TSC - Simulations of MAST - Discharges without Primary Current Swing

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Abstract

We deal with a novel method for current maintenance recently applied to MAST during the heating phase: induction by means of the vertical field coils which serve two purposes: (1) to maintain the plasma equilibrium and (2) to provide the flux-swing to keep the plasma current approximately constant.
On the basis of the MAST data, the TSC code, accounting e.g. for the bootstrap current and additional heating, is used to describe numerically the evolution of the equilibrium and transport parameters of the MAST plasma during the current rise and the NBI phase. The vertical field and divertor coil currents, the injection power and the power deposition profile are prescribed. The simulations show e. g. the following: 1. If the primary current is also prescribed according to the experiments, the plasma current can be reproduced with an accuracy of 10% and the central temperature with an accuracy of 15%. 2. In runs with plasma current control the primary current is computed by means of a feedback; this current deviates from the experimental one by around 15% of its maximum value.

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 be possible.

The just mentioned properties have evoked considerable interest in experiments as MAST [1] and also in future large ST's.

However, the limited flux-swing of the small primary solenoid may not allow long pulse durations, and a solenoid may not be present in fusion power devices. Therefore current drive methods such as NBI current drive, LH current drive and use of high bootstrap current, had been envisaged.

When the β_p increases due to plasma heating, an increase in the vertical field is necessary to maintain the plasma radial position. This increase in vertical field supplies additional poloidal flux and thus an effective loop voltage to the plasma, which (in conjunction with the increasing bootstrap current) has been shown experimentally to sustain the plasma current without input from the central solenoid. This was achieved

on MAST by first obtaining a plasma by means of the merging compression scheme, then ramping up the current by using the central solenoid, and thereafter holding the solenoid current constant. The application of NBI triggers access to H-mode confinement and hence a rapid increase in plasma energy, producing an increasing bootstrap current and requiring a significant increase in vertical field. On the basis of the MAST data [1] the attempt is made to describe numerically the evolution of the equilibrium and transport parameters of the MAST plasma.

The numerical tool is the the TSC - code [2] 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 Ψ 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 $\vec{M} = m_i n\vec{v}$ with the pressure gradient ∇p, the current density $\vec{j}$, the magnetic field $\vec{B}$, and the viscosity force density $\vec{F}_{\vec{v}}$ which is decomposed in an incompressible and a compressible part. Neglecting plasma inertia the force balance reads $\frac{\partial\vec{m}}{\partial t} + \vec{F}_{\vec{v}}(\vec{m}) = \vec{j} \times \vec{B} - \nabla p$. 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 ω, and a gradient part derived from the scalar function Ω. We project the force balance equation into three scalar subspaces by applying the operators $\nabla\cdot$, $\nabla\phi\cdot\nabla\times$ and $\nabla\phi\cdot$ on this equation and get three equations describing the time evolution of A(R,z), ω and Ω. Assuming $\frac{\partial A(R,z)}{\partial t} = \frac{\partial\omega}{\partial t} = \frac{\partial\Omega}{\partial t}$ we retrieve the Grad - Shafranov equation. 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.

To compute the flux surface averaged thermodynamic quantities we use a toroidal coordinate system moving with the flux surfaces. Then we average over the flux surfaces. For the differential total entropy density $\sigma = p(\frac{\partial V}{\partial\Phi})^{\frac{5}{3}}$, we get e.g. (p is the total pressure)

$$\frac{\partial}{\partial t}\sigma = \frac{2}{3}\{\frac{\partial V}{\partial\Phi}\}^{\frac{2}{3}}[V_L\frac{\partial K}{\partial\Phi} - \frac{\partial}{\partial\Phi}(Q_i + Q_e) + \frac{\partial V}{\partial\Phi}(S_e + S_i)] \tag{1}$$

Here the differential volume is given by $\frac{\partial V}{\partial\Phi} = \frac{\partial}{\partial\Phi}\int d\tau = \frac{1}{q}\int\frac{dl}{B_p}$. Γ, Q_e, Q_i, S_N, S_e, S_i and $Q_{\Delta e}$ are the particle, the electron heat flux, the ion heat flux, the particle source, the electron energy source, the ion energy source and the classical equipartition term [2], respectively. V_L is the loop voltage and K the total toroidal current within a prescribed flux surface. 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 and Conclusions

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) ([1], [3]) 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 # 4571 (which stands here as a specific example for a series of shots, e. g. #4172, #4180) 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 from the final state of the merging - compression (MC) phase discussed below (e. g. creating a plasma with the current $I_p \approx 250$ kA). Shot # 4571 [1] demonstrates the ability of MAST to increase the plasma current to 690 MA and to maintain it for 200ms (Fig. 2). The desired (experimental) current (I_d) and the computed current (I_s) differ by around 10%, since the 'bump' in I_d at 200 ms cannot reproduced. The maximum electron temperature (Fig. 3) in the TSC simulation evolves to around 1.2 keV (a_{CT}=0.04). This value is somewhat larger (10%) than the corresponding experimental one. Larger transport coefficients ($a_{CT} \to 0.08$) lead to a better approximation of the experimental maximum electron temperature; however, the deviation between the simulated and the experimental plasma current becomes considerably larger.

The time evolution of the primary current in the preceding simulation follows almost exactly the time evolution of the experimental one. However, if the plasma current is controlled and follows the experimental dependence, the primary current has the evolution of Fig. 4. which shows the 'almost' constancy of the primary current. (TSC - units had been chosen in Fig. 4, the conversion factor is 0.45.) Due to the imperfections of the model the maximum deviation from the experimental current is around 20% of the maximum current.

