Equilibrium Reconstructions with V3FIT and Current Evolution Modeling for 3-D Stellarator Plasmas

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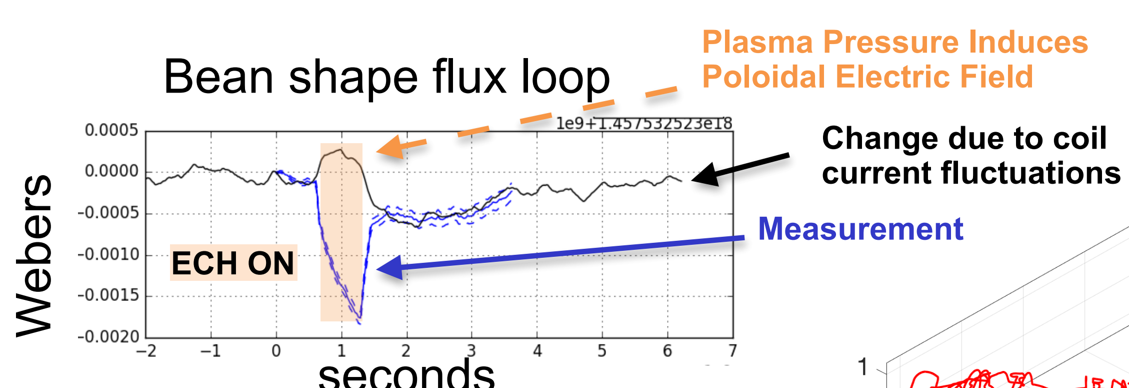
V3FIT Equilibrium Reconstruction

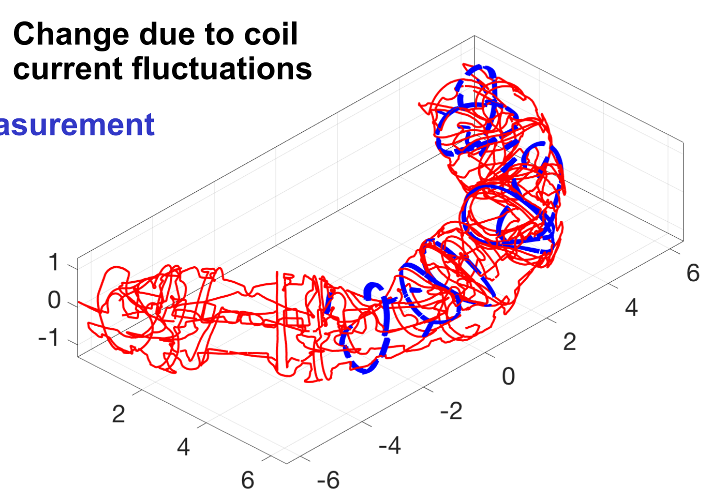
V3FIT[1] is a powerful equilibrium reconstruction tool for magnetic confinement fusion experiments which are inherently 3-D in nature (i.e. stellarators) or have 3-D components (tokamaks with 3-D shaping, reversed field pinches with helical states, etc). Here, we present details of the diagnostic modeling, constraints and the user interface for reconstructions of W7-X plasmas.

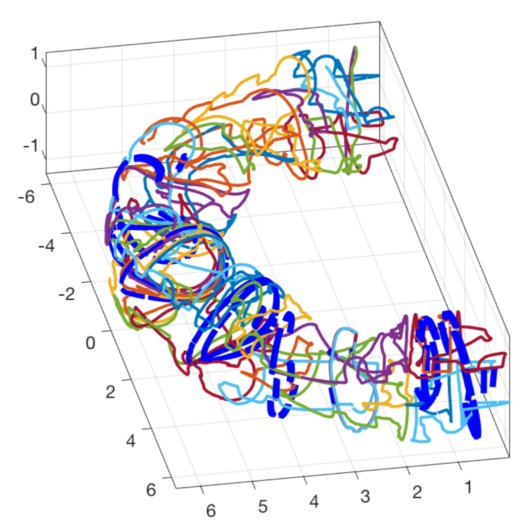
W7-X Magnetics

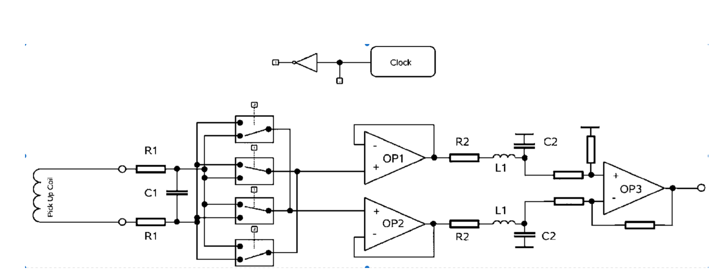
A subset of the total installed magnetic diagnostics[2] were available for OP 1.1

