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New Adaptive Grid Plasma Equilibrium Reconstruction Solver as Module of the SPIDER Code

A.A.Ivanov[1], R.R.Khayrutdinov[2], S.Yu.Medvedev[1], Yu.Yu.Poshekhonov[1]
[1]*Keldysh Institute, Russian Academy of Sciences, Moscow, Russia*
[2]*TRINITI, Moscow Region, Russia*

Equilibrium reconstruction codes become one of the main tools used for interpretation and visualization of experimental data in almost each modern tokamak. In such codes (for example, EFIT [1], LIUQE [2]) 2D equilibrium problem is solved on rectangular grid. Plasma current density and magnetic surface coordinates are reconstructed using magnetic and kinetic experimental data. Polynomials of second or third degree for pressure and poloidal current are chosen to represent dependence of plasma current density on poloidal flux. In such a way good correlation with experimental data is obtained for monotonic profiles with maximum at magnetic axis that are close to parabola. But in the case of non-monotonic, reversed shear or “skin” profiles at the edge, these methods do not work satisfactory, and plasma boundary, pressure and current density profiles are not accurately reconstructed.

To avoid these restrictions and to improve accuracy and efficiency of equilibrium reconstruction needed after each shot in tokamak experiments, new adaptive grid plasma equilibrium reconstruction solver in the frame of the SPIDER [3] code has been developed. Two different methods can be used to solve the reconstruction problem. In the first method, plasma boundary is fixed and plasma profile parameters are obtained as a result of fitting to experimental data; boundary itself can be either reconstructed by direct magnetic measurements, or determined using multi-filament fitting method [4]. In the second method, both plasma boundary and current density profile are calculated with the use of special functions and regularization technique applied during fitting process. 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 normalized poloidal flux with values: $\psi=0$ at plasma axis and $\psi=1$ at the edge, R is major radius. Vacuum vessel is modeled as set of N axially symmetric filaments and current in each i^{th} filament that can be calculated (similar to the model [5]) as the five mode poloidal Fourier moment:

$$I_{PS}=I_0+\sum\{A_m\cos(m\theta_i)+B_m\sin(m\theta_i)\}$$

Coefficients I_0, A_m, B_m are determined as a result of fitting ($m=1\div 5$).

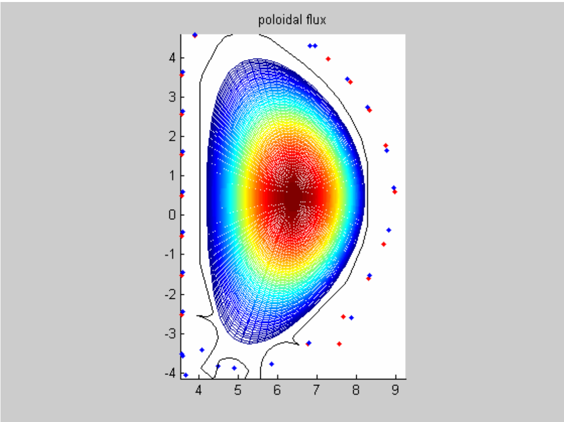
Singular Value Decomposition (SVD) technique is used to obtain "fitting" coefficients with specified errors of measurements. The error of fitting is determined by relation:

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

$$\chi^2_k=\sum\{(S^{calc}_k-S^{exp}_k)^2/\sigma_k^2\} \quad \text{and} \quad \sigma_k=\varepsilon_k * \max\{S^{exp}_k\}.$$

The index k denotes flux loops, magnetic probes and PF coils currents, S^{calc} is the calculated value, S^{exp} is the measured value, ε is relative error of measurement-simulation.

Test of reconstruction model and study of plasma current reconstruction methods has been carried out with the use of fixed plasma boundary equilibrium solver (SPIDER [6]) to sort out the effect of plasma shape change. For this study ITER poloidal system was chosen with real position of magnetic sensors and plasma column (Fig.1). Plasma elongation is k=1.75. The numerical experiments have been performed in the following way: direct equilibrium with given $dP/d\psi$ and $FdF/d\psi$ (derivatives of pressure and poloidal current entering the right hand side of Grad-Shafranov equation) is calculated, magnetic signals and total plasma current are saved; then saved equilibrium parameters are read and dP/dψ and FdF/dψ profiles are reconstructed. Example of comparison between direct and reconstructed profiles is shown in Fig 2. Parabolic fitting for dP/dψ and FdF/dψ is used.



