

## RFP helical equilibria reconstruction with V3FIT-VMEC

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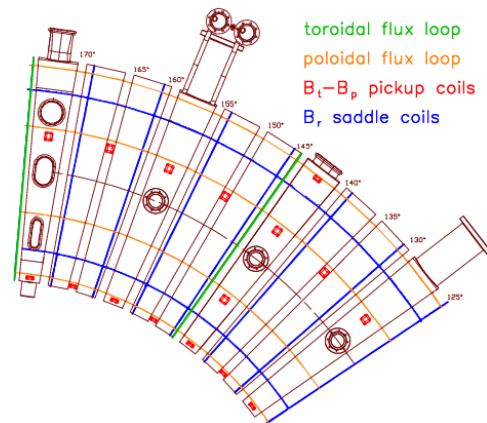
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The study and understanding of the performance of magnetically confined plasmas is strongly based on the possibility of obtaining a reliable reconstruction of the plasma equilibrium. Though many aspects can be addressed with simplified models retaining only some information that can be obtained experimentally (i.e. global plasma quantities and only partially local magnetic field amplitude), it is desirable that one uses as much experimental data as available to obtain a description that reproduces as accurately as possible the real configuration. The inadequacy of over-simplified models is especially apparent when non-axisymmetric effects are important, as is the case for stellarators and Reversed Field Pinches (RFPs).

In the case of the RFP the analysis of observed helical states [1] was addressed both with a linear perturbative approach with the SHEq code [2] and with the non-linear spectral code VMEC [3]. On the one hand SHEq is intrinsically linked to experimental data as it was explicitly developed for the RFX-mod experiment [4]. On the other hand to obtain an equilibrium as congruent as possible with experimental measurements, the V3FIT code [5] was considered. This is a numerical tool developed for stellarators - and adapted to the RFP configuration - that uses VMEC as the equilibrium solver. By changing selected plasma parameters or profiles it minimizes the difference between modelled and observed measurements. In this work we present the first results on the use of V3FIT-VMEC for the reconstruction of helical equilibria in RFX-mod.

### The diagnostics and measurements issue

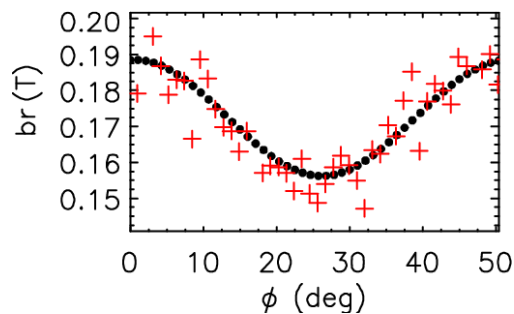
The detailed reconstruction of an axisymmetric equilibrium from external measurements is a tricky task as the solution can be degenerate, so that generally internal measurements are also used. However, when the configuration has 3D features, the degeneracy can reduce significantly, though internal measurements are still valuable.



**Figure 1:** RFX-mod magnetic diagnostics used in V3FIT.

RFX-mod is quite rich in external magnetic measurements and the set used (see figure 1) consists in arrays of 4 (poloidal) by 48 (toroidal) pick-up coils to measure  $B_t$  and  $B_p$ , the same number of saddle coils to measure  $B_r$  and 10 toroidal flux loops. Additionally, 4 sets of 8 poloidally distributed pick-up coils were also used to measure  $B_p$ . Concerning RFX-mod internal measurements, the use of data from the polarimeter as well as data from SXR emissivity and Thomson scattering  $T_e$  profiles are foreseen, but not yet implemented in V3FIT. Presently SXR tomography is used to check a-posteriori the magnetic axis position compared to the result of the reconstruction[1].

When using VMEC for the RFP one has to consider that only the fixed-boundary approach is presently available and this has an impact on how one can compare external measurements to modelled data. Indeed in fixed-boundary one can determine only the model observations



**Figure 2:** One toroidal array of  $b_r$  measurements (red-cross) on a single period. Data spread is used to determine  $\sigma$ .

coming from plasma currents so that the vacuum part has to be estimated otherwise. To this end a full description of RFX-mod windings system was determined and used. As passive structures are neglected, the result is reliable only for sufficiently stationary configurations, as was indeed confirmed by vacuum shots analysis.