The main aim of the TSC - modelling of MAST is to reproduce the data of the induction phase by the primary and of the induction phase by the vertical field coils. In fact, it is possible to reproduce the plasma current during current rise phase almost exactly and during the current maintenance phase by means of the vertical field coils approximately. Thus the efficiency of the induction by the vertical field can be demonstrated by TSC as well. The calculation may be checked by prescribing the plasma current and computing the primary current. This procedure approximately reproduces the constancy of the primary current.

References

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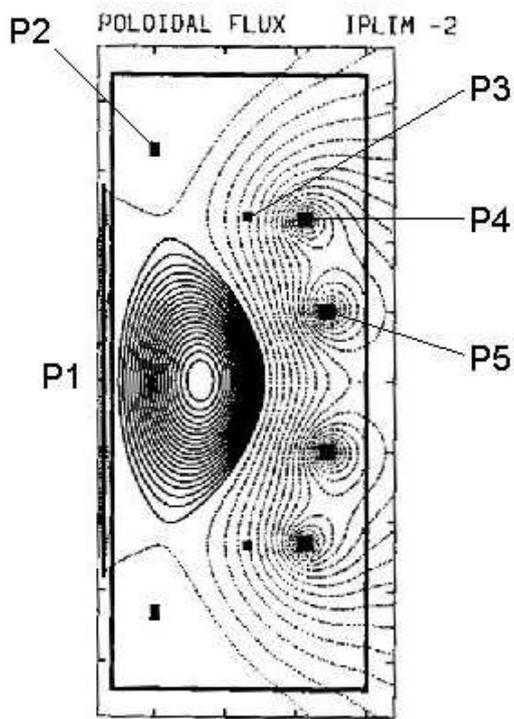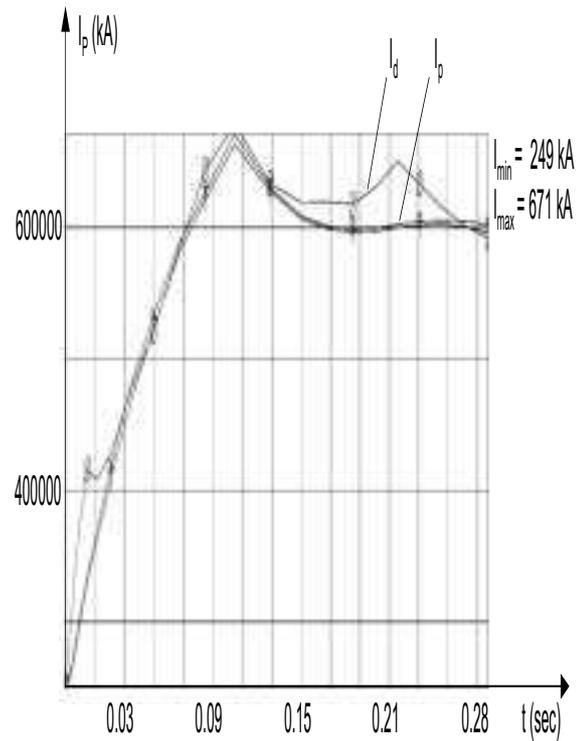
Fig. 1: Geometry of MAST

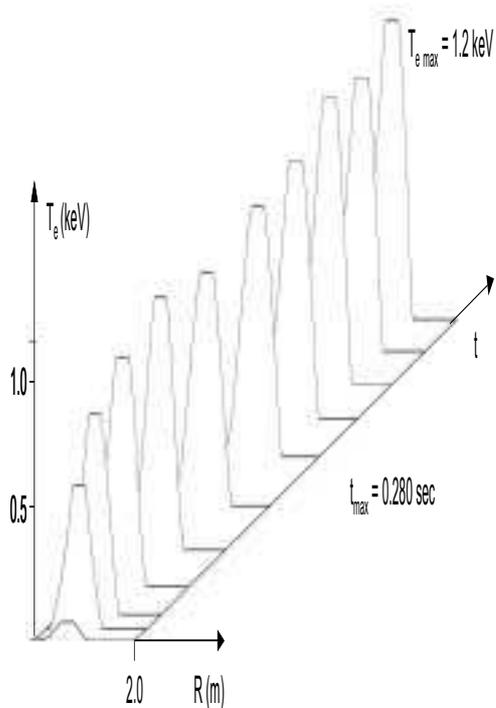Fig. 2: Evolution of the designed (I_d) and the computed current (I_p)
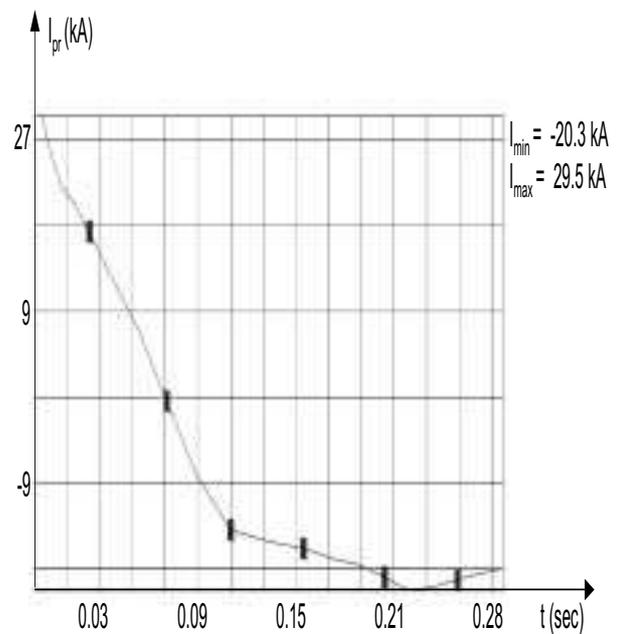

Fig. 3: Evolution of the electron Temperature T_e

Fig. 4: Evolution of the primary current I_{pr}

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