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Magnetic configuration and plasma start-up in the WEST tokamak

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Introduction

This paper describes experimental findings regarding plasma inductive start-up [1][2] in the first year of operation of the WEST tokamak [3]. The results are interpreted with the help of modelling and compared to criteria for a successful start-up from the literature [1][4]. The focus here is on magnetic configuration aspects. Other aspects, in particular burn-through and runaway electron production, will be discussed in a future paper.

Magnetic field requirements for a successful inductive start-up

A successful inductive start-up begins with a breakdown followed by a rise of the plasma current I_p. For this to happen, the poloidal magnetic field $\vec{B}_p$ needs to fulfill a number of conditions [1][4]. First, the breakdown requires a region of low B_p (a 'field null region') in order for electrons to be accelerated by the toroidal electric field E for many turns before hitting the wall. A quantitative criterion established across many tokamaks is $EL_{eff} > 70$V [4], where $L_{eff} = 0.25 a_{eff} B_t / < B_p >$ is the effective field line connection length, with a_{eff} the minor radius of the field-null region and $< B_p >$ the averaged poloidal field at the null region boundary. Then, the parallel current density j generated by the breakdown should be sufficient to create closed flux surfaces. Finally, plasma radial force balance requires the vertical field B_Z to be ramped up in proportion to I_p, and plasma positional stability requires the vertical field decay index $n \equiv -(R/B_Z)\partial B_Z/\partial R$ to be both > 0 for vertical stability and $< 3/2$ for radial stability [5].

The route to a successful start-up in WEST

WEST [3] is a modification of the Tore Supra tokamak based on adding two in-vessel coils (in red in Figure 1) in order to allow diverted configurations, and changing all plasma facing

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components from carbon to tungsten (W), including actively cooled W monoblocs for the divertor target in order to test the technology to be used in ITER. The divertor coils are inserted inside thick casings (in yellow in Figure 1) which constitute axisymmetric passive conducting structures ($\sim 0.3\mathrm{m}\Omega$ each). In addition, two copper stabilizing "plates" ($\sim 0.1\mathrm{m}\Omega$ each, in blue in Figure 1) were added in the upper and lower region of the vessel to increase the accessible elongation range.

Operation on WEST started in December 2016. Although breakdown was achieved easily from the first days, I_p would not take off in spite of many adjustments of the settings (gas prefill, premagnetization coils currents, power supplies voltages). It was suspected early on that the problem came from induced currents in the stabilizing plates perturbing the $\vec{B}_p$ map. After about two months of operation with no successful start-up in the initial (2 plates) configuration, the lower stabilizing plate was therefore removed in June 2017. One month of operation in this second (1 plate) configuration did not lead to successful start-up either, so in October 2017 the upper stabilizing plate was segmented into 6 pieces to strongly reduce induced currents (it would have been much more difficult to remove the plate). After one month of operation in this third (0 plate) configuration, successful start-up was finally achieved in November 2017.

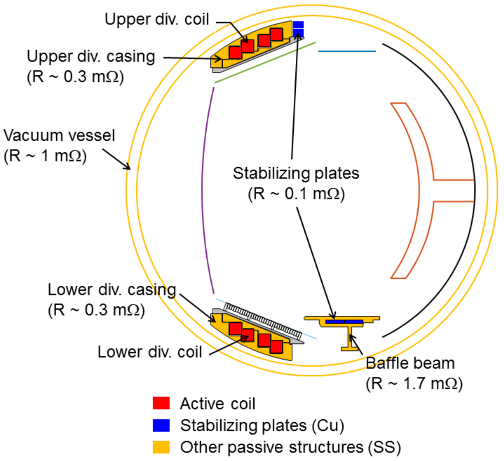

Figure 1: *WEST vacuum vessel configuration*

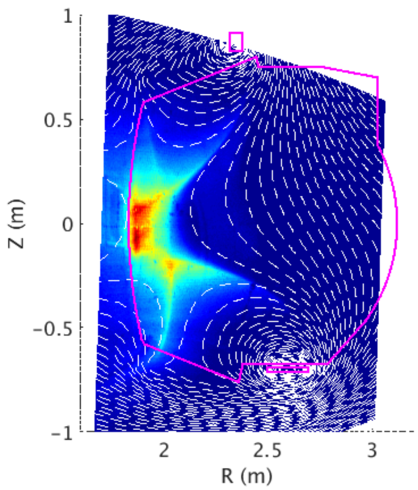

Figure 2: *FEEQS.M magnetic flux contours (white dashed lines) overlayed on a fast camera image for a start-up attempt in the 2 plates configuration (initial currents have been tweaked by* ±100A *in four of the coils in FEEQS.M to improve the match).*

It is important to mention that start-up issues were most likely not due to bad settings but really to machine configuration. Indeed, start-up settings were carefully optimized with the FEEQS.M free-boundary equilibrium code [6] in "plasma-less, inverse time evolution" mode (accounting for the effect of the iron core).

