

## Fast equilibrium reconstruction (FASTEQ) for the control in real time of MHD instabilities in FTU tokamak

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### Introduction

The control of magnetohydrodynamic (MHD) instabilities as the (Neo)classical Tearing Modes ((N)TMs) is one of the major issue for the plasma confinement in fusion devices. Electron Cyclotron (EC) waves are a powerful tool to stabilize the more dangerous (2,1) and (3,2) resistive modes, but the application must be done alive in real time. In order to test the logic and the difficulties of such an application, in FTU a new two-mirrors EC launcher [1], allowing poloidal and toroidal steering in real time, can be used combined with an automatic controller of the mode based on a-priori estimate by ray-tracing of the EC deposition radius  $r_{dep}$  and by EC Emission (ECE) and magnetic correlation of the mode location  $r_{mhd}$ . In this way we get information of the “mean value” of both  $r_{dep}$  and  $r_{mhd}$  at any time and we are able to decide how to react for the stabilization of these modes adjusting the EC injection angles of the new launcher. To achieve this goal it is important to evaluate  $r_{dep}$  in plasma by a fast ray-tracing in real time. A procedure for a fast equilibrium (FASTEQ) is provided, based on a large database of FTU equilibria with plasma boundaries provided by magnetic measurements and plasma axis from the barycentre of the electron temperature profile by a 12-channels polychromator. The Shafranov’s shift, ellipticity, triangularity and plasma current, electron density and temperature profiles are best fitted from many FTU equilibria for different plasma scenarii.

### FASTEQ code

The FASTEQ code allows to reconstruct in real time the plasma equilibrium and calculate the ray-tracing and absorption. The  $\psi$ -poloidal flux surfaces equilibrium map is obtained starting from the acquisition of on-line signals: plasma boundaries internal/external of the Last Closed Surface (LCS) in the major radius ( $r_{s1}/r_{s2}$ ) and vertical ( $z_{s1}/z_{s2}$ ) directions, electron temperature  $T_e$  from the 12 channels of the polychromator, toroidal magnetic field and plasma current. The ray-tracing is calculated by using the on-line signal of the line-averaged electron density,

assuming a given profile. The barycentre of the  $T_e$  profile by the polychromator is taken as the plasma axis  $R_{ax} = \int dR R T_e / \int dR T_e$ . The profile is symmetrized by a virtual channel with the same  $T_e$  value of the opposite polychromator channel, referring both at the same iso- $T_e$  flux surface, as shown in Fig.1. The integration region is also marked. In Fig. 2 a comparison of the plasma axis computed by FASTEQ and the FTU equilibrium code ODIN [2] is shown.