- Compensated Diamagnetic Loops x2 - near triangular plane
  - Uncompensated x2 - near bean-shaped plane
- 100's of 'Saddle' Flux Loops, partial Rogowski coils, complete Rogowski coils
- Signal connections designed to mitigate thermoelectric potentials
- Non-integrated signals are chopped at 2kHz; Sampled at 2 MHz.
  - Down-sampled for long pulse coil tests (20 sec)
- Signal processing handles chopper 'blips', voltage offsets, long term drifts
- A W7-X design objective was to minimized plasma-generated currents
- Electronics designed for 30-minute operation[3,4].
- Large variation in channel-to-channel signal levels
  - Some 'tuning' still required
- Can detect variations as small as 1-5 Amperes in superconducting field coils
  - Signal is highly correlated with change in coil current flux









See Ref 3

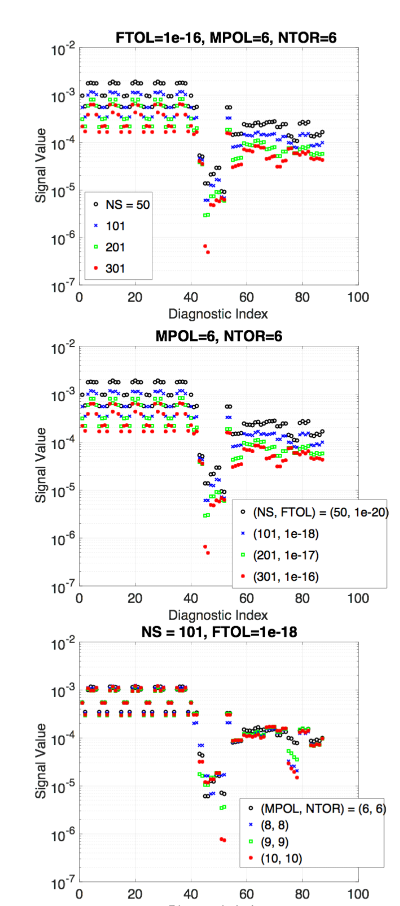
Magnetics-Based Reconstructions

- V3FIT varies the profile specifications and minimizes the difference between model and observation

$$g^2(p)=\sum_i \kappa_i\left(\frac{S_{o,i}-S_{m,i}(p)}{\sigma_i}\right)^2$$

- Profile specifications: Pressure, current (or current density), distance to limiter edge, enclosed toroidal flux

- Calculation of magnetic sensor signals requires plasma current density distribution
- Current density from VMEC output has a 'vacuum-offset'
- Function of VMEC parameters
  - NS
  - FTOL
  - MPOL
  - NTOR
  - + ?
- Vacuum-offset is larger than many measured signals from OP 1.1



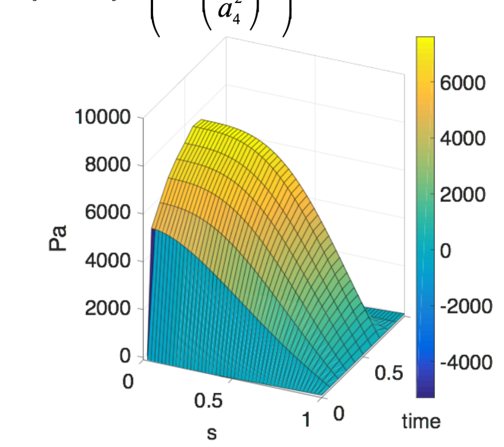
Pressure profile

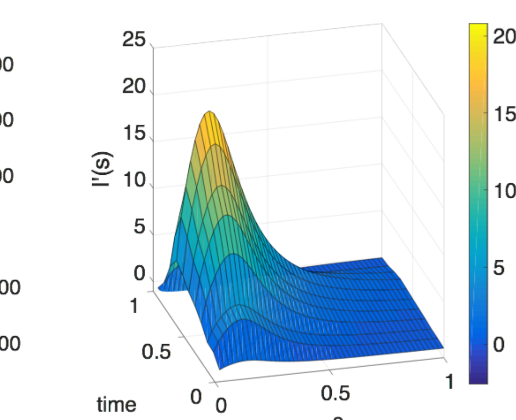
$$p(s)=presscale\cdot\left[\frac{1}{N_0}\left(\left(1+\left(\frac{s}{a_2^2}\right)^{a_3}\right)^{-a_4}-c_0\right)\right]$$

$$N_0=1-c_0 \text{ and } c_0=\left(1+\left(\frac{1}{a_4^2}\right)^{a_3}\right)^{-a_4}$$