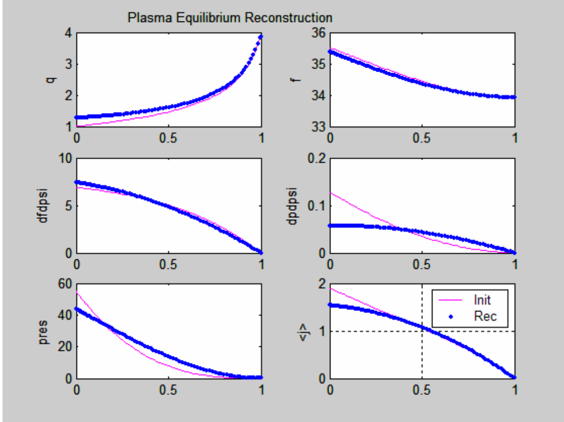
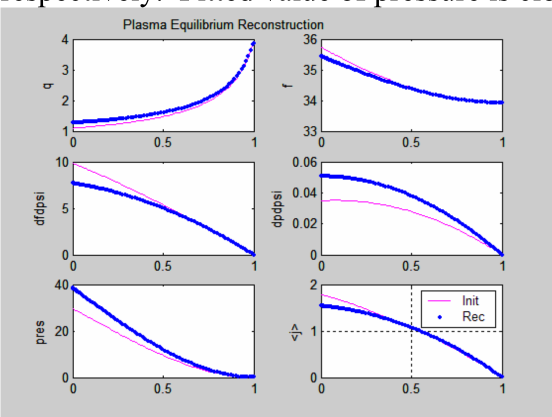
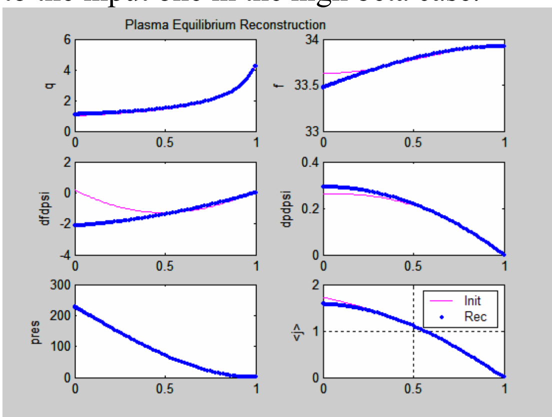


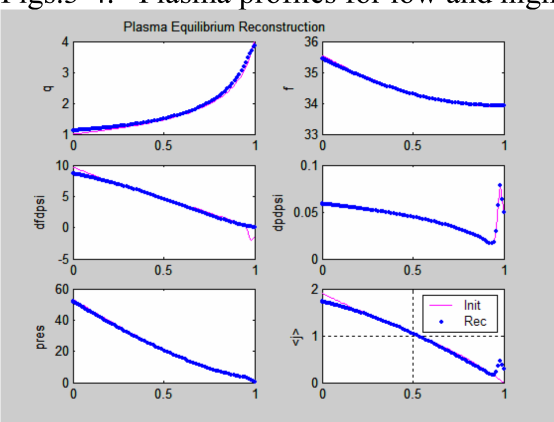
Fig.1-2 ITER poloidal configuration and fixed boundary equilibrium. Plasma profiles: q-safety factor, F- poloidal current, dfdpsi-FdF/dψ , dpdpsi-dP/dψ, pres-pressure, <j>-average current density.

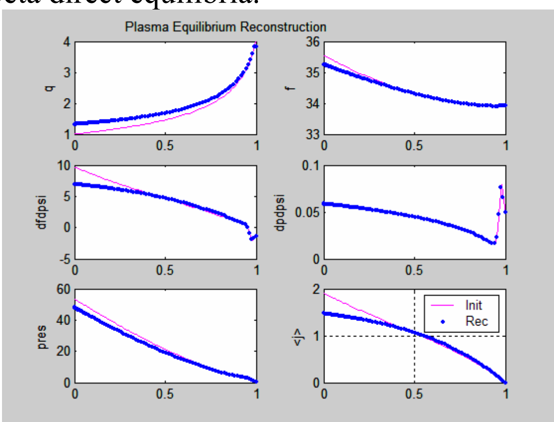
The possibility to determine separately dP/dψ and FdF/dψ profiles was studied using the next approach: different dP/dψ and FdF/dψ profiles which produce equilibrium with high and low beta poloidal values were chosen such that they produce magnetic signals values very close to each other; with these profiles direct equilibrium problem was solved and data are saved; then equilibrium was reconstructed using these data. Comparisons for these cases are shown in Figs. 3,4 for low and high beta cases respectively. Fitted value of pressure is closer to the input one in the high beta case.





Figs.3-4. Plasma profiles for low and high beta direct equilibria.



