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Reconstruction of Tokamak Equilibria with Pedestal Profiles Using the SPIDER Code

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Equilibrium reconstruction codes are the tools of crucial impotence for the interpretation of experimental data in modern tokamaks. In case of non-monotonic reversed shear or "skin" profiles at the edge, the standard reconstruction methods [1, 2] do not perform satisfactorily and plasma boundary shape and profiles are not determined accurately. In particular, the pedestal profile measurements rely upon the magnetic surface mapping onto real space which should be determined self-consistently using the reconstructed free-boundary equilibrium.

To avoid the restrictions of the previous generation of codes and to improve accuracy and efficiency of equilibrium reconstruction, a new adaptive grid plasma equilibrium reconstruction solver in the frame of the SPIDER [3] code has been developed. The automatic mapping of the magnetic surfaces provided by the adaptive grid code allows for a very accurate resolution of the pedestal region while using the adaptive flux grid in the plasma for efficient free-boundary equilibrium calculations.

The changes in the mapping of magnetic surfaces due to the presence of pedestals are estimated for fixed and free boundary equilibrium reconstructions of ELMy TCV shots. Using the measured temperature and density profiles, the current density profile is reconstructed and the influence of the bootstrap current in the pedestal is investigated.

The application of the new method to configurations with large fraction of noninductive current, e.g. the TCV shots with high bootstrap current fraction, is discussed.

1 Equilibrium reconstruction taking into account non-inductive current density

The adaptive grid plasma equilibrium reconstruction solver is a module of the SPIDER code and was presented in [4].

In the reconstruction method, both plasma boundary and current density profile are calculated with the use of basis functions for the profile representation and a regularization technique is applied during the fitting process. The toroidal plasma current density is represented as:

$$j_t = \sum a_k (1-\psi^k) R + \sum b_k (1-\psi^k)/R,$$

where a_k, b_k are fitting coefficients ($k = 0 \div m$), ψ is the normalized poloidal flux with $\psi = 0$ on magnetic axis and $\psi = 1$ at the edge, R is the major radius. A Singular Value Decomposition (SVD) technique is used to obtain the fitting coefficients taking into account the specified measurement uncertainties. The error of the "fitting" is determined by the relation:

$$\chi^2 = \chi^2_{loops} + \chi^2_{probes} + \chi^2_{PF},$$

where $\chi^2_\alpha = \sum (S^{calc}_\alpha - S^{exp}_\alpha)^2/\sigma^2_k$ and $\sigma_k = \varepsilon_\alpha \max S^{exp}_\alpha$, the index α denotes flux loops, magnetic probes and PF coil currents, S^{calc} is the calculated value, S^{exp} is measured value, ε is the relative error of measurement/simulation.

In the presence of non inductive current sources and with a prescribed pressure gradient the following current density representation is used:

$$j_t = p'R + (f f'_{boot} + f f'_{cd})/R + \sum b_k(1-\psi^k)/R,$$

The $f f'_{boot}$ and $f f'_{cd}$ profiles are determined by the magnetic surface averaged toroidal current density

$$< j >=< j_{oh} > + j_{boot} + j_{cd}, \quad f f'_{boot} = j_{boot}/ < 1/R >, \quad f f'_{cd} = j_{cd}/ < 1/R >,$$

2 TCV equilibria with pedestal

Measurements by Thomson scattering of the T_e and n_e profiles near the plasma boundary in ELMy H-mode plasmas in TCV were presented in [5]. Mapping of the data points onto radial coordinates in the plasma midplane was performed using information from the LIUQE equilibrium reconstruction [2] using magnetic measurements only. The pedestal temperature and density profiles in terms of the poloidal flux coordinate combined with the measurements in the plasma core provided the pressure profile in the whole plasma volume.

The measured profiles for the TCV shot #26383 were used in the series of reconstructed equilibria with prescribed bootstrap and noninductive current density. The bootstrap current density profile was calculated in the collisionless limit [6] and then scaled with the parameter C_{boot}.

The results of the reconstruction are given in Figs.1 and 2. The j_{cd} term is added artificially in the center to show the effect of a small central current drive.