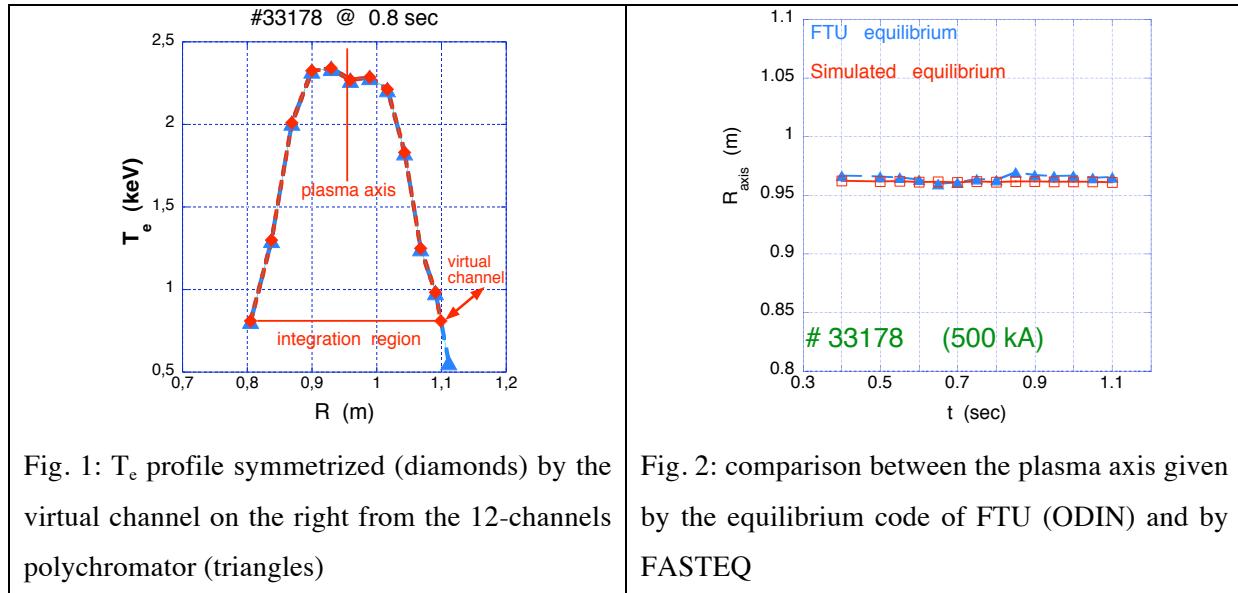


Fig. 1:  $T_e$  profile symmetrized (diamonds) by the virtual channel on the right from the 12-channels polychromator (triangles)

Fig. 2: comparison between the plasma axis given by the equilibrium code of FTU (ODIN) and by FASTEQ

The normalized iso- $\psi_n$  are obtained best fitting many FTU equilibria with different plasma parameters:  $350 \leq I_p \leq 850$  kA,  $4.7 < B_t < 7$  T,  $5 \cdot 10^{19} \text{ m}^{-3} \leq n_e \leq 16 \cdot 10^{19} \text{ m}^{-3}$  and  $1 \leq T_e \leq 8$  keV.

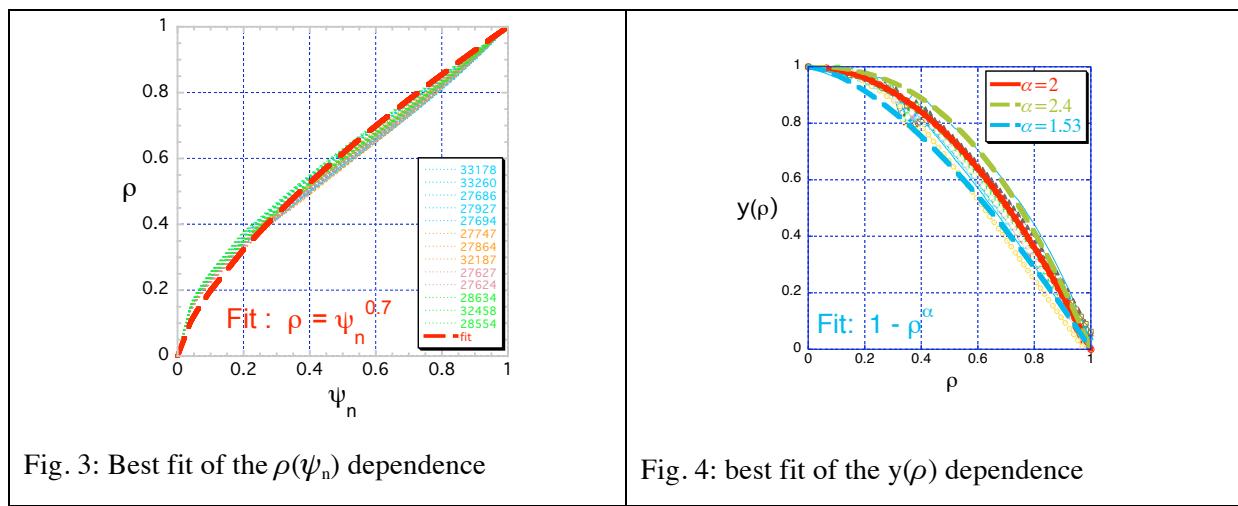
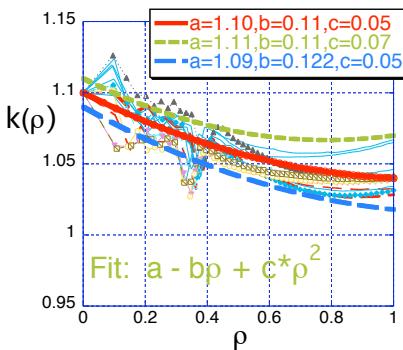
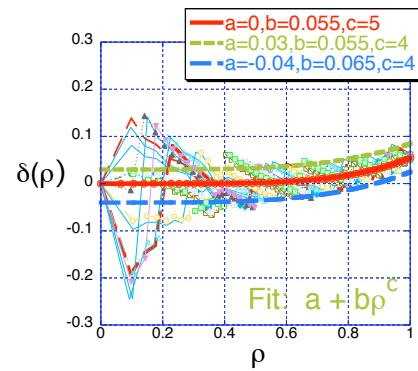