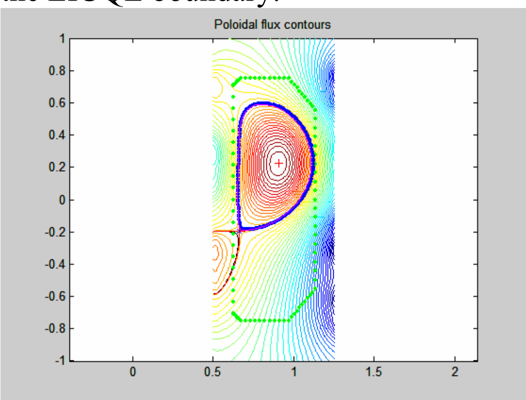


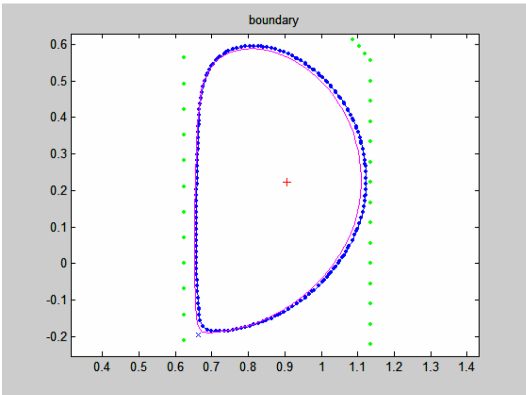
Figs.5-6. Plasma profiles with pedestal in pressure, FdF/dψ and < j> profiles are fitted.

Pedestal pressure profile case was studied in the next series of computations. Two option were used: in the first option, FdF/dψ was fitted resulting in averaged current density <j> profile with pedestal similar to the input dP/dψ profile (see Fig 5); in the second option, the <j> profile was reconstructed and calculated resulting in $FdF/d\psi$ profile with inverse pedestal (see Fig. 6).

Usually in experiments simple reconstruction method is used, in which $dP/d\psi$ and $FdF/d\psi$ profiles are fitted as low order polynomials (linear or parabolic or cubic) and both $dP/d\psi$ and $FdF/d\psi$ are determined simultaneously. This method gives correct results with a restriction that the pressure profile is determined with some scaling factor. To find more accurate estimate for beta, additional information about pressure, at list at the plasma centre, is required. In particular, to reconstruct an equilibrium with pedestal pressure profile accurate measurements are required.

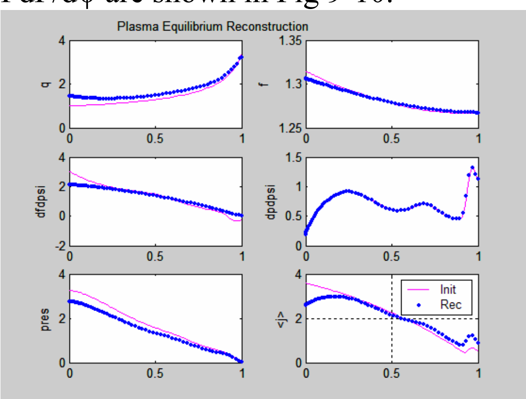
In addition to the sensitivity of the reconstructed profiles to magnetic data, the accuracy of plasma boundary and x-points locations to pressure and current density profiles were studied. As an example for this case the TCV shot #26383 has been chosen. In this shot electron pressure in the pedestal was measured [7]. Standard TCV reconstruction code LIUQE gives linear $dP/d\psi$ and parabolic $FdF/d\psi$ profiles. For the reconstruction studies one time slice t=0.85s was chosen. Experimental values of magnetic probes and loop data, along with PF coils and plasma current were used in modeling. Direct equilibrium was solved using LIUQE profiles for $dP/d\psi$ and $FdF/d\psi$. The resulting equilibrium is shown at the Fig.7. Calculated plasma boundary is close to LIUQE, but has difference in the outboard part of plasma boundary (see Fig.8.). This discrepancy is due to difference in rectangular mesh size and methods of equilibrium calculation. When PF and vessel currents are fitted fixing the same profiles, the resulting plasma boundary is much closer to the LIUQE boundary.

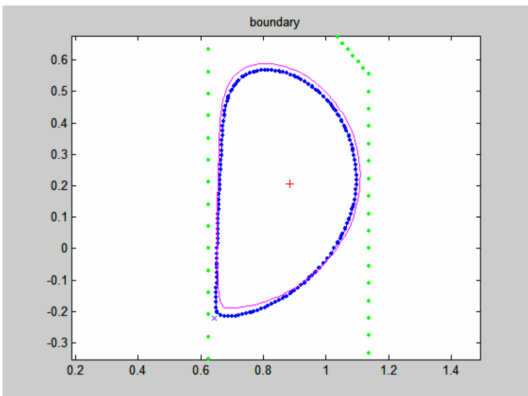




Figs.7-8. TCV poloidal field configuration and free-boundary equilibrium. Plasma boundaries from LIUQE and direct equilibrium are compared.

