Real time plasma boundary reconstruction in RFX-mod tokamak discharges

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Introduction

In the past years, Reversed Field Pinch device RFX-mod has been also operated as a low current tokamak to perform experiments on active control of MHD instabilities. The unique property of the RFP devices is the presence of large systems of independently controlled saddle coils- 192 in RFX-mod. This extends the possibilities of the active control of instabilities such as magnetic islands or kink modes compared to the standard tokamaks. Up to now, these experiments were performed in circular plasma [1]. As a next step, these experiments are expected to be performed in shaped plasma. To achieve a full control of the D-shaped discharge, both plasma shape and current centroid has to be measured and controlled in real time [2]. Within this paper, a method for real time plasma boundary reconstruction is presented as well as a comparison of the new method with MAXFEA simulation data.

Method Principle

The proposed method of the real time plasma boundary reconstruction is based on determination of plasma shape using the vacuum magnetic potential Φ that fulfils equation $\nabla^2\Phi = const$, axisymmetry condition and is linked to the magnetic field by $\boldsymbol{B} = \nabla\Phi$. The potential form in cylindrical coordinates is

$$\Phi = \Phi_0 \cdot \theta + \sum_{k=1}^{N} \cos(k \cdot \theta) \cdot (A_c^k \cdot r^k + B_c^k \cdot r^{-k}) + \sin(k \cdot \theta) \cdot (A_s^k \cdot r^k + B_s^k \cdot r^{-k}) \quad (1)$$

where θ and r are the cylindrical coordinates, Φ_0 is a model constant proportional to the plasma current, $A_{c,s}^{\ k}$, $B_{c,s}^{\ k}$ are the harmonic coefficients of the model determined in real time from magnetic sensors and N is the number of the harmonics coefficients. The poloidal flux Ψ is computed as

$$\psi_a - \psi_b = 2\pi R_0 \cdot (r_{FL} \cdot \int_{\theta b}^{\theta a} \frac{\partial \Phi}{\partial r} d\theta - \int_{ra}^{rb} \frac{1}{r} \frac{\partial \Phi}{\partial \theta} dr) , \quad (2)$$

where ψ_a and ψ_b are the poloidal fluxes at point a and b, $\theta_{a,b}$ are the azimuthal coordinates of the points, $r_{a,b}$ are the radial coordinates, r_{FL} is the minor radius of the flux loops (the vessel of the RFX-mod is circular, so the minor radius of all flux loops as well as all pick-up coils is the same) and R_0 is the major radius of the device.

The harmonic coefficients in the equation (1) are computed using circular harmonics of the poloidal magnetic field and the magnetic flux. There are 8 pick-up coils measuring the poloidal magnetic field and 8 flux loops in RFX-mod. To achieve higher precision, the flux harmonics are computed from the flux difference between each flux loop and a reference flux loop located on the high field side. Due to limited amount of sensors, just the first 3 harmonic coefficients of the poloidal magnetic field and the poloidal flux can be computed. However, for obtaining reliable plasma boundary reconstruction, at least 4 harmonic coefficients are needed. In addition, the 3 harmonics computed from the 8 sensors are strongly affected by the aliasing effect arising from the presence of higher harmonics of both poloidal magnetic field and poloidal flux produced mainly by the field shaping coils. To deal with the problem, the contribution of the harmonics higher than 3 originating from the poloidal field coils to the sensor signals is subtracted and pure plasma harmonics are computed. In the next step, the harmonics generated by the currents in poloidal field coils are added to the plasma harmonics. The harmonics generated by a unit current in each poloidal field coil are computed before the experiments, so that the approach is real time applicable- the unit contributions are multiplied by the poloidal field coil current and afterwards added. The consequence of using this approach is that the first 3 harmonics computed from the magnetic measurements are affected just by the aliasing originating from the higher plasma harmonics, so the resulting aliasing error is reduced. In the last step, the 4^{th} harmonic needs to be estimated. The poloidal field coils contribution to this harmonic is computed in the same way as in case of the first 3 harmonics. Using the MAXFEA simulations [3], it was found that the plasma current contribution to the 4^{th} harmonic is negligible. After applying these three improvements, the potential coefficients in (1) are estimated with sufficient precision from the set of sensors used on RFX-mod.

