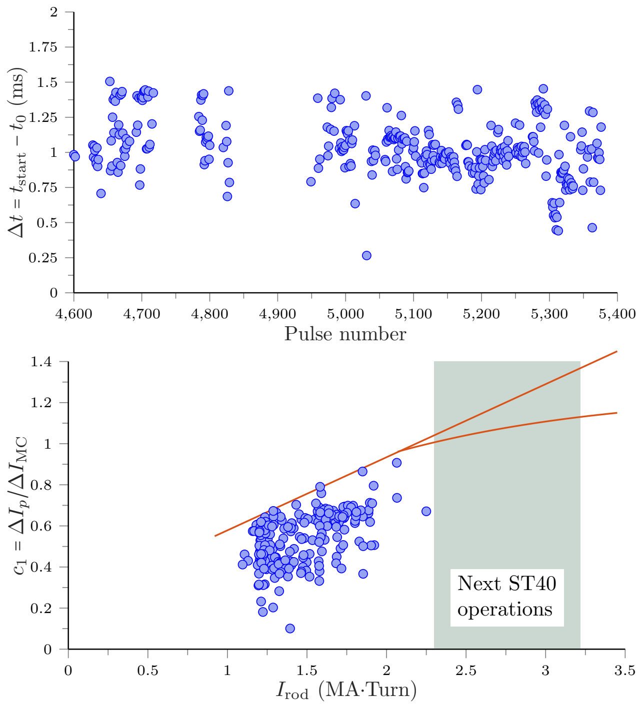

Figure 4: *(a) shows the delay time* $\Delta t = t_{\mathrm{start}} - t_0$ *against pulse number. (b) shows the constant* c_1 *against rod current. Note, both gas timing and vertical field is varying within these pulses, therefore we only concentrate on the highest optimised performance pulses.*

References

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