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Status and perspectives of MAST start-up in the absence of solenoid flux

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Spherical Tokamak (ST) based Component Test Facility (CTF) or ST Power Plant requires high values of plasma current I_p: nevertheless the I_p start-up and ramp-up have to be obtained without a central solenoid, due to the high neutron flux (there being no space for an effective shield). The use of the poloidal field coils (PF) is one of the most promising techniques to achieve this goal. In fact, the peculiar characteristics of the ST equilibria allow for using the PF coil magnetic flux alone in order to obtain an initial current and for ramping it up to the flat-top value. Among the present large ST devices, MAST is particularly suitable to test those new techniques, due to the large space inside its vacuum vessel that contains all the PF coils. Two different methods has been investigated on MAST: Merging Compression (M/C) and Double Null Merging (DNM).

1. Comparison of M/C and DNM on MAST

In the M/C scheme, first developed on START and successfully used on MAST [1] since the initial phase of the experiment, two plasmoids are formed around the P3 coil, whose current is abruptly ramped down: after that, the use of the other PF coils and the mutual attraction of the two current rings lead to the merging (see Fig. 1b). The low inductance of the final ST plasmas optimizes the effect of the increasing vertical field flux, providing a first ramp-up of the toroidal current I_p, even in absence of central solenoid assistance. The extrapolation of this method to a CTF is not very promising, since it needs coils inside the vacuum vessel that should be shielded from neutrons and that can pollute the initial plasma.

In the newer DNM scheme, first performed on START [2], the two plasmoids should form in the low-order nulls between two couples of PF coils (P2 and P3 in MAST, see Fig. 1c). Those coils – in principle – can be located externally to the vacuum vessel, allowing for a better extrapolation to CTF or ST Power Plant. The break-down is induced by fast ramp-

down of the P2-P3 currents, then – as in the M/C – the two plasma rings are forced to merge by quickly increasing the vertical field and by their mutual attraction.

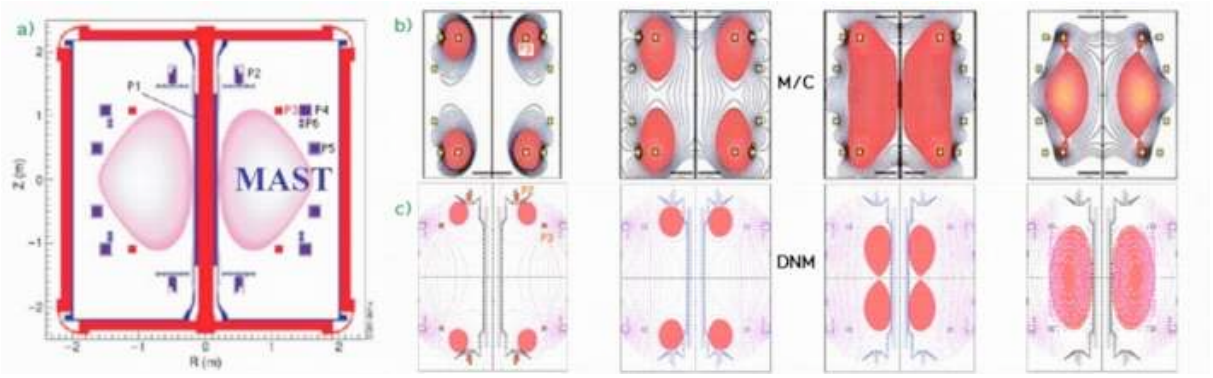

Fig. 1: a) PF coil set-up of MAST; b) equilibrium simulation of M/C; c) the same for DNM

Both techniques give good results [3]. In more detail, a current I_p~400 kA has been obtained with M/C, slowly decaying in ~0.4 s without central solenoid flux. On the other hand, the DNM has been tested by disconnecting the central solenoid and connecting its power supply to the P2 coil, in order to match the fast decrease of the P3 current. Plasma currents up to 370 kA are obtained, which slowly decay in ~0.3 s. Clear evidence of BV ramp-up effects are observed: increasing the vertical field can yield a I_p~300 kA flat-top (with no decay) of about 100 ms and also the final plasma external radius is larger with respect to the lower BV discharges. The ST plasmas have high temperatures (peak T_e~0.5 keV) and densities (peak $n_e \sim 9 \bullet 10^{19}$ m^{-3}). Either M/C or DNM plasmas represent a good target for NBCD, opening the possibility (when enough NBI power will be operative on MAST) to produce and sustain a full non-inductive plasma with toroidal current of the order of 700 kA. The major difference of DNM plasmas with respect to the M/C ones is the independence of the final toroidal current upon the initial P3 current (see Fig. 2c): a variation of I_{P3} of more than 30% does not show any effect on the final I_p in DNM experiments, on the contrary $I_p \propto I_{P3}$ for M/C both in MAST and in START.