Interpretative modelling method

In order to interprete experimental results, we reconstruct the magnetic field map with two different approaches: direct time evolution of Maxwell's equations with the above-mentioned FEEQS.M code [6], or identification based on magnetic measurements with the FREEBIE-ID code [7]. The two methods give results consistent with each other as well as with fast visible tangential camera images, as illustrated in Figure 2. FREEBIE-ID has the advantage of identifying the plasma current.

Analysis of experimental cases

We now analyze one case from each phase of operation, namely shots 50433 (2 plates), 50874 (1 plate) and 51898 (0 plate). In each case, a successful plasma breakdown was obtained and maintained for 50ms or more, but only in the last case did I_p really take off. In the first two cases, over most of the plasma duration, the light pattern on fast camera images does not show signs of closed flux surfaces. Only for a very brief period of the order of 1ms are closed flux surfaces visible, and they seem to be lost due to a positional instability.

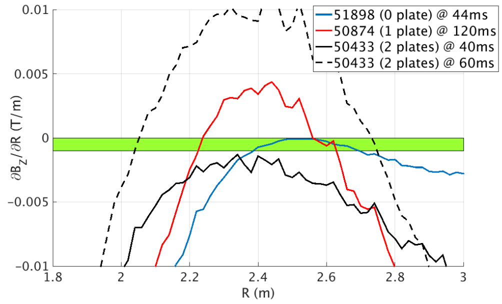

Figure 3: *Profile of* $\partial B_Z/\partial R$ *at the vessel midplane for 3 start-up attempts (see text for details). The green band indicates roughly the positional stability window.*

According to the modelling, the breakdown criterion $EL_{eff} > 70\text{V}$ [4] is fulfilled in all cases (although not with much margin for the 1 and 2 plates cases), consistently with experimental observations. The parallel current density j generated by the breakdown, as identified by FREEBIE-ID, is $\sim 10\text{kA}/\text{m}^2$. The magnetic field created by this j appears marginal to close flux surfaces in the 1 and 2 plates cases, again in agreement with observations (here it is worth mentioning that it took many shot-to-shot adjustments to produce closed flux surfaces in the 1 and 2 plates cases). Finally, positional stability is addressed by Figure 3, which presents, for the three cases, the $\partial B_Z/\partial R$ profile at the vessel midplane calculated by FEEQS.M near the time when closed flux surfaces are visible (plain lines). For the 2 plates case (black), a $\partial B_Z/\partial R$ profile is also shown 20ms later (dashed line) to stress the fast temporal evolution for this case (the other two cases evolve much more slowly). Inserting an estimate of the necessary B_Z for radial force balance [1] at $I_p = 10\text{kA}$ (which is an upper bound according to FREEBIE-ID), the above-mentioned stability criterion becomes $-1\text{mT}/\text{m} < \partial B_Z/\partial R < 0$, which is indicated by the green band in Figure 3. Clearly, only the 0 plate case (blue) fulfills this criterion over a significant region. Once again, this is consistent with fast camera observations of positional instabilities in the 1 and 2 plates cases. We note that KSTAR reported positional stability issues at start-up [8].

Discussion and conclusion

In conclusion, inductive start-up in WEST was hindered by the presence of toroidally continuous copper stabilizing plates inside the vessel. One message of this paper is therefore that the insertion of such structures in future machines should be considered with great caution.

As we saw, the plates did not prevent plasma breakdown but made the closure of flux surfaces difficult, and positional stability apparently impossible. It therefore seems that there was an increasing level of difficulty in meeting the breakdown, flux surface closure, and positional stability conditions. Simple estimates may "explain" this observation. A comparison between the three conditions can indeed be made by rewriting each of them in the form $< B_p > /a_{eff} < X$. The $EL_{eff} > 70$V breakdown condition implies $< B_p > /a_{eff} < 3 \cdot 10^{-3} EB_t \approx 11$mT/m (for typical WEST values $E = 1$V/m and $B_t = 3.6$T). Flux surfaces may close if the poloidal magnetic field generated by the plasma, $\sim \mu_0 \cdot j \cdot a_{eff}/2$, is larger than the vacuum field $< B_p >$, i.e. if $< B_p > /a_{eff} < \mu_0 \cdot j/2 \approx 6$mT/m (taking $j = 10$kA$/m^2$ as suggested by FREEBIE-ID). Finally, if we consider that $|\partial B_Z/\partial R| \sim < B_p > /a_{eff}$, the stability condition at $I_p = 10$kA implies $< B_p > /a_{eff} < 1$mT/m. Therefore, $X_{breakdown} = 11$mT/m $> X_{closure} = 6$mT/m $> X_{stability} =$ 1mT/m.

This hierarchy, although it is clear in WEST, is not universal but depends on the values of E, B_t and j. Of these three quantities, j is obviously the most difficult one to estimate for future devices. During the first year of operation of WEST, j seemed to saturate during the breakdown phase at lower values than those stated in [1][2]. This may be related to poor machine conditioning. Future experiments (with improving machine conditions) and analysis may confirm this hypothesis.

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