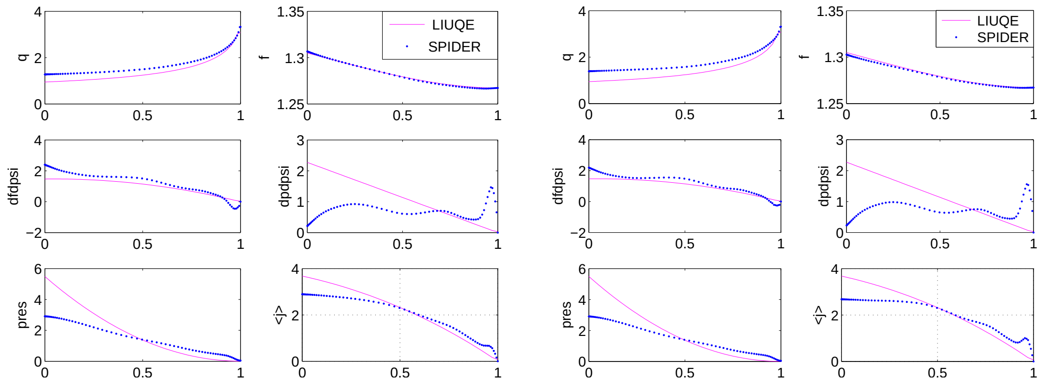

Figure 1. The plasma profiles for the reconstructed TCV equilibria (LIUQE, magenta; SPIDER, blue dots) versus normalized poloidal flux for the TCV shot #26383. The parameter C_{boot} is 0.5 (left 4 frames) and 1 (right 4 frames).

The table below gives the χ^2 values for the reconstruction with the relative errors for flux loops 1%, magnetic probes 50% and PF coil currents 50%.

C_{boot}	0.0	0.5	1.0	1.4	2.8
χ^2	8.3728	8.3823	8.6541	8.2727	8.2954

The effect of plasma equilibrium on the mapping of the Thomson system observation volumes onto flux coordinates is demonstrated in Fig.3. The derivative of the z-coordinate with respect to the normalized poloidal flux is plotted for a series of reconstructed equilibria with different values of C_{boot}. The variation of the value of $dZ/d\psi$ is mainly due to changes in the internal inductance in the reconstructed equilibria that results in the poloidal flux redistribution.

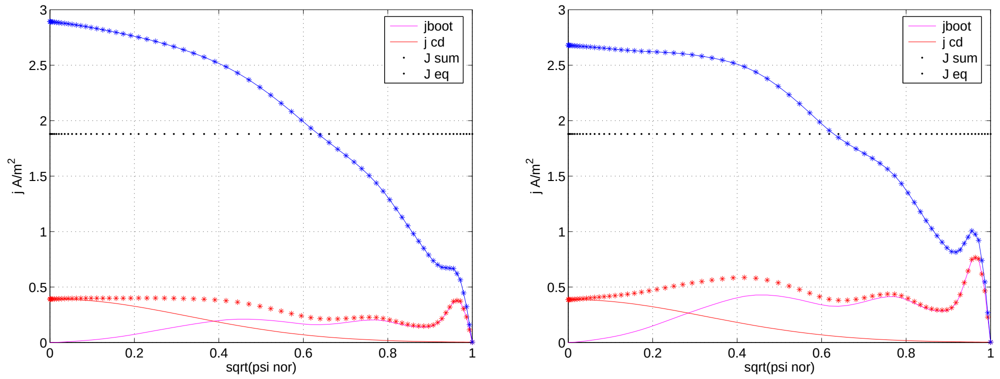

Figure 2. The bootstrap, ECCD and total current density. The plasma toroidal current averaged over the cross-section is plotted for reference. The parameter C_{boot} is 0.5 (left frame) and 1 (right frame).

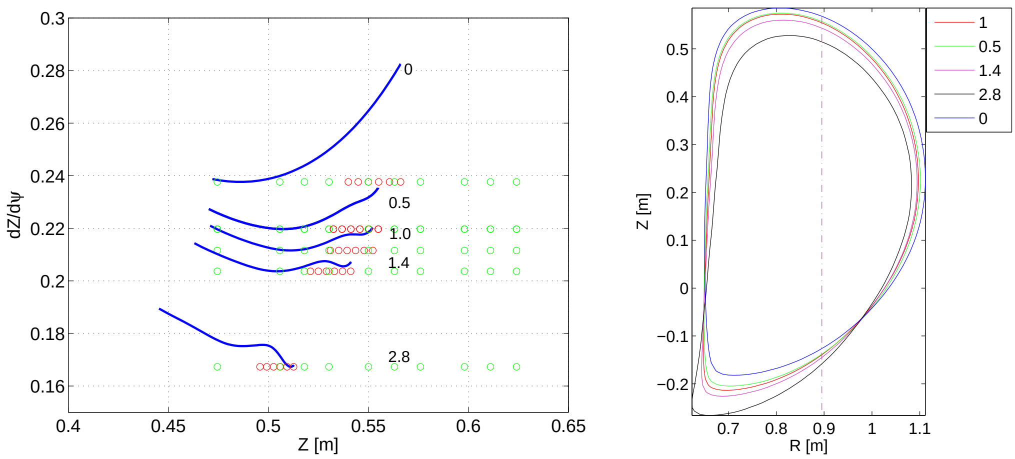

Figure 3. Z-coordinate derivative with respect to the normalized poloidal flux ψ. The positions of the observation volumes are marked by green circles. The red circles mark the positions of the magnetic surfaces $\sqrt{\psi} = 0.95, 0.96.0.97, 0.98, 0.99, 1.0$. On the left the plasma boundaries for the considered equilibria are plotted. The parameter C_{boot} values are shown.