A magnetic reconstructions of the M/C and DNM plasmas in the early stages of their formation has been performed. The magnetic analysis is complicated by the presence of strong eddy currents on the passive machine elements, which are difficult to take into account in the present EFIT version working on MAST. For the early phase of the discharges, it is necessary to determine and subtract the passive current effects from the magnetic signals. This is possible only by pre-analyzing a “zero-shot”, i.e. a shot with the same waveforms of the PF coil currents but without plasma current (no gas puffing). A spherical multipolar

expansion [3] of the flux function ψ is used in the magnetic reconstruction. The combined analysis of "zero" and "plasma" shot determines (through a best-fit of the ~100 magnetic sensor signals) the input data for the Grad-Shafranov plasma equilibrium solver [4]. In this solution, the functional forms of the kinetic pressure and of the diamagnetic current are fixed ($P(\psi) \propto \psi^{0.5}$, to allow for hollow pressure profiles, and $I_{dia}(\psi) \propto \psi^{0.5}$). A cross-check with the EFIT reconstruction at later time slices (typically t>16 ms) shows good agreement between the two codes, while the obtained plasma shapes match well with the visible light measurements during the early formation phase. In Fig. 2 the magnetic reconstruction of a typical M/C discharge is compared with one of a DNM shot.

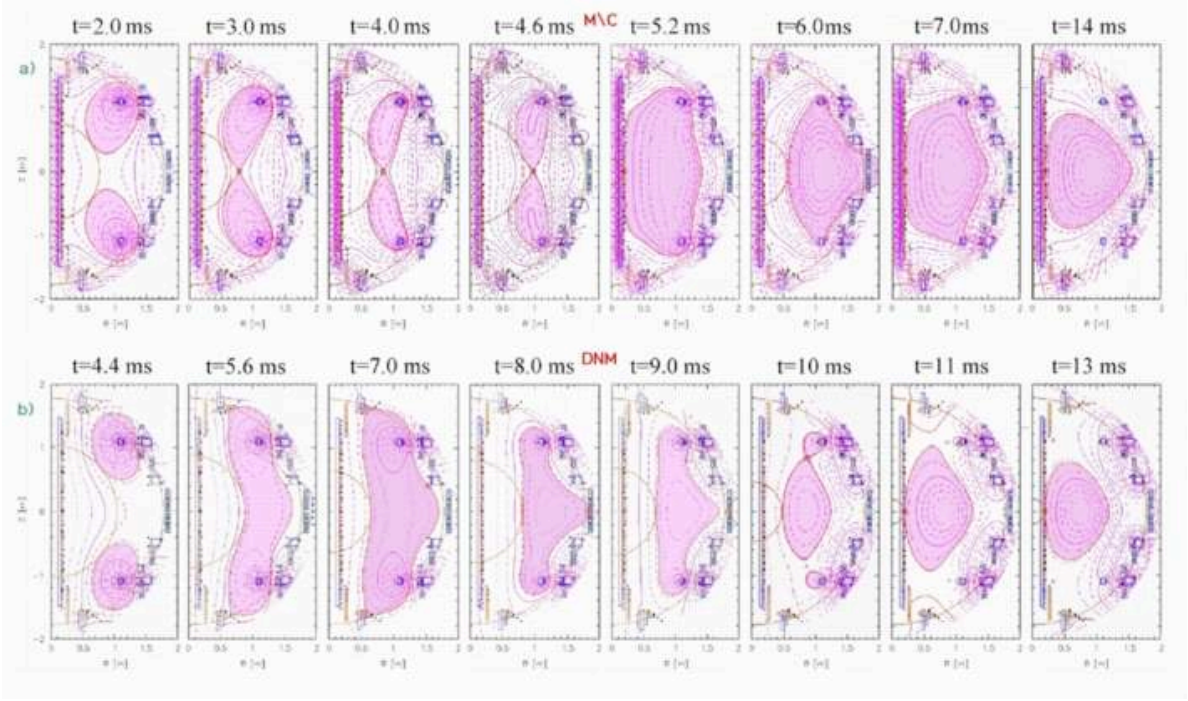

Fig. 2: a) equilibrium reconstruction for M/C MAST shot 14412; b) the same for DNM shot 13198