Fig. 3: Best fit of the  $\rho(\psi_n)$  dependence

Fig. 4: best fit of the  $y(\rho)$  dependence

In Fig. 3 the dependence of the normalized iso-minor radius surfaces  $\rho$  on  $\psi_n$  is shown: the best fit gives  $\rho = \psi_n^{0.7}$  instead of the usual exponent 0.5. The Shafranov's shift is given as  $\Delta(\rho) = y(\rho) (R_{ax} - R_{LCS})$  with  $R_{c,\rho}$  and  $R_{LCS}$  the centre of the reconstructed  $\rho$  surface and of the last closed surface, respectively. The latter centre is given by the on-line boundary signals:  $R_{LCS} = (r_{s2} - r_{s1})/2 + r_{s1}$ . The vertical plasma limits are generally neglected because the  $R_{ax}$  is at about  $z=0$ . In Fig.4 the best fits of the function  $y(\rho) = (R_{c,\rho} - R_{LCS}) / (R_{ax} - R_{LCS})$  are shown. The best fitted function  $y(\rho)$ , ellipticity  $k(\rho)$  and the triangularity  $\delta(\rho)$  are plotted in Figs. 4-5-6.

The 3 fits considered for  $y(\rho)$ ,  $k(\rho)$  and  $\delta(\rho)$ , enveloping the experimental data, give differences up to about 0.06% in the simulated equilibrium. The dispersion of data for  $\delta(\rho)$  in the range  $0 < \rho < 0.025$  is due to numerical errors; very low triangularity is typical in FTU.

Fig. 5: Best fit of the ellipticity  $k(\rho)$ Fig. 6: Best fit of the triangularity  $\delta(\rho)$ 

Finally, the iso- $\rho$  flux surfaces are parameterized as:

$$R = a \rho \cos[\vartheta + \delta(\rho) \sin(\vartheta)] + R_{\text{LCS}} + \Delta(\rho) \quad z = a \rho \sin \vartheta k(\rho)$$

In Fig. 7 the FTU equilibrium and ray-tracing from ODIN and FASTEQ codes are compared for the discharge #33178 at 0.7s, 500 kA, 5.4 T with electron peak density  $6 \cdot 10^{19} \text{ m}^{-3}$  and temperature 2.4 keV. The simulated equilibrium is given here for  $y(\rho)=1.-\rho^2$ ,  $k(\rho)=1.1$  and  $\delta(\rho)=0$ ; the density profile is fitted as:  $n_e(\rho) \sim n_{e,\text{av}}(1-\psi_n)$  and  $T_e(\psi_n) = T_{e,0,\text{poly}}(1-\psi_n^{0.8})^{1.7}$ . The calculated  $r_{\text{dep}}$  is about at the same location of  $r_{\text{dep}}$  by ODIN -4% corresponding at  $\Delta r \sim 1 \text{ cm}$ . The 2 EC power depositions, located inside the same 2 channels of polychromator, are seen at the same position by the automatic controller. The fast  $r_{\text{dep}}$  calculation [3] is provided considering 3 optical rays: one central and 2 outer rays of the injected beam. The a-priori estimate of  $r_{\text{dep}}$  is the mean value of the deposition location of these 3 rays:  $r_{\text{dep}} = (r_{\text{dep\_central}} + r_{\text{dep\_outer}} + r_{\text{dep\_outer}}) / 3$ .

