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Plasma current formation in MAST without use of central solenoid

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Designs of a Spherical Tokamak Component Test Facility (CTF) or ST Power Plant feature high plasma currents but a central solenoid is not possible due to the high neutron flux (there being no space for an effective shield). However the design and the equilibrium properties of an ST lend themselves to novel techniques both for obtaining an initial current, and for ramping it up to the operational value.

Two methods of initial start-up which do not require use of the central solenoid have been tested on MAST, and are described in this paper. The merging-compression (M-C) scheme, pioneered on START, is routinely used on MAST and can generate ST plasmas of 0.4MA (Section 1). The novel 'Double Null Merging' method (DNM) also appears very promising and plasma current of 340kA has been generated on MAST (Section 2).

1. Merging – Compression start-up

Further studies have been made of the 'merging – compression' process used to initiate most MAST discharges. In this process plasma rings form around the P3 coils (see Fig 4 for coil layout), merge, and then are compressed to form the ST plasma. It is found that, over the range of P3 coil currents available, the final plasma current is linearly proportional to the P3 coil current (Fig 1). However the thermal energy of the plasma just after compression appears to be a quadratic function of the P3 current (Fig 2).

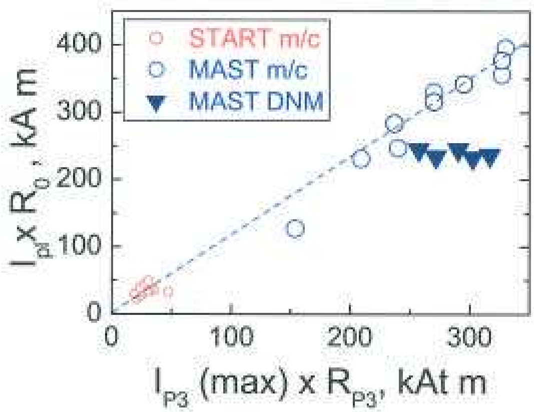

Fig 1 *Plasma current vs. induction coil current on MAST and START (normalised to major radius and coil radius). For M-C, I_{pl} is proportional to induction current*

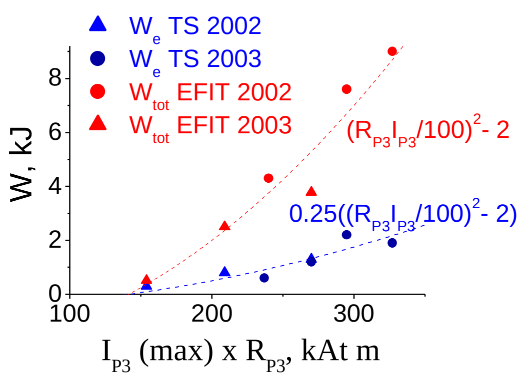

Fig 2 *Electron energy (from Thomson scattering) and total energy (estimated from EFIT) for M-C in MAST, evaluated at 12ms (just after M-C)*

Plasma merging experiments at Princeton and Tokyo [1,2] show large increases of ion temperature during merging, attributed to transfer of magnetic energy to thermal energy during the reconnection. Most recently [3], experiments on TS-3/4 on merging spheromak and spherical torus plasmas show that ion heating is maximum for the spheromak, and decreases with toroidal field. On a 10μ-sec timescale during tokamak merging the thermal ion temperature in TS-3/4 increases from ~15eV to ~50eV, whereas the electrons remain at around 15eV. Estimates of total thermal energy in MAST made using EFIT also suggest (Fig 2) that the ions in MAST are hot; however measurements on MAST using Thomson scattering (for electrons) and