It is quite clear that, in both cases, the initial plasmoids form around P3, therefore a proper DNM has not been obtained on MAST in its present configuration. Probably the reason of such behaviour is the poor quality of the null between P2 and P3 (low multipolarity and small zone of vanishing poloidal field): the very high loop voltage near P3 (~100 V) causing a break-down around these PF coils. Nevertheless DMN discharges appear different from M/C. Magnetic reconstruction shows that, during the M/C start-up, a real merging of the two plasmoids happens (see time slices t=3-4.6 ms in Fig. 2a). On the contrary, DNM start-up seems to show a secondary break-down on the midplane (t=5.6 ms in Fig. 2b) in which a large high multipolar null is present at the beginning (t=4 ms, again in Fig. 2b): this phenomenon could explain the I_p dependence on the vertical field and its independence from I_{P3}.

2. Perspectives of non-solenoid start-up on MAST

Two possible ways for obtaining start-up without central solenoid flux on MAST have been proposed. The first one (that does not imply any hardware modification) is to try a true DNM by forming the plasmoids at the X-point obtainable between P3 and P5 (see Fig. 3), and pushing them away to assist the merging by employing the P4 coil. Nevertheless the possibility that break-down still occurs around P3 is not eliminated since the null quality is again quite poor. A second possibility – that implies hardware implementation on MAST – arises from the consideration that in the present "DNM" discharges the role of the two toroids born around P3 is simply to provide a strong bulk ionization to the equatorial null.

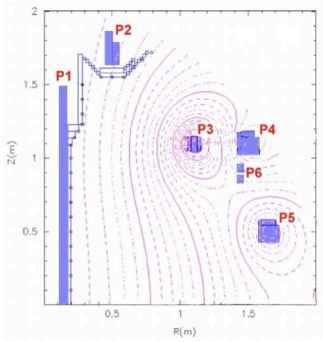

Fig. 3: Low order null between P3 and P5

The same effect should be obtainable by forming an arc discharge flowing from a low voltage (~100-200 V DC), located on top of the higher P3, extending on the equatorial plane up to the high multipolarity null obtained with a combination of current in the PF coils, and ending upon a grounded hot cathode, lower than the bottom P3 (see Fig. 4). An arc current of the order of I_{arc}=3 kA should be easily obtainable and could sufficient to provide the requested pre-ionization. A simulation of such a kind of start-up is shown in Fig. 4.

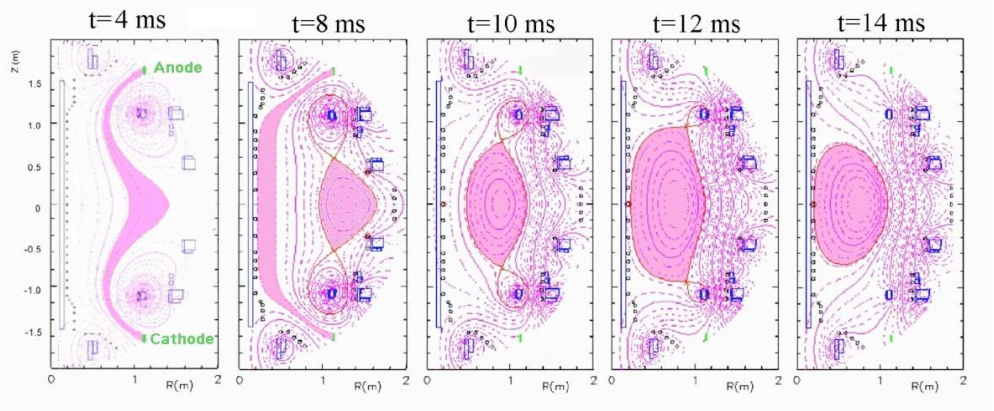

Fig. 4: Simulation of the electrode-assisted start-up

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[1] SYKES, A., et al., Nucl. Fusion **41** 1423 (2001)
[2] GRYAZNEVICH, M., et al., Proc. 21st EPS Conf. on Pl. Ph. and Control. Fusion, Montpellier, 1994, ECA, Vol. **18B**, pt.1, p.22
[3] SYKES, A., et al., 32nd EPS Conference on Plasma Phys., Tarragona, 27 June – 1 July 2005 ECA Vol. **29C**, P-4.112 (2005)
[4] ALLADIO, F. and MICOZZI, P., Nucl. Fusion **37**, 1759 (1997)