As the separatrix is defined as a specific contour line of the poloidal flux, the value of the flux needs to be computed first. The separatrix flux is equal to the flux at the point defining the plasma boundary: plasma-wall contact point in limiter regime or at the X-point in divertor regime. The flux value at this point is determined using equation (2), the starting point of the integration being at the flux loop nearest to the point defining the plasma boundary and the ending point being the point defining the plasma boundary. To perform the integration, the position of the bounding point has to be found. First of all, let us concentrate on the method of real-time X-point position computation. At X-point, two conditions are fulfilled: both poloidal and radial component of the magnetic field are equal to 0. As the magnetic field in the vacuum region can be expressed from the magnetic potential, finding the X-point position is equivalent to solving a set of 2 equations with two unknowns. However, solving the equations in cylindrical coordinates in real time is not realistic- a real time cycle of the RFX control system takes 0.2 ms and the plasma boundary must be reconstructed during this period. Owing to this restriction, an alternative solution was found. Both radial and poloidal magnetic field around the expected X-point position are approximated by a quadratic form in each real time control system step. To avoid the computation of time consuming functions like sine or cosine, both components of the magnetic field were estimated at fixed 25 grid points covering the region of 20 X 20 cm around the expected X-point position so that all the time consuming processes can be pre-computed. The quadratic forms in Cartesian coordinates representing both radial and poloidal component of the magnetic field are computed by the least square method implemented as a matrix multiplication. The original set of equations in now expressed in the form of the quadratic forms and has 4 analytical solutions- the one corresponding to the X-point is the solution located inside the initial grid. If the X-point is out of the initial grid or outside the vessel, the discharge is considered to be in limiter regime. In the limiter regime, the plasma-limiter contact point needs to be determined. It is done in the following way: first of all, the flux loop with the highest flux value is selected. In the second step, the magnetic flux at the limiter surface around the selected flux loop is approximated by a quadratic function. The quadratic function is estimated using the signals at the neighbouring flux loops of the selected flux loop. At last, the highest value of the poloidal flux at the limiter surface and the corresponding position are computed from the quadratic function.

Results

The results obtained by the method described above were compared with the results of the Grad-Shafranov equation solver MAXFEA. The comparison for a double null discharge number 34501 at time *0.75 s* is shown in Figure 1. The inputs to MAXFEA are the currents in the poloidal field coils, the plasma current, the poloidal β and the internal inductance. The outputs are the reconstructed equilibrium and the signals at the magnetic sensors. Using the sensor signals computed by MAXFEA, the method proposed in this article was used to reconstruct the plasma boundary- see Figure 1. The results of both methods are very close to each other, the difference exceeds 1 cm just in the region of the lower X-point and on the high

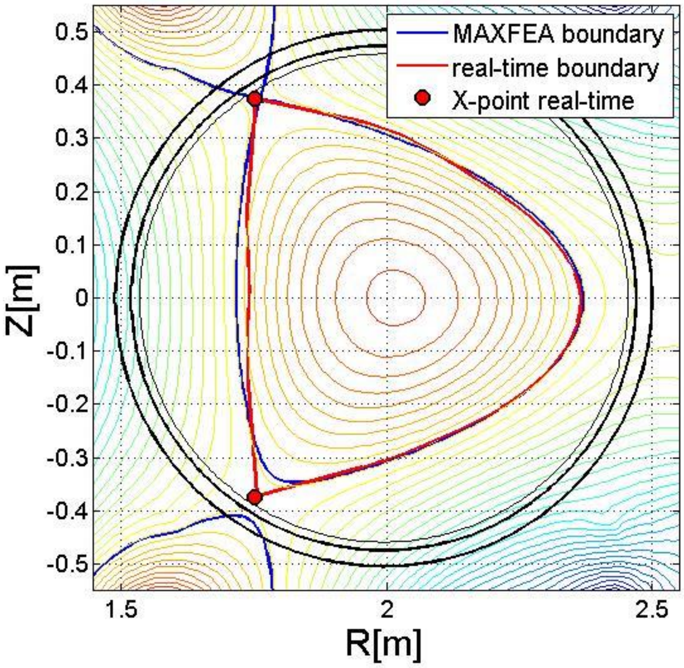

Figure 1:.Equilibrum reconstruction from MAXFEA (separatrix is blue, flux surfaces are represented by the contour lines) compared to the boundary reconstructed by the new method (red separatrix). The X-points are represented by the red points.

field side. The difference is caused by the errors in both methods. On the other hand, the precision of the method is acceptable for the RFX experiments.

Conclusion and future plans

The described method is capable of reconstructing the plasma boundary in real time for various plasma configurations-circular plasma, elongated plasma as well as strongly shaped double null discharges. The resulting error compared to the MAXFEA reconstruction is lower than 1 cm in most of the regions. The boundary reconstructed using the method is used to produce feedback signals for a new plasma shape controller [4]. In future the method will be also applied to reconstruct the plasma boundary in single null discharges. Last, but not least, another estimate of the magnetic potential coefficients ought to be made, so the method will be useful for modern tokamak devices with D-shaped vacuum vessel.

Acknowledgement

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053 and from Erasmus Mundus International Doctoral College in Fusion Science and Engineering. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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