Kinetic equilibrium reconstruction on TCV: towards a self-consistent approach

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Introduction

Magnetic equilibrium reconstruction (M.E.R.) is a basic requirement for post-experiment analysis in tokamaks. It aims to find the solution of toroidally symmetric MHD force-balance equilibrium, described by the Grad-Shafranov equation, which best matches a set of magnetic measurements. However, when only external magnetic measurements are used, it is known to provide poor identification of the plasma internal profiles $p(\rho)$ and $j(\rho)$, where p is the total plasma pressure, j the total current density and ρ is a generic flux surface radial coordinate.

Improvements of M.E.R., generally referred to as "kinetic equilibrium reconstruction" (K.E.R.), are based on including internal measurements of magnetic field and kinetic profiles (from MSE, polarimetry, Thomson scattering...) and using models to complement measurements. The K.E.R. may differ from M.E.R. in physically important cases when profile features significantly affect the equilibrium solution, for example when strong off-axis current drive is applied, $p(\rho)$ is flattened by the presence of NTM, when the H-mode regime provides an edge pedestal or internal transport barrier are formed. The K.E.R. is generally the starting point for more advanced studies on MHD stability or gyrokinetic transport analysis and it has been implemented at different level of complexity and integration in many tokamaks [5],[6].

In this work we improved the K.E.R. for TCV [1] experiments by coupling self-consistently the free-boundary equilibrium solution with kinetic measurements available, the current diffusion equation, heat transport equation for ions and the computation of heat and current sources. So far only constraints from n_e and T_e measurements had been used. The motivations for improving the K.E.R. for TCV are in particular the refined current profile tailoring capabilities for NTM studies, using ECCD, and the recent upgrade of the Neutral Beam Heating system (NBH) allows higher β_N H-mode operation. Furthermore TCV lacks diagnostics for internal current profile measurements. We will show how the new implemented K.E.R. provides better agreement with physical expectation.

Implementation

The implemented K.E.R., summarized in Fig. 1, consists of a loop between several codes dedicated for solving specific physical problems. The free boundary equilibrium code LIUQE [2] provides the time evolution of $\psi(R,Z;t)$ to the fitting routines which map the kinetic measurements from (R,Z) position into a 1D radial profile. The available kinetic measurements are usually T_e and n_e from the Thomson scattering diagnostic [1]. In some experiments T_i measurements are available from CXRS diagnostic [1]. The time evolution of kinetic profiles and $\psi(R,Z)$ map are used to compute the Electron Cyclotron driven current with TORAY-GA [3]. All these inputs are passed to the transport code ASTRA [4] which computes the full time evolution of the current diffusion equation, i.e. the flux surface averaged Ohm's law. In order to compute $p(\rho,t)$, ASTRA can either take the T_i measurements from CXRS if available or solve for the ions heat diffusion equation taking into account the power source contribution from NBH and equipartition. The I_p estimate from magnetic measurements is given directly to ASTRA as a boundary condition.

