Abstract

The talk presents a theory of uncertainties in the reconstructions of the plasma current density and pressure profiles in the Grad-Shafranov equation. The associated technique was incorporated into the ESC code. Potential variances in $q$- and $p$-profiles have been calculated for different sets of external and internal measurements envisioned for equilibrium reconstruction in ITER. It was shown that complementing the external magnetic measurements with either Stark line polarization signals (MSE-LP) or with recently proposed for ITER line Stark line polarization signals (MSE-LS) can significantly improve the reliability of the reconstructed plasma profiles and the magnetic configuration.

The talk presents a theory of uncertainties in the reconstructions of the equilibrium configuration. The associated technique was incorporated into the ESC code.
1 Set of signals for equilibrium reconstruction

ITER $B=5.3 \ T$, $I^p=15 \ MA$ $\beta = 2.8$% $\gamma = 1$ MeV NBI in ITER

One of unique features of ITER is its 1 MeV neutral beam injection.

A center line of 1 MeV NBI in ITER

Contents

1. Set of signals for equilibrium reconstruction
2. Variances in tokamak equilibrium reconstruction
3. "Rigorous" theory for "non-rigorous" reality
4. Capabilities of diagnostics for equilibrium reconstruction

4.1 Good looking magnetic only reconstruction
4.2 Magnetic signals & MSE-LP
4.3 Magnetic signals & line shift MSE-LS
4.4 Magnetic signals & both MSE-LP & MSE-LS
4.5 Free boundary, magnetic signals & both MSE-LP & MSE-LS
4.6 Curious case, NO $B$-signals, $\xi \neq 0$, $\Phi$ & both MSE-LP & MSE-LS

5. Summary
Measurements of the Line Shift due to MSE was proposed by Nova Photonics as a diagnostics of ITER configuration.

<table>
<thead>
<tr>
<th>Signal name</th>
<th>Relative $\xi$</th>
<th>Absolute $\xi$</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-coils</td>
<td>0.01</td>
<td>0.01 T</td>
<td>local probes</td>
</tr>
<tr>
<td>$\Psi$-loops</td>
<td>0.01</td>
<td>0.001 Vsec</td>
<td></td>
</tr>
<tr>
<td>$\Phi$-loop</td>
<td>0.01</td>
<td>0.001 Vsec</td>
<td></td>
</tr>
<tr>
<td>Diamagnetic loop</td>
<td>0.01</td>
<td>0.1 T</td>
<td></td>
</tr>
</tbody>
</table>

$\xi$ used here for calculating variances in equilibrium reconstruction in ITER:

The question, neglected by present practice, is what level of perturbations can not be distinguished given the finite accuracy of measurements.

$\xi$ is solution can be perturbed by

$\delta \Phi \frac{\partial \Phi}{\partial p} = \delta \Phi \frac{\partial L}{\partial \overline{\Phi}} + \frac{\partial}{\partial \overline{\Phi}} \frac{\partial (\overline{\Phi})}{\partial p} \overline{\Phi} - \frac{\partial}{\partial \overline{\Phi}} \frac{\partial (\overline{\Phi})}{\partial p} \overline{\Phi} = \Phi \cdot \nabla$

In tokamaks the Grad-Shafranov (GSh) equation describes the configuration.

The level of variances $\xi, \delta T, \delta P$ determines the very value of reconstruction.

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The theory of variances has been created in 2006 by L.Zakharov, J.Levandowski, V.Drozdo and D.McDonald.

The problem is reduced to solving the linearized equilibrium problem
\[
\bar{\Psi} = \bar{\Psi}^0 + \psi, \quad \Delta^* \psi + T'(\bar{\Psi}) \psi + P'(\bar{\Psi}) \psi = -\delta T(a) - \delta P(a) r^2
\]
for \(N\) possible perturbations
\[
\xi = \sum_{n=0}^{N-1} \alpha_n(x) \, \eta_n(\alpha)
\]
where \(x\) is the poloidal coordinate at the plasma boundary, and \(0 \leq \alpha \leq 1\) is the square root from the normalized toroidal flux.

The response of the diagnostics to each of \(N\) solutions \(\psi_n\) can be calculated in a straightforward way.

ESC is based on linearization of the GSh equation. It was complemented with a routine for analysis of variances.