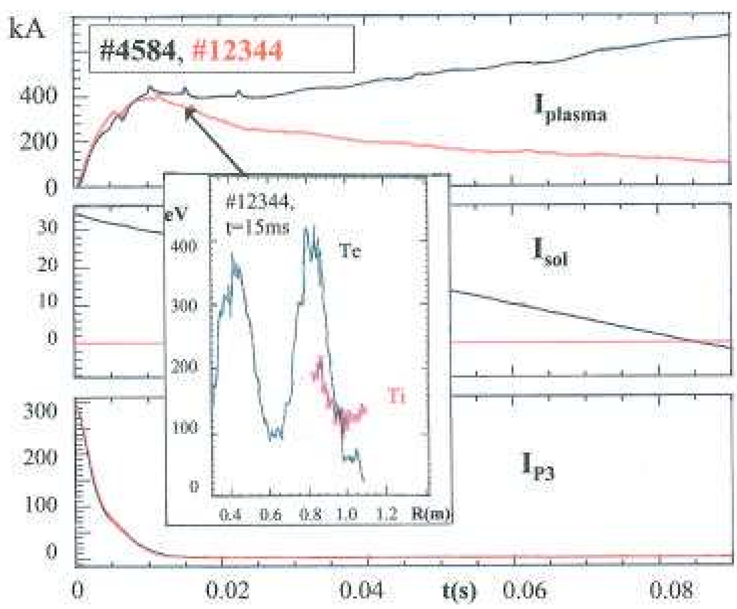

Fig3 *The M-C process on MAST, both with (black) and without (red lines) the central solenoid. Without the solenoid, the initial plasma of 400kA decays away over ~300ms. Electron and ion temperature profiles just after merging are shown (inset).* T_e *is hollow (*T_i *is only measured in the outer region). The density profile is peaked with central electron density ~* $5x10^{19}m^{-3}$

Charge Exchange Recombination Spectroscopy (in fully stripped carbon, for ions) show (see inset in Fig 3) comparable temperatures at the 200eV level for both ions and electrons; at the longer timescales of merging (~ms) and high densities (~$5x10^{19}m^{-3}$) on MAST, ion heating may have dissipated. More detailed studies of the merging process, including an examination of possible high-energy ions (as observed following other reconnection processes on MAST) are in progress. In addition, improved wall modelling is being developed to improve the accuracy of EFIT during the plasma formation stage, where eddy currents (induced by the rapid swing in P3 current) can be large.

The Merging-Compression process is shown to save considerable volt-seconds of flux which otherwise has to be supplied by the central solenoid. The saving depends on the internal inductance and stored energy of the plasma, the ramp rates used and the auxiliary heating applied, but is typically 0.14 – 0.22Vs (the total presently available from the solenoid is ~0.8Vs). Improvements to the process are under consideration, in the form of a larger capacitor bank which would increase the P3 current, and the use of slim-line P3 coil supports to reduce losses during formation.

Data from both START and MAST provide an empirical scaling for the M-C process. If we assume a fraction f of the OH coil current (P3 in MAST) is converted into the initial plasma ring current, and that the compression in major radius increases plasma current as 1/R, we derive the empirical scaling $I_{plasma} = (f \times 2 \times I_{OH}) \times R_{OH}/R_0$. On START an OH coil swing of 85kAt in each coil produced a merged plasma of 140kA after compression from 0.35m to 0.25m, giving f = 0.59. On MAST, a P3 swing of 300kAt in each coil produces a merged ST plasma of 480kA after compression from 1.1m to 0.8m: giving f = 0.58. This scaling suggests that the induction coils should be at large radius to maximise the compression effect, which would both amplify the plasma current and produce adiabatic heating, as demonstrated on the ATC (Adiabatic Toroidal Compressor) tokamak [4].

Applicability of M-C to a fusion device such as a CTF is debatable. The scheme itself is very robust but the start-up coils need shielding from the final D-T plasma.

2. The DNM scheme

A scheme suggested [5] by the TS-3/4 team at Tokyo appears promising, in that it combines high flux input, with plasma merging with associated plasma heating: plasma is formed in low-order nulls, which are inside the vacuum vessel whereas the coils that produce them are outside.

This 'Double Null Merging' (DNM) concept has been tested on MAST, albeit using internal coils, by forming nulls between the P2 and P3 coils as shown in Fig 4 :

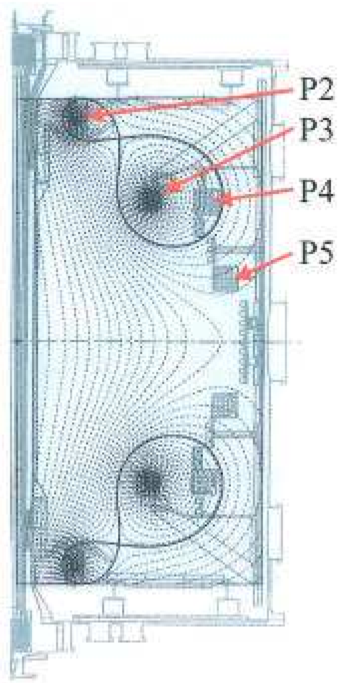

Fig 4 *Half section of MAST, showing location of main poloidal field coils and DNM equilibrium. The quadropole nulls between P2 and P3 have* $|B|$ *< 0.008T over a diameter of 12cm*