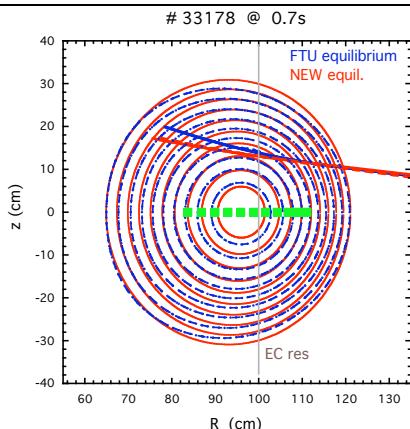
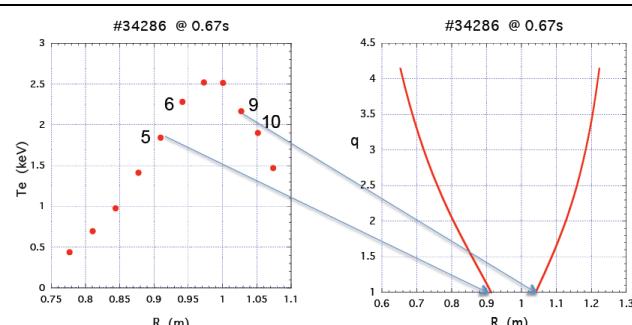
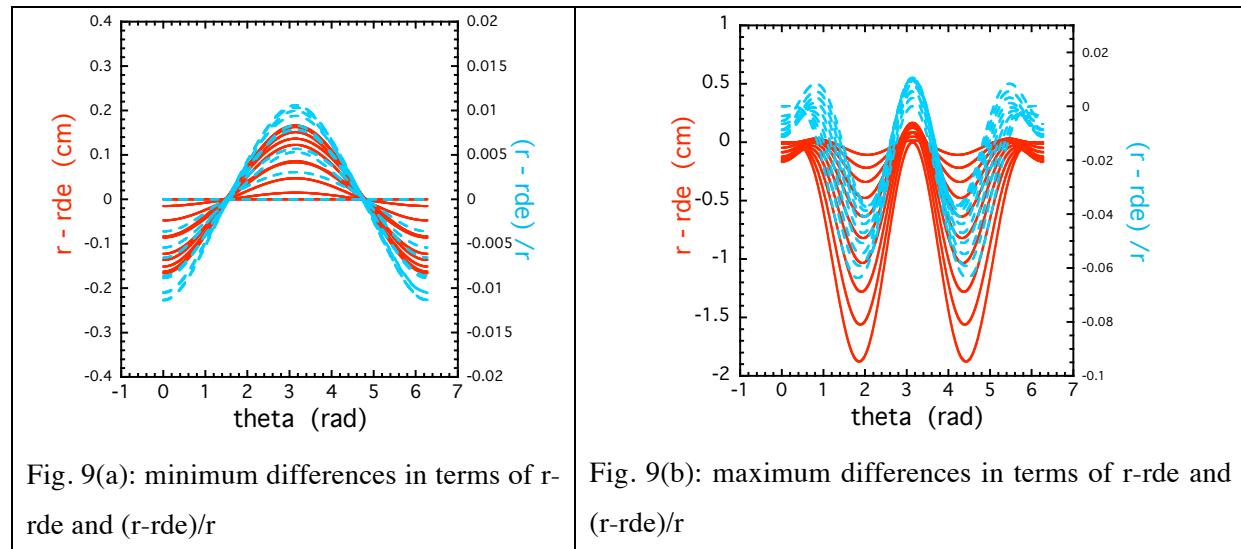


Fig. 7: ODIN and FASTEQ equilibria

Fig. 8: comparison of the  $q=1$  location with the polychromator channels (left) and the profile given by FASTEQ code (right) for the shot #34286 at 0.67s.

FASTEQ gives also the q profile in cylindrical approximation using the fitted plasma current profile  $I_p(\psi_n)/I_p = 1.9\psi_n - 0.9\psi_n^2$ : an example is shown in Fig.8 where the q=1 location is compared with the inversion radius position from the polychromator channels.

The different combinations of the 3 fits for  $y(\rho)$ ,  $k(\rho)$  and  $\delta(\rho)$ , used in the equilibrium reconstruction, give the error bar estimate w.r.t. the FTU equilibrium. The minimum and maximum error bars found are shown in Fig. 9, being theta the angle spanning the poloidal section, r and rde the minor radius from FASTEQ and ODIN, respectively.



### FASTEQ on MARTe real time framework

The fast equilibrium code is now implemented using the MARTe real time framework and runs over the backup feedback control system [4] in  $\sim 44$   $\mu$ sec.

### Conclusions

A procedure for a fast equilibrium (FASTEQ) for the real time MHD control using a new two-mirrors EC launcher is provided, based on a large database of FTU equilibria by using plasma boundaries by magnetic measurements and plasma axis by the 12 channels of polychromator. The Shafranov's shift, ellipticity, triangularity and electron density and temperature profiles are best fitted from the data of many FTU equilibria for different plasma scenarii. The good agreement found with the FTU equilibrium code ODIN encourages to take into account both these codes in the automatic controller.

### References

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