Another important aspect is a correct

determination of the variances ( $\sigma^2$ ) that can be ascribed to the measurements as this has an effect on the path along which V3FIT searches the solution that minimizes the  $\chi^2$ . As the helical equilibrium determined with VMEC is obtained including only the dominant helicity (toroidal periodicity 7 for RFX-mod) and its harmonics, one can determine  $\sigma$  by considering the spread of data on this periodicity as shown in figure 2, where we over-plot  $b_r$  measurements on a single period. This can be done for all the diagnostics to obtain the required variances.

### The equilibrium reconstruction

The V3FIT convergence process proceeds by changing parameters that specify the  $q$  profile and pressure profile. A good parameterization improves the reconstruction. For RFX-mod we have clear indication of non-monotonic  $q$  profiles in helical states [1-2]. These can be easily accommodated with VMEC's spline parametrization, but the use of too many free parameters can lead to unphysical oscillations in the resulting  $q$  profile.

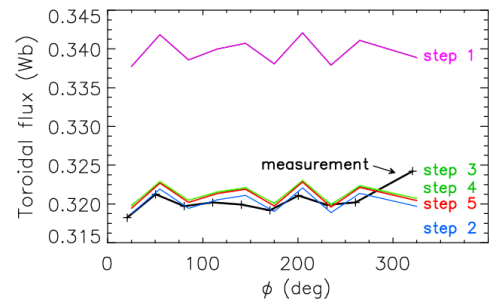
In figure 3 we show the evolution of the convergence process of V3FIT for the toroidal flux:

5 steps were necessary to obtain a convergence using the full diagnostic system as described above. The resulting equilibrium gives a good match also with other data as shown in figure 4 for one array of  $b_r$  measurements. In this figure one can also notice the effect of smaller modes as their phase locking (localized at about  $320^\circ$ ) cannot be modelled with VMEC since they are not harmonics of the  $n=7$ .

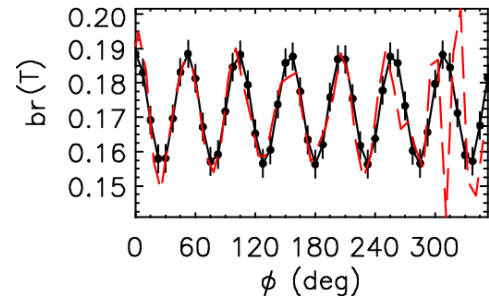
In order to consider the minimum number of free parameters, we have considered only the spline parametrization for  $q$ , aiming at the determination of a possibly better option to be implemented in VMEC. On this path the  $q$  profile was fitted using only four points as shown in figure 5. V3FIT was used to obtain modelled data neglecting any matching to experimental measurements.

The aim is to understand how the equilibrium changes with respect to the free parameters. As a key characteristic of the configuration is the presence of a reversed magnetic shear in the plasma

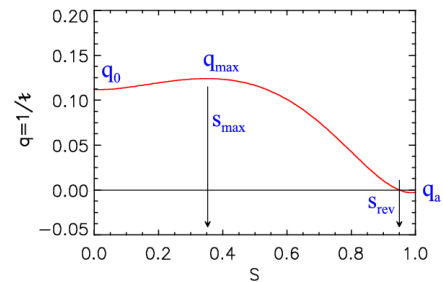
core, both the effect of the  $q$  on axis ( $q_0$ ) and the maximum value of  $q$  ( $q_{\max}$ ) were investigated, as well as the effect of an external perturbation that can be considered by changing the shape of the last closed magnetic surface of the plasma. As an example in figure 6 we show the effect of a  $q_0$  scan on the topology of the configuration and the measurements. For this analysis V3FIT was used to get modelled data and not to optimize the equilibrium. On the left panel the different  $q$  profiles considered are plotted with different colours, while on the right panel we show the resulting position of the magnetic axis and the amplitude of the  $m=1, n=7$  mode of the toroidal magnetic field. As  $q_0$  increases and the  $q$  profile becomes monotonic, the configuration goes from having a helical axis (blue surfaces) to having an axisymmetric axis (red surfaces) characterized by the Shafranov shift. The transition takes place when  $q_0$  becomes larger than  $q_{\max}$ . By changing  $q_{\max}$ , while keeping  $q_0$  constant one can also see what happens during the transition: as long as there is a slight reversed shear the configuration has a helical axis, though the plasma core can loose its bean shape before going



