TSC - Modelling of MAST - Discharges and of High $\beta_p$-States in Tight Aspect Ratio Plasmas

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1 Introduction

The properties of spherical tori such as natural elongation, paramagnetism, a natural divertor configuration and a strong bootstrap effect point toward a considerable improvement of the tokamak performance at tight aspect ratios. In particular, a large plasma current at a low toroidal magnetic field and an improvement of the confinement due to the decorrelation of microinstabilities by enhanced $\vec{E} \times \vec{B}$ drift seem to possible.

The just mentioned properties have evoked considerable interest in experiments as MAST [2] and also in future large ST’s (‘LST’ [3]). On the basis of the MAST data [2] the attempt is made to describe numerically the evolution of the equilibrium and transport parameters of the MAST plasma. Also the evolution to high $\beta_p$-States needed in large devices as a prerequisite for ignition is considered.

The numerical tool is the the TSC - code [1] which is briefly described in the next section.

2 TSC - Code

Because of axisymmetry the magnetic field $\vec{B} = \nabla \phi \times \nabla \Psi + g \nabla \phi$ may be decomposed in a poloidal part described by the two dimensional flux function \( \Psi \) and a toroidal part determined by the one dimensional toroidal field function \( g \). The plasma motion follows from the force balance connecting the momentum density $\vec{M} = m_h n \vec{v}$ with the pressure gradient $\nabla p$, the current density $\vec{j}$, the magnetic field $\vec{B}$, and the viscosity force density $\vec{F}_\nu$ which is decomposed in an incompressible and a compressible part. Neglecting plasma inertia the force balance reads \( \frac{\partial \vec{M}}{\partial t} + \vec{F}_\nu(\vec{M}) = \vec{j} \times \vec{B} - \nabla p \). The momentum density $\vec{m}$ = $\nabla \phi \times \nabla A + \omega \nabla \phi + \nabla \Omega$ is decomposed into a poloidal part (with stream function \( A(R,z) \)), a toroidal part, described by the function \( \omega \), and a gradient part derived from the scalar function \( \Omega \). The force balance equation and the remaining Maxwell - MHD equations are advanced by a two dimensional, time dependent, free boundary computational scheme. The circuit equations for the poloidal field coils are coupled to the Maxwell - MHD equations for the plasma via the boundary conditions.

The plasma description in TSC is completed by using e. g. the semi-empirical Coppi - Tang model for the heat conductivities with $a_{CT}$ as adjustable coefficient.
3 Results concerning MAST and LST

The modelling by TSC is in general based on geometrical device - data and on initial plasma parameters. The geometry (Fig. 1) of the 'MegAmp' Spherical Tokamak (MAST) [2] may be characterized by the dimensions of vessel cylinder (height \( H_V = 4.4 \) m, radius \( r_V = 2 \) m) the positions of the vertical field coils (P4, P5), of the induction coil (P3), the divertor coil (P2) and of the primary solenoid (P1). The geometry of the flat top plasma of shot \# 2482 is determined by the half axis \( a \approx 54 \) cm and the major radius \( R_0 \approx 74 \) cm, the elongation \( k \approx 1.9 \), and the triangularity \( \delta = 0.3 \) (Fig. 1). The initial data are obtained (except shot \# 2898) from the final state of the merging - compression (MC) phase discussed below (e. g. creating a plasma with the large current \( I_p \approx 300 \) kA).

Shot \# 2482 [4] demonstrates the ability of MAST to reach 1 MA by first using the MC - method and then applying induction by the primary solenoid which increases the current to 1 MA (Fig. 2). The maximum electron temperature (Fig. 3) in the TSC simulation evoloves to around 1.3 keV \((a_{CT} = 0.08)\). This value is somewhat larger (20\%) than the corresponding experimental one. Larger transport coefficients \((a_{CT} \rightarrow 0.16)\) lead to a better approximation of the experimental maximum electron temperature; however, the maximum current in the primary P1 becomes considerably larger (almost by a factor 2 for \( a_{CT} = 0.16 \)) than the experimental one. The choice \( a_{CT} = 0.08 \) effects both, providing the computed primary current and the maximum electron temperature close to the corresponding experimental values. Besides the 1 MA - shot \#2482 the following shots with similar shape parameters during the flat top phase as in Fig. 1, but different plasma current and temperature evolutions were considered; the main results can be summarized as follows:

1. Shot \#2274: Here the current produced during the MC - phases is increased by means of the primary to its maximum of \( \approx 460 \) kA. Either the maximum plasma current or the the maximum primary current are reproduced within an accuracy of 15\% for \( a_{CT} = 0.16 \). The electron temperature exceeds the measured one by around 20\%. Neglecting the impurities might be the reason for this discrepancy.

2. Shot \#2700: This is a shot with improved confinement, i.e. \( a_{CT} = 0.08 \) allows to reproduce the maximum electron temperature within a margin of around 5\% and the currents within 20\%. The improved confinement might be a prerequisite for the H - mode observed (experimentally) in a later phase of this shot.

3. Shot \#2875: In this shot a hollow temperature profile was seen which, however, cannot be reproduced by the code because it may be caused by impurities which are not included. \( a_{CT} = 0.16 \) is needed for an approximate reproduction of the electron temperature. This may be explained by the above - mentioned impurities reducing the confinement time.

4. Shot \#2898: The merging - compression - method is not used, the direct induction by the primary solenoid is used instead. Therefore a larger current swing of the primary is needed to get the same plasma current. In fact, this is reproduced in a simulation with plasma position control.

5. The 2d - simulation of the 'merging - compression' method (shots \#2274, \#2700, \#2482, \#2875) leads to a plasma current of \( \approx 300 \) kA and to a vessel current of \( \approx 2 \)
400 kA. This phase comprises the initialization of the coil currents (essentially \( J_{P3} \)) and that of the vessel current density. The breakdown around the coils occurring experimentally prior to the generation of the central plasma cannot be modelled, a small central plasma is assumed instead. This evolves to a large plasma (also around the P3 - coils) and finally to a centered 300 kA plasma.

The main results concerning an LST \(^3\) with the plasma current \( I_p \approx 2.5 \) MA, aspect ratio \( A = 1.2 \), major radius \( R_0 = 156 \) cm, center post current \( I_{cp} = 3 \) MA and the NBI - power \( P_n = 90 \) MW, may be summarized as follows:

The time evolution of the toroidal magnetic field is shown in Fig. 4. This field evolves from the paramagnetic state to the diamagnetic state. The paramagnetism at \( t = 0 \) enhances the vacuum magnetic field by a factor \( \approx 2 \). During the flat - top phase the toroidal field goes down to \( \approx 0.2 \) T at \( R = 2.25 \) m thus becoming lower than the vacuum value by a factor 2.

The maximum value of \( \beta_{vac} \) is \( \approx 0.4 \). Since the Troyon limit \( \beta_T = 0.51 \) \(^3\) is not exceeded it is possible to reduce the centerpost current somewhat.

4 Summary and conclusions

One aim of the TSC - modelling of MAST is to reproduce the data obtained after the merging - compression phase during the induction phase. In general there is reasonable agreement of most of the experimental data with the modeling. In particular the H -mode enhancement of the confinement time can be reproduced.

Another aim is to understand the processes of the merging - compression phase qualitatively. Although the 'resonant stellarator phase' is neglected, the build up of the central plasma roughly agrees with the observation.

Due to the low toroidal field the transition from paramagnetism to diamagnetism is an important effect in a 'LST'. It can reduce the toroidal field to roughly 50% of the vacuum value.

References


