# Equilibrium reconstruction for shaped tokamak discharges in RFX-mod

D. Terranova, R. Cavazzana, C. Finotti, O. Kudlaček, G. Marchiori, L. Marrelli
*Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA)*

RFX-mod is a reversed field pinch device that now runs routinely also as a low current tokamak with circular cross-section (maximum $I_p$~150 kA). Recently strong efforts were devoted to modifying the configuration of the field shaping coils to obtain single and double null plasmas. For these discharges it has become imperative to adequately calculate plasma equilibrium in order to assess its stability and devise any improvement in the control system. Though at this stage axi-symmetry is a correct assumption, a fully 3D approach will allow the determination of equilibria in presence of external perturbations that might perturb the axi-symmetric geometry of the system as observed in several tokamak experiments. In RFX-mod both RMP and non-RMP experiments were done in circular tokamak plasmas and are foreseen also in shaped discharges by means of the flexible system for controlling MHD instabilities.

From the axi-symmetric point of view, some of the work done on plasma boundary reconstruction is presented at this conferences [1] along with the use of MAXFEA [2], while in this work we present first results on equilibrium reconstruction with V3FIT/VMEC [3,4] using diagnostics information. This is a preliminary step towards the reconstruction with external perturbations. Note that while MAXFEA is a free-boundary Grad-Shafranov solver that assumes axi-symmetry and can deal with a separatrix surface, on the other hand V3FIT and VMEC are fully 3D codes providing a solution to the force balance equation through a spectral approach, both in fixed-boundary and free-boundary, but cannot model X points.

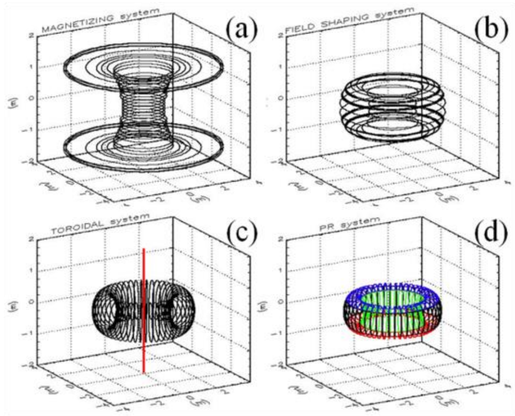


**Figure 1:** RFX-mod modeling of external windings. Toroidal filed coils (c) are modeled in a simplified way with a single wire (red line).

Here we concentrate only on free-boundary solutions as we are dealing with shaped plasmas whose LCFS structure is not know precisely a priori. In figure 1 we show the modeling for external windings of RFX-mod: (a) ohmic, (b) field shaping, (c) toroidal field, (d) saddle coils for active control. Note that we adopted a simplified structure for the toroidal filed system represented as a single wire in the centre of the torus. Also we can neglect currents in passive structures as generally the configuration is quite stationary. A detailed description of the windings model and a check with vacuum measurements can be found in [5] where a thorough description of V3FIT used in RFP discharges is presented.

From the diagnostics point of view, V3FIT uses both magnetic and kinetic (SXR, temperature, density) measurements, however in this work we assume a pressure profile as determined from temperature and density measurements, while we directly use in V3FIT only magnetic diagnostics information. The implemented measurements for the axi-symmetric case are: one poloidal array of 4 $B_r$ saddle probes and $B_t$ pick-up coils, one poloidal array of 8 $B_p$ pick-up coils, 1 toroidal flux loop and 8 poloidal flux loops as well as the corresponding poloidal flux differences which are directly acquired as part of RFX-mod real-time control of the equilibrium. Given the simplified modeling of the toroidal field winding, we model but do not use $B_t$ measurements in the reconstruction as the field ripple is clearly measurable by the pick-up coils, but cannot be properly modeled in this simplified case. Also we prefer to use poloidal flux differences instead of poloidal flux measurement, since the former are directly linked to plasma position and shape and the latter include also a systematic contribution that cannot be modeled properly.