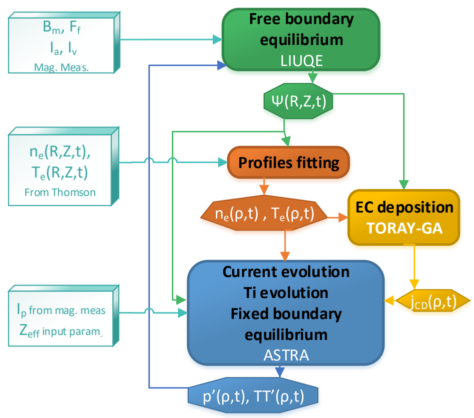

Figure 1: *Implementation scheme*

We define $\psi_N \equiv (\psi - \psi_A)/(\psi_B - \psi_A)$ where ψ is the magnetic poloidal flux, ψ_A its the value at plasma axis and ψ_B at the plasma boundary. From $p(\rho)$ and $j(\rho,t)$ ASTRA computes the self-consistent free functions $p'(\psi_N)$ and $TT'(\psi_N)$ which enter in the RHS of the Grad-Shafranov equation. In M.E.R. they are written with a set of basis functions and the coefficients are found in order for the equilibrium solution to minimize the error with a set of external magnetic measurements. However, without the use of internal measurements, only few basis functions can be used in order to avoid degeneracy. Instead, in the K.E.R. implemented in this work the free functions computed by ASTRA are used directly in LIUQE RHS, closing this way the iteration loop. This means in particular that the free boundary equilibrium has a fully consistent $j(\rho,t)$ time evolution. A crucial parameter that determines the time evolution of $j(\rho,t)$ is the effective charge number Z_{eff}. In this work we specified it in order to find consistency between results and magnetic measurements and we kept it fixed over the iterations. A relaxation procedure is used to help convergence between iterations. All codes are run for the

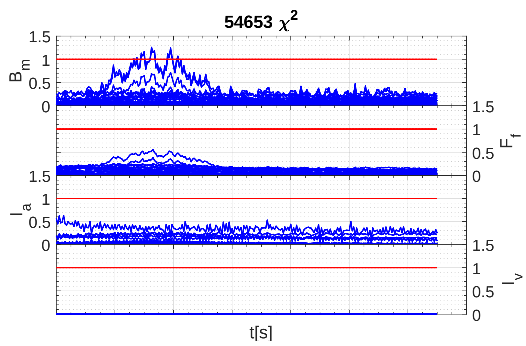

Figure 2: *Measurement consistency* ($\chi^2 < 1$).

full time interval of the discharge, and iterated over the entire time sequence.

Example Results

The implemented scheme converges in few iterations (3∼8) reaching an increment on ψ less than $10^{-4}\%$. The reconstructed quantities are consistent with measurements within their uncertainty ($\chi^2 < 1$), as shown in Fig. 2. To assess the capabilities of the K.E.R. we compared it against the M.E.R. for two TCV experiments.

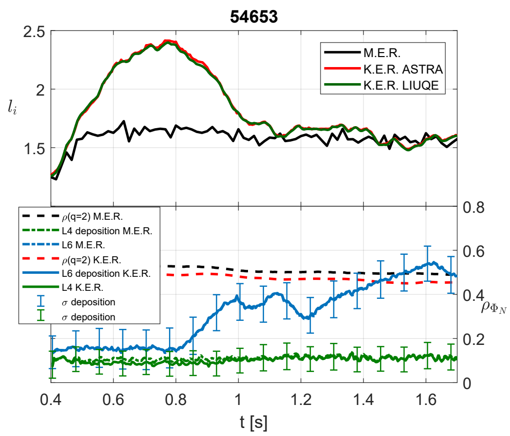

Figure 3: ρ_{ψ_N} *launcher deposition location (top). M.E.R. v.s. K.E.R.* l_i *(bottom).*

The experiment #54653 is a limited L-mode plasma with electron-cyclotron driven central current drive (CD) from one launcher (L4). As shown in Fig. 3, another launcher (L6) initially adds central CD, but is progressively moved towards the plasma edge starting at 0.8s reaching the $q = 2$ flux surface and then returning. The sweeping of the current deposition location of launcher L6 produces in K.E.R. a peaked $j(\rho,t)$ during on-axis CD (Fig. 4 top) and a broader profile in off-axis phase (Fig. 4 bottom), that M.E.R. (black line) is not able to reconstruct.

The full time evolution of $j(\rho,t)$ in the free boundary equilibrium code LIUQE (Fig. 4 green) is consistent with current density diffusion equation solved in ASTRA evaluation (Fig. 4 red). This is achieved, as explained in previous section, by using $p'(\psi_N)$ and $TT'(\psi_N)$ computed by ASTRA directly as the free functions for the free boundary equilibrium code LIUQE as shown in Fig. 5 (green and red lines). The p' and TT' obtained from the basis function expansion in LIUQE M.E.R. (black line) are also given in Fig. 5 for comparison.