The square root from the normalized toroidal flux, \(l\) is the poloidal coordinate at the plasma boundary, and \(0 \leq \nu \leq 0\) is
\[
\sin \nu = \int_{-l}^{l} f \, d\nu, \quad \cos \nu = \int_{-l}^{l} f \, d\nu, \quad dN + rN + \frac{3}{2}N = N
\]
(2.5)
\[
\int_{dN>u} f \, d\nu = \int_0^\infty f \, d\nu, \quad \int_{\frac{3}{2}N>u} f \, d\nu = \int_0^\infty f \, d\nu
\]
for possible perturbations
\[
\tilde{\nu}(\nu) - (\nu)J\nu = \phi \frac{\partial}{\partial \nu} + \phi \frac{\partial}{\partial \nu} + \phi \vec{\nabla} \phi, \quad \phi + \frac{\partial}{\partial \nu} \phi = \phi
\]
The problem is reduced to solving the linearized equilibrium problem.

The theory of variances has been created in 2006 by L.Zakharov, J.Levandowski, V.Drozdo and D.McDonald.

ESC can use an extended set of basis functions

\[\psi_n \text{ has been used to perturb} \ \tilde{\nu} \text{ functions} \]

8 functions

\[\Phi \tilde{\Psi} \text{ and} \ \tilde{\Phi} \tilde{\Psi} \text{ symmetry profiles} \]

\[\tilde{\Delta} \tilde{\Psi} \text{ background current density} \]

\[\tilde{\Pi} \text{ background pressure} \]

\[\tilde{\Psi} \text{ trigonometric expansion} \]
After solving the perturbed GSh equation, the problem is reduced to a matrix problem. The working matrix $A$ weights $\delta S$ based on their accuracy.

$$δS = A \delta X, A = A_M \times N.$$  

Here, $\lambda_i$ are the eigenvalues of the matrix problem. The columns of matrix $A$ are the normalized eigen-vectors of the problem. $\lambda_i \equiv \lambda_{ij} 1 \times N \lambda = \lambda_{ij}$

$$\mu_r = \mu_r = \mu_M \equiv \mu_{ij} 1 \times N \mu = \mu_{ij}, \lambda M \cdot \eta = \lambda M.$$  

The solution of matrix problem (3.5) generates a hierarchy of eigen-perturbations each corresponding to columns of matrix $V$.

The solution of matrix problem (3.5) represents the normalized eigen-values of the problem.

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The solution of matrix problem (3.5) represents the normalized eigen-values of the problem. The columns of matrix $A$ are the normalized eigen-vectors of the problem.
In terms of columns of matrix $V$, the eigen-perturbations $\vec{X}_k$ can be defined as:

$$\vec{X}_k \equiv \gamma_k V_k,$$

(3.6)

where factors $\gamma_k$ scale each physical perturbation to the most limiting value among characteristic $\xi_{\text{max}}$, $\delta T_{\text{max}}$, $\delta P_{\text{max}}$.

Calculation of RMS of the signals $\bar{\vec{S}}_k$ generated by each $\vec{X}_k$:

$$\delta \bar{\vec{S}}_k = A \vec{X}_k = \gamma_k w_k \vec{U}_k,$$

(3.7)

determines variances $\bar{\sigma}_k$ in reconstruction of each eigen-perturbations as:

$$\bar{\sigma}_k \equiv \sqrt{\frac{1}{M} \sum_{m=0}^{M-1} (\delta \bar{\vec{S}}_k)^2} = \gamma_k w_k \sqrt{M},$$

(3.8)

The spectrum of $\bar{\sigma}_k$ with $\bar{\sigma}_k > 1$ are "invisible" for diagnostics.

Perturbations $\vec{X}_k$ with $\bar{\sigma}_k > 1$ are "invisible" for diagnostics.

Different combinations of signal lead to different residual variances.

Reference signal errors used here for calculating variances in equilibrium reconstruction in ITER:

<table>
<thead>
<tr>
<th>Signal name</th>
<th>$\epsilon_{\text{relative}}$</th>
<th>$\epsilon_{\text{absolute}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-coils</td>
<td>0.01</td>
<td>0.01 T</td>
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<tr>
<td>local probes</td>
<td>0.01</td>
<td>0.001 V/sec</td>
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<td>0.01</td>
<td>0.001 V/sec</td>
</tr>
</tbody>
</table>

Calculation of RMS of the signals generated by each signal.

Calculation of RMS of the signals $\bar{\vec{S}}_k$ generated by each signal:

$$\delta \bar{\vec{S}}_k = A \vec{X}_k = \gamma_k w_k \vec{U}_k,$$

where factors $\gamma_k$ scale each physical perturbation to the most limiting value.

In terms of columns of matrix $V$, the eigen-perturbations can be defined as:

$$\vec{X}_k \equiv \gamma_k V_k,$$

(3.6)

Eigen-values $\gamma_k$ determine visibility of eigen-perturbations.
KiloGb's of reconstructions "data" can be easily generated.