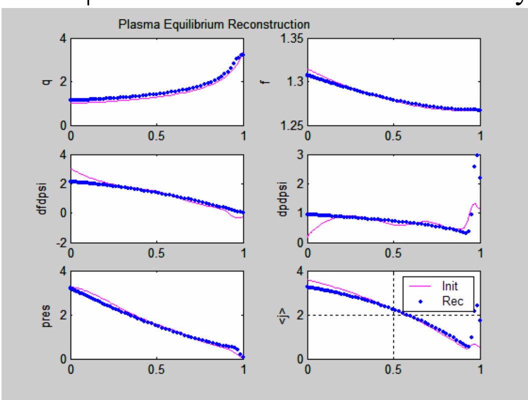
The pedestal $dP/d\psi$ and the $FdF/d\psi$ profiles corresponding to the equilibrium with bootstrap current were chosen to match the plasma boundary to LIUQE boundary and solve direct equilibrium in the next series of computations. The pedestal $dP/d\psi$ and reconstructed $FdF/d\psi$ are shown in Fig 9-10.

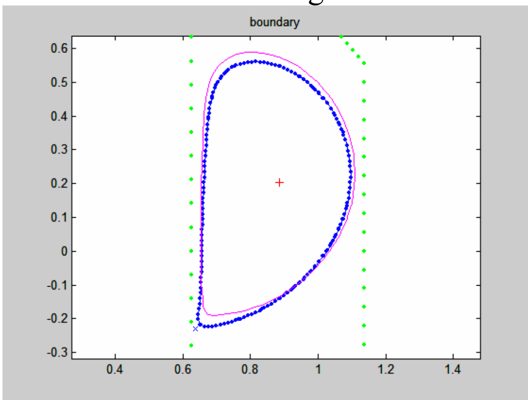




Figs.9-10. Plasma profiles and boundaries from LIUQE and reconstructed equilibria.

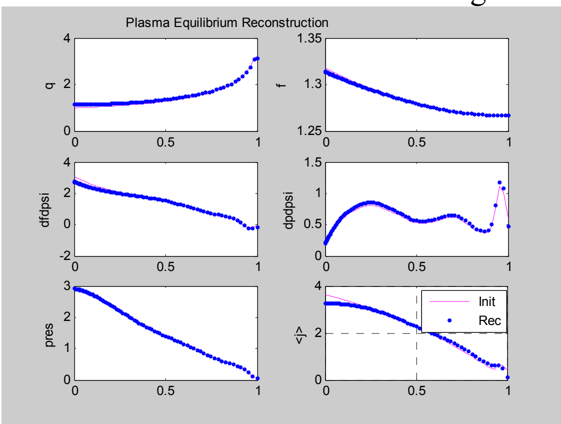
The plasma temperature and density profiles with pedestals were specified in the next series. Reconstruction was run with the corresponding pressure profile P(ψ) and FdF/dψ was fitted. Profiles and boundary for this case are shown in Fig.11-12.

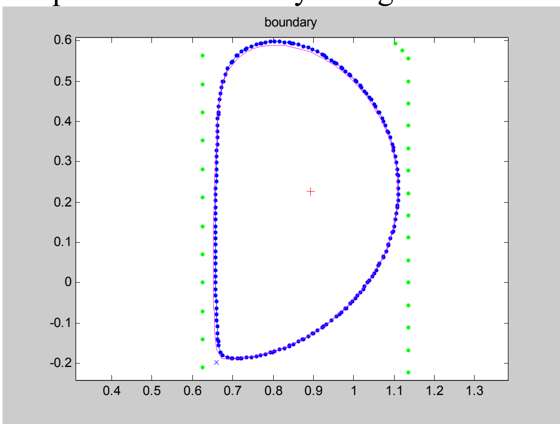




Figs.11-12. Plasma profiles and boundaries from LIUQE and reconstructed FdF/dψ.

Finally, bootstrap current was included into reconstruction procedure. Reconstruction was calculated with prescribed pressure profile, $\langle j\rangle - \langle j_{boot}\rangle$ was fitted. Profiles for this case are shown in Fig.13 and comparison of boundary in Fig.14.





Figs.13-14. Plasma profiles and boundaries from LIUQE and reconstructed equilibrium with fitted $\langle j\rangle - \langle j_{boot}\rangle$.

Conclusions

1. High accuracy plasma equilibrium reconstruction module on the basis of the adaptive grid solver SPIDER has been implemented.
2. The new method of the $\langle j \rangle$ reconstruction taking into account bootstrap current has been developed.
3. Sensitivity of reconstructed profiles dP/dψ and FdF/dψ to magnetic data were studied. It was found that absolute values of pressure profiles can not be determined without additional constraint on fitting parameters in the case of polynomial representation of current density profiles.
4. To solve correctly equilibrium reconstruction problem it is necessary to use additional kinetic plasma data from experiment.

References

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