A run of V3FIT will look for the best values of some selected set of free parameters that minimize the $\chi^2$ values between modeled and observed signals. These parameters derive from profile parametrizations adopted in VMEC. In this case we used for the pressure profile a two-power function and for the radial derivative of plasma current a two-power function with one Gaussian peak. This choice leads to a total of 9 free parameters to be adjusted. In this case the q profile is an output of the equilibrium reconstruction.

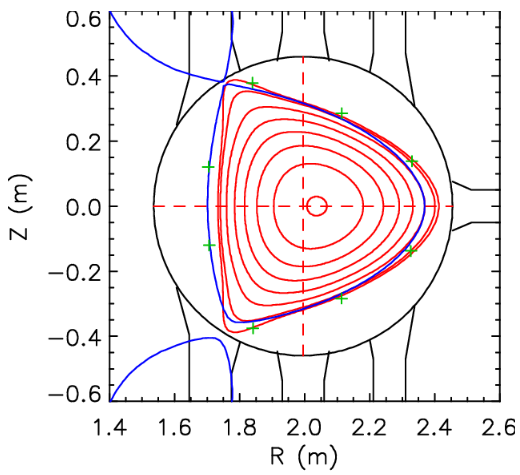


**Figure 2:**.Equilibrum reconstruction from V3FIT (red) compared to MAXFEA (blue, separatrix) and estimated plasma edge with eqflu (green crosses).

In figure 2 we show the final equilibrium for shot #34535 at 0.7 s ($I_p$=75kA) as computed in a free boundary run with V3FIT (red surfaces), compared to the solution obtained with MAXFEA (blue surface defining the separatrix which cannot be modeled by VMEC) and the estimate of plasma boundary from external measurements obtained with the eqflu reconstruction (green crosses) as described in paper [1] at this conference. Given the different approaches adopted and the limitation in diagnostic information for internal profiles (leading to a certain level of degeneracy in the equilibrium), the agreement looks reasonable in terms of flux surfaces structure. However some differences are observed in terms of global plasma quantities as V3FIT gives $\beta_p$=0.59 and $l_i$=0.754 (internal inductance per unit length), while MAXFEA gives $\beta_p$=0.29 and $l_i$=0.96. Also final q profiles are different with MAXFEA leading to $q_0$=0.84 and $q_a$=3.25, while V3FIT has $q_0$=1.06 and $q_a$=3.92. One should consider that being axi-symmetric MAXFEA cannot model the real system of saddle coils. In addition some global plasma parameters are to be provided a priori in order to reach an equilibrium, so that some freedom is given to the user in setting up the code and the result could be adjusted further. A further difference concerns the use of information on external windings. In V3FIT we are keeping the currents flowing into all external windings fixed to measured values and the current in saddle coils (quite low) is averaged toroidally in order to force axi-symmetry. On the other hand MAXFEA does not have a model for saddle coils and needs to self-adjust in the convergence process the current flowing into one of the field shaping coils so that one needs to check if the final value for this current is compatible with the actual measurement. In both cases any error in the measurements of these currents cannot be directly inserted into the reconstruction.