For \( k_J + k_P = 2 \) typically used, the reconstruction looks very good.

Good looking magnetic only reconstruction

Plasma boundary is well specified, \( \Phi \)-loop, \( B \)-coils are used.

Perturbations \( \delta_{J_k} \) and \( \delta_{P_k} \) on the left plot are RMS for \( g \)-profile and variances in \( p \)-profile as functions of \( a \) and \( q \) \([\text{MPa}]\). Signals \( \delta S_m / \epsilon_m \) generated by perturbations \( \delta_{J_k} \) and \( \delta_{P_k} \).

For \( k_J + k_P = 5 \), typically used, the reconstruction looks very good.  

KiloGb's of reconstructions "data" can be easily generated.
4.1 Good looking magnetic only reconstruction (cont.)

Plasma boundary is well specified, $\Phi$-loop, $B$-coils are used

$q_{i0}=0$ $i_1=21$ $k_0=0$ $k_1=7$

$a$    0    0.2    0.4    0.6    0.8

$p$ [MPa] $i_0=0$ $i_1=21$ $k_0=0$ $k_1=8$

$a$    0    0.2    0.4    0.6    0.8

$\delta S_m/\epsilon_m$ generated by perturbations

$p$ profile and variances as functions of $a$

$q$ profile and variances for $k_J \leq 4$, $k_P \leq 3$

$\delta S_m/\epsilon_m$ generated by perturbations

Testing $k_J+k_P=7$ shows that the reconstruction is, in fact, not so good

$\delta S_m/\epsilon_m$ generated by perturbations

$q$ profile and variances as functions of $a$

$\delta S_m/\epsilon_m$ generated by perturbations

$q$ profile and variances as functions of $a$

$\delta S_m/\epsilon_m$ generated by perturbations
4.1 Good looking magnetic only reconstruction (cont.)

Plasma boundary is well specified, $\Phi$-loop, $B$-coils are used

$q_{i0}=0 \ i_{1}=21 \ k_{0}=0 \ k_{1}=16$

$g_{d}$ Signal

$log_{10}$ of Errors in $j,q,p$ Variance=$1.000e+02$

Test of $k_{J}+k_{P}=16$ shows that with no constrains the reconstruction has no scientific value and is a sort of "beliefs"

Leonid E. Zakharov, Conference on Diagnostics of High Temperature plasma, Zvenigirod, RF, June 3-8, 2007

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4.2 Magnetic signals & MSE-LP

Fixed plasma boundary with ($\Phi$ & $B$ & MSE-LP) signals

Magnetic signals & MSE-LP
Only perturbations with \( a < 1.5 \) might be potentially troublesome for all \( k \). Signals and variances of \( q \) and \( p \) profiles and variances as functions of \( a \).

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4.2 Magnetic signals \& MSE-LP (cont.)
Use of MSE-LS can compete with MSE-LP in its value for reconstruction.

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Fixed plasma boundary with (Φ & B & MSE-LS) signals

Log$_{10}$ of Errors in $j$, $q$, $p$ Variance = $1.000 \times 10^{2}$

$I_{p}=15.000 \ [MA] \ \ B_{t}=5.3000 \ [T]$

$\text{err} B_{p}=0.010 \ 0.0100 \ [T]$

$\text{err} g_{F}=0.010 \ 0.0010 \ [Vsec]$

$\text{err} MSE-LS=0.010 \ 0.0050 \ [T]$

Log$_{10}$ of Errors in $j$, $q$, $p$ Variance = $1.000 \times 10^{2}$

$I_{p}=15.000 \ [MA] \ \ B_{t}=5.3000 \ [T]$

$\text{err} B_{p}=0.010 \ 0.0100 \ [T]$

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$\text{err} MSE-LP=0.010 \ ^{2}[^{o}]$

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$\text{err} B_{p}=0.010 \ 0.0100 \ [T]$

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Log$_{10}$ \{\bar{\sigma}_k, \bar{\sigma}_k q, \bar{\sigma}_k p\} in case of (Φ & B & MSE-LS)

Log$_{10}$ \{\bar{\sigma}_k, \bar{\sigma}_k q, \bar{\sigma}_k p\} in case of (Φ & B & MSE-LP)

Log$_{10}$ \{\bar{\sigma}_k, \bar{\sigma}_k q, \bar{\sigma}_k p\} in case of (Φ & B)

4.3 Magnetic signals & line shift (cont.)

Fixed plasma boundary with (Φ & B & MSE-LS) signals

4.3 Magnetic signals & line shift MSE-LS

Use of MSE-LS can compete with MSE-LP in its value for reconstruction.

