Real-time magnetic equilibria for NTM stabilisation experiments

L.Giannone, M.Reich, W.Treutterer, R.Fischer, J.C.Fuchs, K.Lackner, H.R.Koslowski, M.Maraschek, P.J.McCarthy[1], A.Mlynek, R.Preuss, J.Stober and the ASDEX Upgrade Team
Max-Planck-Institut für Plasmaphysik,
EURATOM-IPP Association, D-85748 Garching, Germany
[1]*Department of Physics, University College Cork, Association EURATOM-DCU, Cork, Ireland*

Introduction

Real-time magnetic equilibria in ASDEX Upgrade are required for the microwave ray tracing code, TORBEAM [1], to calculate the mirror angle necessary for depositing ECCD current on the rational surface where a neoclassically driven tearing mode island, NTM, is located. This scheme for suppression of NTM's seeks to improve tokamak performance by raising the operational limits on poloidal beta, β_p [2, 3].

A real-time Grad-Shafranov solver, constrained to fit 40 magnetic probes and 18 flux loop differences, is used to calculate the magnetic equilibrium. The solver is based on an innovative algorithm using discrete sine transforms and a tridiagonal solver that realises an equilibrium poloidal flux matrix on a 33x65 grid in 0.65 ms [4]. The real-time Grad-Shafranov solver is being extended to include constraints on the current profile in the plasma core from the Motional Stark Effect, MSE, diagnostic. The Shafranov integrals and the confinement parameters β_p and plasma inductance, l_i, are also calculated in real-time.

The q-profile is calculated from the flux surface contour integrals at five values of normalised poloidal flux. Rational surfaces can then be located as a function of normalised radius by spline interpolation. These normalised radii and the poloidal flux matrix are available on the real-time reflective memory network for the TORBEAM simulations with a 3 ms cycle time.

Shafranov integrals

The safety factor, q(ψ_N), along the contour of constant normalised poloidal flux, ψ_N, is [5] :

$$q(\psi_N) = \frac{B_o R_o}{2\pi} \oint_C \frac{1}{R^2 B_{pol}} ds \tag{1}$$

where B_o is the toroidal magnetic field on the torus axis at position R_o and B_{pol} is the poloidal magnetic field. The line elements of the contours of constant ψ_N are returned by a specially developed contouring subroutine [6]. The B_r and B_z components of the poloidal magnetic field at the midpoints of the line elements forming the contour are evaluated by four point interpolation of the gradients of ψ_N on the grid.

The Shafranov integrals, S_1 and S_2, are contour integrals on the last closed flux surface :

$$S_1 = \frac{s^2}{V\mu_o^2 I_p^2}\oint_C B_{pol}^2((R-R_o)\bar{e}_R + Z\bar{e}_Z).\bar{n}ds \quad (2)$$

$$S_2 = \frac{s^2}{V\mu_o^2 I_p^2}\oint_C B_{pol}^2 R_o \bar{e}_R.\bar{n}ds \quad (3)$$

where $\bar{n}$ is the vector perpendicular to the line element of the contour, s is the distance around the contour and V is the plasma volume. The poloidal beta, β_p, can be calculated using these values and the plasma inductance, l_i :

$$l_i = \frac{2s^2}{\mu_o V I_p^2}\int_{\Gamma_{pl}} \frac{B_{pol}^2}{2\mu_o} dV \quad (4)$$

$$\beta_p = 0.5S_1 + (1 - 0.5(1 - \frac{R_c}{R_o}))S_2 - 0.5l_i \quad (5)$$

where R_c is the radius of the magnetic axis.

The first step of locating the normalised radius of the q surface at m/n= 4/3,3/2 and 2/1 rational surfaces from the poloidal flux matrix is the evaluation of contour integrals for q at five values of normalised poloidal flux. The five contour integrals are carried out in five parallel instances of the subroutine. The normalised radius of the chosen rational surface is then found by spline interpolation of the normalised radii for these contour integrals. The five contour integrals and the spline interpolation are performed in 0.30 ms on the Dell precision T5500 with dual quad-core 3.46 GHz CPU's running with LabVIEW 2009 RT. The three values of normalised radius of the rational surfaces and the poloidal flux matrix are communicated in real-time to the control system. Including the evaluation of the Shafranov integrals to calculate β_p and l_i in real-time, a 3 ms cycle time can be easily maintained. This performance is satisfactory, as the time required for TORBEAM calculations is typically a factor of ten longer.

Real-time Grad-Shafranov solver

A loop for data acquisition allows up to 128 channels with a 10 kHz sample rate to be recorded. Simultaneously a function parameterisation algorithm is performed. The plasma current, its radial and vertical position and 95 other values of interest for plasma control are calculated. This loop can be executed with a cycle time of 0.5 ms. It is planned to offer the control system the possibility of using the "fast" loop scheme of rtEFIT to perform ISOFLUX shape and position control [7]. The real-time Grad-Shafranov solver runs in a second parallel loop with a 3 ms cycle time.