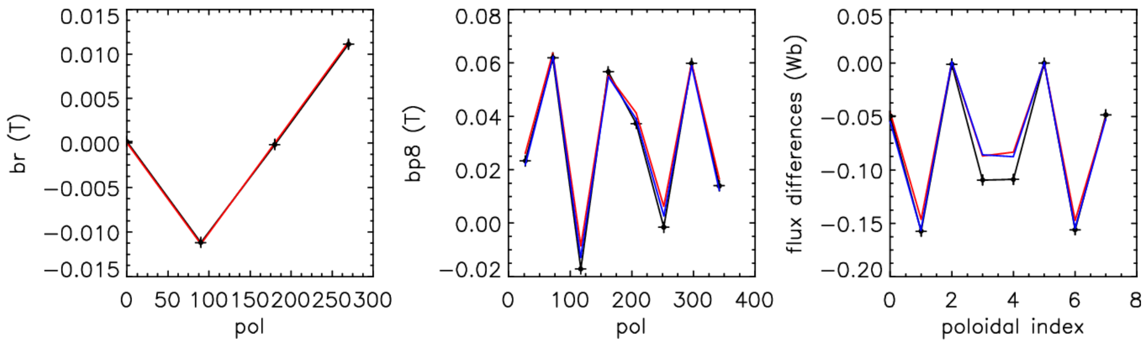


**Figure 3:**.Observed (red), V3FIT (black) and MAXFEA (blue) modeled signals: from left, measurements for radial magnetic field (no value from MAXFEA), poloidal magnetic field and poloidal flux differences.

In figure 3 we show the comparison between observed and modeled signals that were used in the convergence process. The match is good though one can see the difference in two values of the poloidal flux differences from V3FIT, located in the high-field-side region where flux surfaces appear squeezed as compared to MAXFEA (and eqflu). On the other hand in the low-field-side region V3FIT flux surfaces agree with eqflu while MAXFEA differs from both. This aspect needs further investigation and will be part of a thorough benchmark between the two codes. Indeed V3FIT allows as free parameter also the current flowing into external windings so that a fair comparison will be possible also in this respect.

The role of passive structures has been neglected so far as in general the currents flowing into external windings are stationary as the configuration itself. However this is not always the case and indeed a reconstruction has been attempted for some shots that end with a disruption prior to the fast termination. It is known that disruptions can lead to a global equilibrium modification away from axi-symmetry so that a 3D tool would be required. This reconstruction is indeed quite a difficult task as there is clear evidence of the effect of passive structures. To address this issue it was devised a simplified model to described currents flowing into the shell. RFX-mod has two sets of $B_p$ measurements located on the inner and outer surface of the shell at one toroidal location allowing a determination of currents with poloidal mode number $m_{shell}$ up to 3, by considering the magnetic field jump. These currents are modeled with a large number of filaments located poloidally on the shell and grouped according to $m_{shell}$. In this way one can provide a small number of reconstruction parameters that describe and can be adjusted by V3FIT to take into account passive effects from the shell. Preliminary tests have been attempted to find the minimum number of filaments required in order to have a smooth field and to try a reconstruction. No clear result has yet been obtained though the technique provides a good improvement in the reconstruction. A required next step will be the description of the outer set of $B_p$ pick-up coils in V3FIT in order to provide a further constraint to the reconstruction.

**Conclusion**

Double null tokamak discharges are obtained in RFX-mod and work is in progress to produce single null plasmas as well. Two codes are available to calculate free-boundary plasma equilibrium from measurements: MAXFEA and V3FIT/VMEC. In this work we presented first results for double null plasmas with V3FIT as a starting point for the analysis of equilibria with external perturbation in future RMP and non-RMP experiments. A very preliminary approach to take into account currents in passive structure is presented as a possible way to study also non stationary plasmas, though this requires further analysis.

**Acknowledgments**: This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

**References**

[1] O. Kudlaček, R. Cavazzana, C. Finotti, G. Marchiori, P. Zanca, P5.062 *this conference*
[2] P .Barabaschi, "The MAXFEA code", Plasma Control Technical meeting, Naka (Japan), 1993
[3] J.D. Hanson, S.P. Hirshman, S.F. Knowlton, L.L. Lao, E.A. Lazarus and J.M. Shields, Nucl. Fusion **49** (2009) 075031
[4] S.P. Hirshman and J.C. Whitson, Phys. Fluids **26** (1983) 3554
[5] D. Terranova, L. Marrelli, J.D. Hanson, S.P. Hirshman, M. Cianciosa and P. Franz, Nucl. Fusion **53** (2013) 113014