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Fixed plasma boundary with (Φ & B & MSE-LS) signals

4.3 Magnetic signals & line shift MSE-LS
MSE-LS can pick up the details of the current drive.

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Both MSE-LP & LS allows for a reliable reconstruction of q- and p-profiles.

With MSE-LS only perturbations with $k \geq 13$ might be potentially troublesome.

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Free boundary expands the $k$ range but does not affect the reconstruction.

$$0 = \tilde{\gamma}(0)$$

$0 \neq \tilde{\gamma}$

If $\vec{\xi} = 0$:

$$0 = \tilde{\gamma}(0)$$

$0 \neq \tilde{\gamma}$

For all $k$ and $\phi$-profiles can be reconstructed in all spectrum of $\tilde{\gamma}$

$p$-profile and variances $\bar{\sigma}_k$, $\bar{\sigma}_q$, $\bar{\sigma}_p$ generated by perturbations.

$\tilde{\gamma}$ and $p$-profiles for all $k$ and $\phi$-profiles can be reconstructed in all spectrum of $\tilde{\gamma}$.

---

Free boundary expands the $k$ range but does not affect the reconstruction.

$p$-profile and variances $\bar{\sigma}_k$, $\bar{\sigma}_q$, $\bar{\sigma}_p$ generated by perturbations.

For all $k$ and $\phi$-profiles can be reconstructed in all spectrum of $\tilde{\gamma}$.

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4.4 Magnetic signals & both MSE-LP & MSE-LS (cont.)
Free boundary, magnetic signals & both MSE-LP & MSE-LS (cont.)

Free boundary plasma with \((\Phi \& B \& MSE-LP \& MSE-LS)\) signals

\[ q_{i0} = 0 \quad i_1 = 21 \quad k_0 = 0 \quad k_1 = 32 \]

\[ a \quad 0 \quad .2 \quad .4 \quad .6 \quad .8 \]

\[ p \quad [\text{MPa}] \quad i_0 = 0 \quad i_1 = 21 \quad k_0 = 0 \quad k_1 = 32 \]

\[ a \quad 0 \quad .2 \quad .4 \quad .6 \quad .8 \]

\[ gd \quad \text{Signal} \quad k_0 = 0 \quad k_1 = 32 \]

\[ m \quad 0 \quad 50 \quad 100 \]

\[ \log_{10} \text{of Errors in } j, q, p \text{ Variance} = 1.000 \times 10^2 \]

\[ k \quad 0 \quad 10 \quad 20 \quad 30 \]

\[ \log_{10} \text{of Errors in } j, q, p \text{ Variance} = 1.000 \times 10^2 \]

\[ k \quad 0 \quad 5 \quad 10 \quad 15 \]

\[ \log_{10} \text{of Errors in } j, q, p \text{ Variance} = 1.000 \times 10^2 \]

\[ I_{pl} = 15.000 \quad [\text{MA}] \quad B_t = 5.3000 \quad [\text{T}] \]

\[ \text{err} \quad g_Y = 0.010 \quad 0.0010 \quad [\text{Vsec}] \]

\[ \text{err} \quad g_F = 0.010 \quad 0.0010 \quad [\text{Vsec}] \]

\[ \text{err} \quad MSE-LP = 0.010 \quad 0.10 \quad [\text{°}] \]

\[ \text{err} \quad MSE-LS = 0.010 \quad 0.0050 \quad [\text{T}] \]

\[ \log_{10} \{ \bar{\sigma}_k, \bar{\sigma}_q, \bar{\sigma}_p \} \text{ in case of } (\Phi \& B \& MSE-LP \& MSE-LS) \]

\[ \| \bar{\xi} \| \neq 0 \]

\[ \log_{10} \{ \bar{\sigma}_k, \bar{\sigma}_q, \bar{\sigma}_p \} \text{ in case of } (\Phi \& B \& MSE-LP) \]

\[ \| \bar{\xi} \| = 0 \text{ (MSE-LP \& MSE-LS) together can do the job for external } B\text{-coils} \]

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The extension of the theory of equilibrium reconstruction capability in ITER, even with NO \(B\)-coil signals, \(h\) and \(p\)-profiles can be reconstructed over extended spectrum of \(a\) with perturbations of \(u\) and \(v\) for all extended \(q\)-profiles.

Free boundary, \(\Phi\) \& MSE-LP signals, NO \(B\)-signals (cont.)