An m/n=3/2 NTM mode was present in a 1 MA discharge with 10 MW NBI heating and 900 kW ECRH heating (26827). Shown in Figure 1, is the time evolution of the values of q at

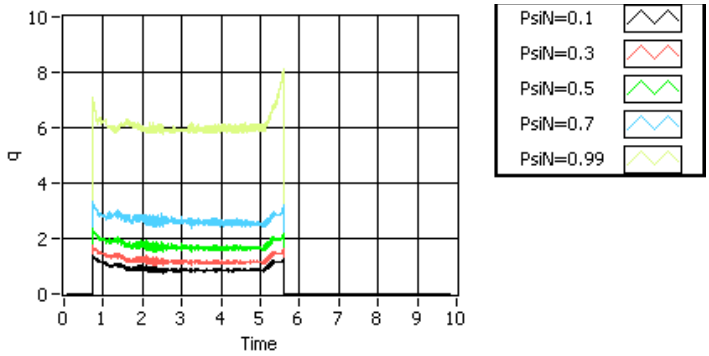

Figure 1: *Time evolution of q at given values of normalised radius*

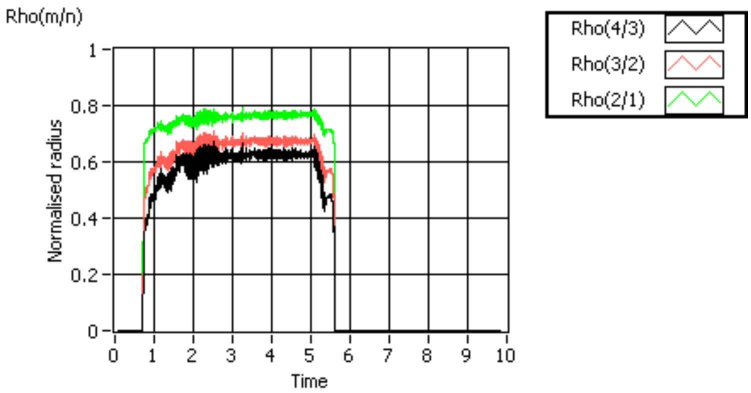

Figure 2: *Time evolution of radial location of rational q values.*

5 normalised values of poloidal flux. These 5 values of q and the associated normalised radii are the inputs to spline interpolation subroutine. Shown in Figure 2, is the time evolution of the radial location of 3 rational q surfaces.

The location of the m/n=3/2 NTM can also be inferred from temperature fluctuation measurements at the mode frequency of the NTM. The phase jump of the fluctuation is related to the change in phase of the temperature fluctuation around the NTM magnetic island. These measurements indicate that the NTM is located at a normalised radius of about 0.5 [3]. The aim is to choose basis current profiles for the Grad-Shafranov solver, so that the predicted normalised radius is sufficiently accurate to perform NTM stabilisation experiments.

MSE constraints

A third loop executes a Grad-Shafranov solver that additionally fits nine spatially localised measurements from the Motional Stark effect diagnostic [8]. The accuracy of the q profile is improved by the measurements of the polarization angle, γ_m :

$$tan(\gamma_m) = \frac{c1 * B_r + c2 * B_t + c3 * B_z + c4 * E_r/vBeam}{c5 * B_r + c6 * B_t + c7 * B_z + c8 * E_r/vBeam + c9 * E_z/vBeam} \tag{6}$$

where c1..c9 are a set of coefficients for each channel relating the local components of electric field (E_r and E_z), magnetic field (B_r and B_z) and diagnostic beam velocity, vbeam, to γ_m. The components of the poloidal magnetic field at the centre of the measurement volume are also evaluated by a matrix-vector multiplication using pre-calculated Green's functions. The toroidal component of the magnetic field, B_t, is calculated from :

$$(RB_t)^2 = (R_o B_o)^2 + 2\int_{\psi_{boundary}}^{\psi} FF^{'} d\psi \qquad (7)$$

where $FF^{'}$ are those terms of the current profile representing the poloidal current. The left hand side terms of the response matrix are the B_r and B_z calculated for each MSE measurement volume and for each current basis function. The right hand side terms of the response matrix use the B_t from the previous iteration and the measured γ_m. These nine additional constraints on the response matrix typically allows the number of fit coefficients to be raised from 4 to 6 [9].

Conclusion

A real-time Grad Shafranov solver is used to calculate the magnetic equilibrium that best fits the input magnetic probe and flux loop inputs. Contour integrals on flux surfaces of the poloidal flux matrix allows real-time evaluation of the normalised radius of rational q surfaces, β_p and l_i. Measurements of the magnetic field components inside the plasma from the MSE diagnostic are necessary inputs to the real-time Grad-Shafranov solver to improve the predicted normalised radius of the rational q surfaces for NTM stabilisation experiments on ASDEX Upgrade.

References

[1] E. Poli et al., Comp. Phys. Comm. **136**, 90 (2001)

[2] M.Marschek et. al, Nucl. Fusion **45**, 1369 (2005)

[3] M.Reich et al., Progress on ECCD-based NTM rt-control at ASDEX Upgrade, EPS 2011

[4] L.Giannone et. al, http://accelconf.web.cern.ch/AccelConf/pcapac2010/papers/thpl024.pdf

[5] D.W.Swain and G.H.Neilsen, Nucl. Fusion, **22**, 1015 (1985)

[6] Q.Ruan, L.Wenzel and Scientific Computing Group, National Instruments

[7] J.R.Ferron, M.L.Walker, L.L.Lao et. al, Nucl. Fusion, **36**, 1055 (1998)

[8] L. L. Lao, H. E. St. John, Q. Peng et. al, Fusion Science and Technology, **48**, 968 (2005)

[9] L.L. Lao, J.R. Ferron, R.J. Groebner et. al, Nucl. Fusion, **30,** 1035 (1990)