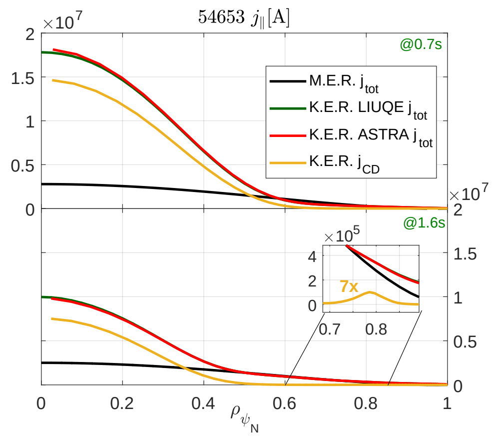

Figure 4: *comparison M.E.R. v.s. K.E.R.*

The time evolution of the current profile is also reflected in the global current peaking factor l_i in Fig. 3 (top), that the K.E.R. is able to follow while M.E.R. finds a constant value all along the discharge. It is worth noticing that we did not use at this stage the sawtooth model within ASTRA simulation and therefore $j_{\|}$ resulted to be too peaked during on-axis CD phase giving an unphysical $q_0 << 1$.

As a second example we performed the K.E.R. of the H-mode diverted plasma 59429, heated with NBH and ECH. During the H-mode phase the kinetic measurements of n_e and T_e from

Thomson scattering presented a pedestal feature at the plasma edge as shown in Fig. 6 (bottom). This feature is reflected in the computed bootstrap current (Fig. 6 top green line) and therefore in the total current (Fig. 6 top blue line).

Conclusions and outlooks

A self-consistent kinetic equilibrium reconstruction (K.E.R) routine has been developed to analyze TCV experiments. The pressure is constrained by kinetic measurements while the flux surface averaged Ohm's law provides the full time evolution of $j(\rho,t)$, used to compute p' and TT', provided directly to the free boundary equilibrium. The iterations converge and produces results consistent with experimental data. We compared it against magnetic equilibrium reconstruction for two experiments where internal profile features modify significantly the plasma state. The K.E.R. improved in both cases the reconstruction consistently with physical expectation. The present method is compatible with real-time implementation and will be tested with RAPTOR [7] and RT-LIUQE [2]. A sensitivity study on the input parameters to quantify the variance of the results is also foreseen.

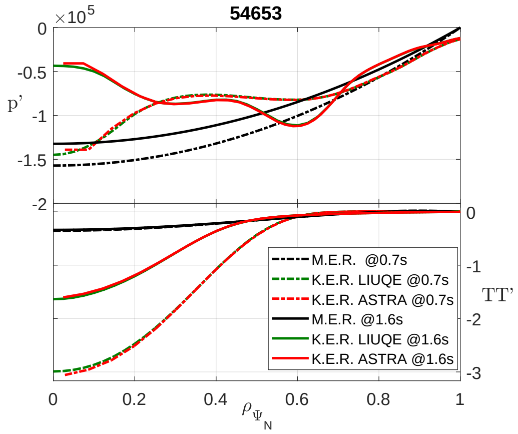

Figure 5: $j_{||}$ *p' and TT' comparison between M.E.R. and K.E.R. during on-axis (0.7s) and off-axis (1.6s) CD*

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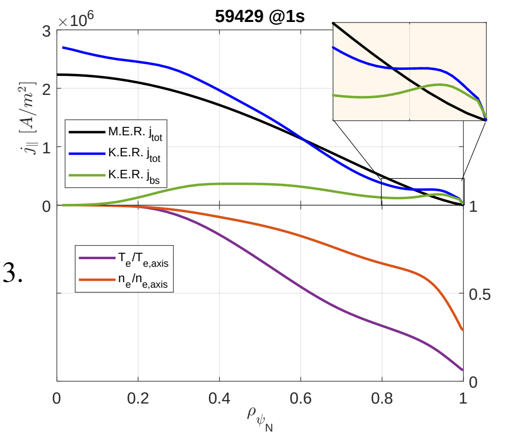

Figure 6: *Edge pedestal during H-mode phase*

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