Disruption Analysis on Tore Supra using a Fast Equilibrium Code

F. Saint-Laurent, G. Martin, F. Sourd

Association EURATOM-CEA, CEA/DSM/DRFC,
CEA-Cadarache, 13108 Saint-Paul-Les-Durance (France)

1 - INTRODUCTION

The localization of runaway electron impacts during disruptions is of major importance on Tore Supra: the actively cooled first wall, made of stainless steel, must be locally protected against possible damages. Due to its circular shape, disruptions are moving horizontally generally towards high field side. In the CIEL configuration, the toroidal pumped limiter (TPL) is a toroidal conducting ring located at the bottom of the vacuum vessel. During disruptions, the plasma flux variation induces huge current in the TPL that strongly modifies the magnetic flux map and consequently the plasma displacement. Eddy currents generated in the actively cooled elements located in front of the magnetic captors might also influence the trajectory.

In order to study this plasma displacement, we have developed a fast equilibrium code (MAESTRO) which takes into account these induced currents. From magnetic measurements (radial and tangential magnetic field components on a circular poloidal shape taken as the reference surface), which define boundary conditions, a finite difference method is used to calculate the flux map inside the reference surface.

2 – MAESTRO CODE

The MAESTRO code solves the Grad-Shafranov equation assuming an axisymmetric geometry, using a mesh of square elements and boundary conditions (flux and tangential field $B_{th}$ components on a reference surface closed to the captors) given by magnetic measurements. So a ferromagnetic model for the iron core of the machine is useless, and no attempt is made to reproduce the PF coil currents. The plasma toroidal current profile is parameterized using

$$J_\Psi = \lambda \cdot \left( \frac{R}{R_o} - \delta \cdot \frac{R}{R_o} \cdot (1 - \delta) \right) \left( 1 - \Psi \right) ^\alpha,$$

where $\Psi$ is the normalized flux (0 on magnetic axis, 1 on the boundary), $\lambda$ is a normalization parameter constrained by $I_p$, $\delta$ a free parameter related to the kinetic pressure, ie to the measured $\beta_{diam}$, and the peaking free parameter $\alpha$ being adjusted in order to minimize the $\beta + l_s/2$ parameter measured on the reference surface. The code structure is shown on the figure 1. After an initialization stage, a best guess of the plasma localization and of the peaking parameter is assumed to start the main loop on time slit measurements. $\lambda$ and $\delta$ are fixed from $I_p$ and $\beta_{diam}$ measurements. Due to the lack of captors closed to the TPL, a direct treatment of boundary conditions including the large TPL current is not precise enough. So a subtraction of the TPL current contribution to the flux and $B_{th}$ is firstly performed before to solve the differential equation system, and then the flux distribution of the TPL current is added to recover the full flux map. Then the
plasma localization is found, the Shafranov integrals on reference surface are computed, and a new toroidal current profile is determined. A first convergence test is performed to align current and flux distributions, and a second one to convergence on the $\beta + l_n/2$ parameter. A poloidal distribution of eddy currents $I_{\text{ed}}$ (with the constraint of a null integral over poloidal angle) localized in the actively cooled panels in front of magnetic captors can then be estimated from the remaining difference between measured and calculated $B_{\text{th}}$.

MAESTRO is a Matlab$^\text{TM}$ script using the standard toolboxes. Two versions were implemented: a very fast version, using 4 cm width elements ($51 \times 51$ element mesh) and a direct inversion of the matrix of finite differences system of equations, and a fast version, using a refined mesh (2 cm width, $99 \times 99$ element mesh), a LU factorization of the main matrix acting as a pre-conditioner for the conjugate gradient squared method (CGS) used to solve the system of equations. Typical CPU time on a Pentium$^\text{®}$ III @ 930 MHz computer is 140 ms per iteration for the first version, and 830 ms per convergence for the second one.

**3 – DISRUPTION ANALYSIS**

Figure 2 shows the analysis of a major disruption at $I_p = 1.2$ MA. As expected the plasma displacement is strongly affected by the toroidal current induced in the TPL structure. This current increases with the characteristic time of the TPL (Resistance = 0.9 m$\Omega$, $L/R = 11$ ms), slower than the $I_p$ decreases (figure 2b).

Figure 1 : Diagram of the MAESTRO code implementation.

Figure 2 : plasma trajectory (a), time evolution of plasma current, induced current in TPL, and eddy currents in actively cooled panels (b), for a major disruption at 1.2 MA.
The field created by the TPL current deviates the initial horizontal plasma displacement toward the bottom of the vessel. The TPL current reaches a maximum value of typically 15% of the initial $I_p$. This quite large value leads the plasma to end generally on the bottom of the inner first wall, closed to the leading edge of the TPL, with single null configurations. For a smaller plasma current ($I_p < 0.8$ MA), the ending point can reaches directly the TPL surface.

These results are in accordance with the localization of the first wall activation generated by runaway electron impacts. A higher activation has been measured on the high field side of the vessel, between the equatorial plan and the leading edge of the TPL. To reproduce the $B_{th}$ measurements, eddy currents in first wall structure and TPL fingers must be included (figure 3). Their distribution is mainly a dipole component closed to the TPL, associated with eddy currents circulating in the fingers of the limiter. Crossing with the main magnetic field, a lateral tilting force estimated to 1200 N is then applied on each finger. A simple model based on the time variation of the perpendicular $B_{ed}$ component to the panels and to the fingers and including the characteristic time and resistance of structures is able to reproduce qualitatively the MAESTRO findings (figure 4). Eddy current loops inside adjacent TPL fingers create a net toroidal current seen as a current dipole and well measured by the magnetic captors $B_{th}$. Lower currents are generated inside the higher resistive stainless steel panels.

Figure 3 : Magnetic field components on the boundary. A $I_{ed}$ distribution is needed to reproduce the $B_{th}$ measurements.

Figure 4 : Eddy current poloidal distribution from MAESTRO equilibrium solver (blue) and from the simple model describes in the text (red).
4 – DISRUPTION WITH A PLATEAU OF RUNAWAY ELECTRONS.

Disruption during the \( I_p \) ramp-up generates generally a plateau of runaway electrons self-sustaining the equilibrium even when turning off the PF generator voltages. On the contrary of high \( I_p \) disruptions, a slow evolution towards low field side direction leads to runaway hard impacts on the bottom of the outboard limiter. From the 2D isoflux map obtained by the equilibrium reconstruction, fast electron trajectories for a given kinetic energy can be drawn (figure 5). At the end of the runaway plateau, the single null flux configuration generates a X point topology for fast electron trajectories which opens the possibility of hard impacts not only on the well protected (by CFC) front surface of the limiter, but also in private zones farther the plasma edge. These findings are essential in order to locally protect the stainless steel panels of the first wall.

5 – PROSPECTS AND CONCLUSION.

The MAESTRO code is commonly used to study plasma trajectories during dynamical evolutions. A detailed study of plasma breakdown is planed to optimize the plasma initiation. The perturbation induced by the TPL current, which will vary with the breakdown loop voltage must be taken into account. The analysis of the data using MAESTRO code will be compared with the simulations from the PROTEUS equilibrium code.

The code itself will be improved by including a more realistic poloidal geometry and electrical characteristic of the first wall panels. A direct adjustment of the peaking parameter using a cost function based on the \( B_n \) differences is also under development. Finally alternate parameterizations of the toroidal current profile will be tested, specially using a separate flux dependence for the pressure and magnetic contributions.