3 High bootstrap current cases

A TCV fully non-inductively driven shot (#21655) [7] is considered, using the same pressure profile as in LIUQE but assuming about 70% bootstrap current fraction (Fig.4, left). This hollow current density profile, obtained assuming some broad current profile deposition, leads to a reversed shear profile, which the LIUQE specification of ff' is unable to reproduce. Fig.4 (right) shows the difference between LIUQE and SPIDER reconstructed profiles.

In Fig.5 (left) a high bootstrap fraction case with central ECCD current drive is shown for the TCV shot #22895. Even assuming a central co-CD deposition, which is not the case experimentally, we find a reverse shear safety factor profile due to about 70% bootstrap fraction. Comparison of the reconstructed profiles with the LIUQE data is shown on Fig.5 (right).

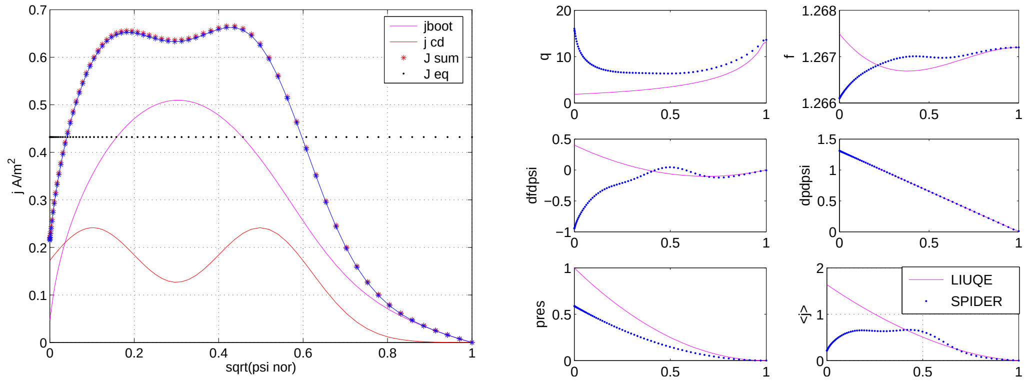

Figure 4. The bootstrap, ECCD and total current density for the TCV shot #21655 (left). The plasma profiles for the LIUQE and SPIDER reconstructed equilibria versus normalized poloidal flux (right).

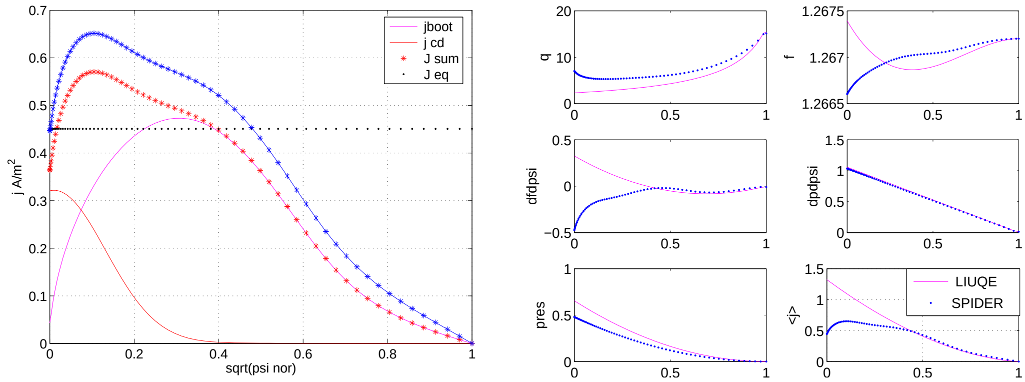

Figure 5. The bootstrap, ECCD and total current density for the TCV shot #22895 (left). The plasma profiles for the LIUQE and SPIDER reconstructed equilibria versus normalized poloidal flux (right).

4 Conclusions

1. An improved equilibrium reconstruction method with the prescribed bootstrap and non-inductive current density and reconstruction of $< j >$ has been applied to TCV shots with edge pedestal, internal transport barrier and high bootstrap fraction.
2. The sensitivity of the reconstructed averaged current density profile $< j >$ and the plasma boundary to magnetic data was studied. It was found that the values of χ^2 do not strongly depend on the scaling factor for the bootstrap and non-inductive current profiles and some additional constraint on fitting parameters such as MSE data is required.
3. To solve correctly equilibrium reconstruction problem it is necessary to use additional plasma kinetic and MSE data from experiment.

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