Although low order (quadropole) nulls of this type are not generally used in tokamaks, experiments on MAST show that breakdown can be obtained provided that the local loop voltage exceeds ~2.5V and that the P2, P3 and P4 currents are adjusted to give a suitable null position.

High Speed Video cameras confirm that the initial plasma forms in rings centred between the P2 and P3 coils, the rings being limited by the nearby graphite surfaces. The next stage is to merge these two rings together on the midplane. In the present MAST coil configuration this is difficult as the remaining PF coils in MAST (P4 and P5) are at lower height than the plasma rings, so applying field from them will not aid merging. However it is found that merging can occur if the P2 current is reversed after the formation of the rings.

After optimisation, ST plasmas with currents of up to 340kA have been obtained. Waveforms and plasma temperatures are very similar to those produced by the M-C process shown in Fig 3; however the plasma current obtained is now independent of the current in P3, as shown in Fig 1, provided this lies within limits required to produce a suitable null for breakdown.

Summary and future plans

The two schemes (M-C and DNM) show promise for start-up in non-solenoid ST fusion devices. They combine high flux input with plasma merging, which may provide plasma heating. Modelling, supported by results from MAST, indicates that application of high power NBI heating to an established high confinement ST plasma necessitates a large increase in vertical field required to maintain equilibrium, providing significant flux [6]. This should enable the initial plasma current to be sustained and indeed ramped up, as indicated in Fig 5.

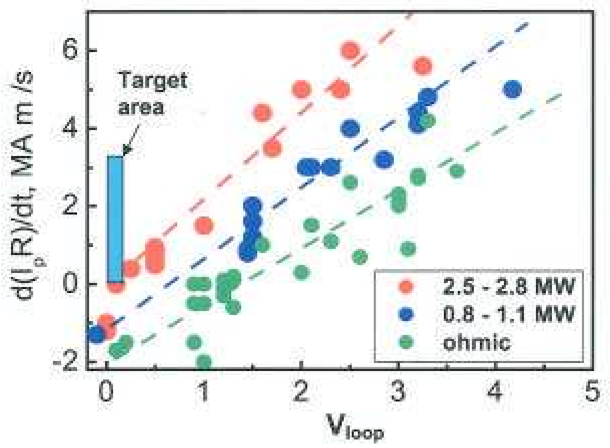

Fig 5 *MAST results: for these established H-mode discharges, current ramp rate increases, at given solenoid loop voltage, as NBI power increases. These results suggest that for injection powers greater that 3MW in MAST, positive current ramp can be achieved even at zero solenoid loop voltage.*

It is planned to apply high power NBI (up to 5MW) later in 2005, with plans for significant increases later. In addition, a variant of the DNM scheme, based on breakdown in nulls between the P3 and P5 coil pairs, is also to be tested: this should combine the advantages of DNM with improved control from the nearby P4 coil.

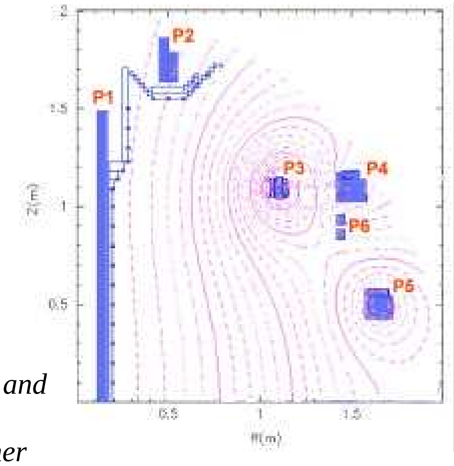

Fig 6 Proposed DNM based on a null between the P3 and P5 coils in MAST. The initial plasma rings would be limited against the P6 coil before being pushed together by field from the P4 coil.

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