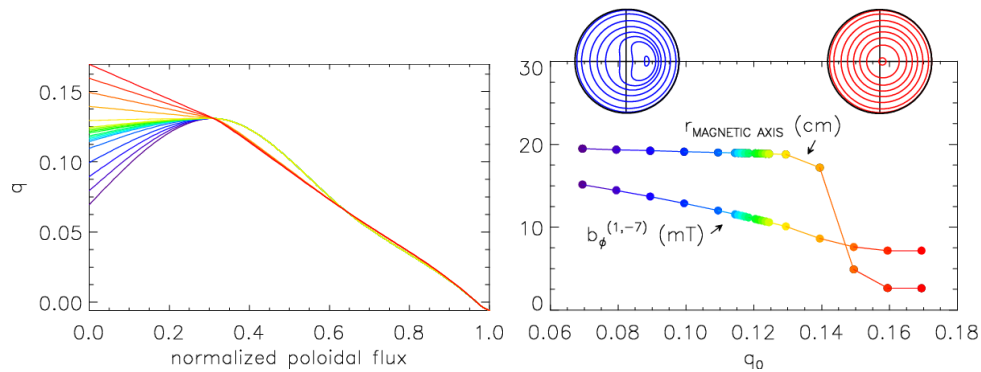
**Figure 3:** V3FIT convergence steps compared to experimental data.



**Figure 4:** Comparison between experimental (red-dashed) and modelled (black)  $b_r$  data.



**Figure 5:**  $q$  profile parametrization for RFP helical states ( $S$  is the normalized poloidal flux).



**Figure 6:** Left: profiles used for the  $q_0$  scan. Right: effect of the scan on the position of the magnetic axis (and topology) and on the amplitude of the  $m=1, n=-7$  mode of the toroidal magnetic field.

to a fully axisymmetric configuration with a monotonic  $q$ . As a final indication, the increase of the non-axisymmetric shift (that can be experimentally obtained by means of an external helical perturbation) produces an increase in the shift of the helical axis with respect to the vacuum vessel centre as long as the  $q$  profile is non-monotonic.

As a general remark, the full diagnostics layout is necessary for the reconstruction of helical states. On the other hand, for axisymmetric cases this is not true as some measurements do not provide any information (e.g.  $b_{\phi}$  measurements) and it is not necessary to consider a full coverage of the machine so that a reduced diagnostics set is considered. This is the case for the reconstruction of multiple helicity RFP and tokamak equilibria for RFX-mod.

### Summary and future plans

V3FIT proved to be an extremely valuable tool for the reconstruction of 3D helical RFP equilibria. A successful reconstruction and comparison to experimental data was obtained considering the full magnetic diagnostics layout. Internal magnetic measurements are not yet available in V3FIT, but both the use of SXR and Thomson scattering data allow for an a-posteriori check of the equilibrium in particular by determining the magnetic axis position.

Numerical tools are being developed to improve the estimate of the vacuum part of the signals necessary to determine the measurements that are fitted by V3FIT: while stationary conditions are easy to deal with, phases with time varying currents in the windings require a careful determination of the effect of passive structures. Experimentally a transfer function for the dominant mode was determined and will be used in the future to run V3FIT also in non-stationary conditions. We also plan to test different profile parametrizations, and to include internal diagnostics in V3FIT reconstructions.

### References

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