Enclosed current profile

$$I_{enclosed}(s)=curtor\frac{2}{\pi}\arctan\left(\frac{a_2 s^{a_3}}{(1-s)^{a_4}}\right)$$

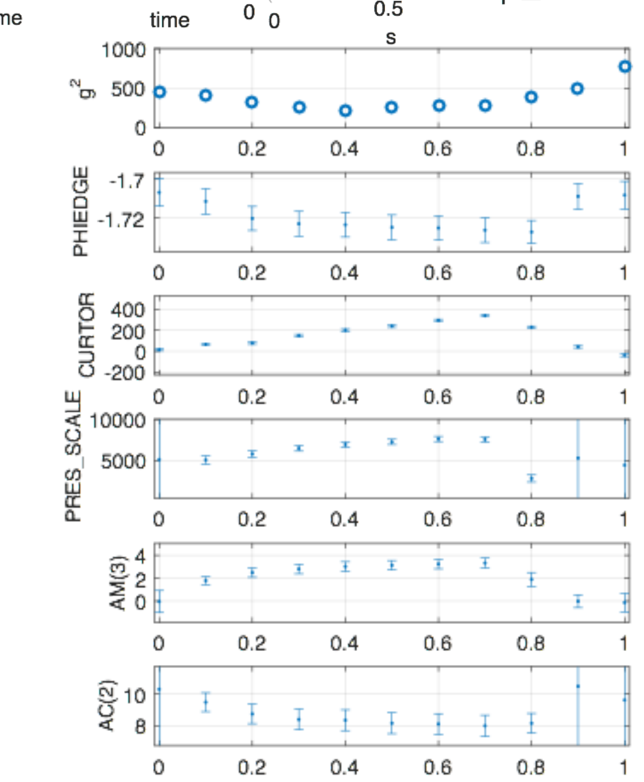




- Pressure Profile: Two_Lorentz
- Current Profile : Sum_atan

- Initial guess (**Fit Parameter**):
  - AM: (1, 1, 1, **1**, 1, 1, 1, 1, 1)
  - PRES_SCALE: **5000**
  - AC: (0, 1, **10**, 1.5, 1)
  - CURTOR: **200**
  - PHI_EDGE=**1.7104**

- Minimal solution found
  - Magnetic constraints only
  - Free boundary solution
  - Field coils current variations included
  - Thomson and ECE added soon



With magnetics alone:

- The pressure profile *shape* is similar to Thomson Scattering, but differs in magnitude by up to 40%
- Current density profile is poorly constrained
- Low-Beta reconstructions: influenced by uncertainties & weights applied to individual diagnostics
- Variations in main field coils are important to include in the model
- As the uncertainties are minimized, the reconstructions will improve

References

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Current Evolution in 3-D

For typical discharges during the OP1.1 run campaign of W7-X, the net toroidal current and current density profile do not reach steady-state. When modeling the current evolution in 3-D plasmas, both poloidal and toroidal currents are linked with both poloidal and toroidal fluxes. In contrast, in toroidally axisymmetric plasmas, the poloidal flux is linked only with the toroidal current and the toroidal current is linked only with the poloidal flux. Compared to an equivalently-sized axisymmetric configuration, the current diffusion in 3-D plasmas is enhanced, leading to a faster relaxation of the current profile to its steady-state. Implications for the time-evolution of the current and rotational transform profiles in stellarator plasmas are discussed.

Time Evolution

3d susceptance matrix[5] links toroidal and poloidal currents and magnetic fluxes

$$\mu_0\begin{pmatrix} I \\ F \end{pmatrix}=\begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix}\begin{pmatrix} \Psi' \\ \Phi' \end{pmatrix}$$

$S_{12} = S_{21} = 0$ for Tokamaks
$S_{11} \approx S_{12} \approx S_{21}$ for Stellarators

1-D diffusion equation for rotational transform

$$s=\Phi/\Phi_{LCFS} \qquad ' = d/ds$$

Any non-inductive source

$$\frac{d\iota}{dt}=\frac{1}{\Phi_{LCFS}^2}\frac{d}{ds}\left(\eta_\parallel V'\left[\frac{\langle B^2\rangle}{\mu_0}\frac{d}{ds}(S_{11}\iota+S_{12})+p'(S_{11}\iota+S_{12})-\langle \mathbf{J}\cdot\mathbf{B}\rangle\right]\right)$$

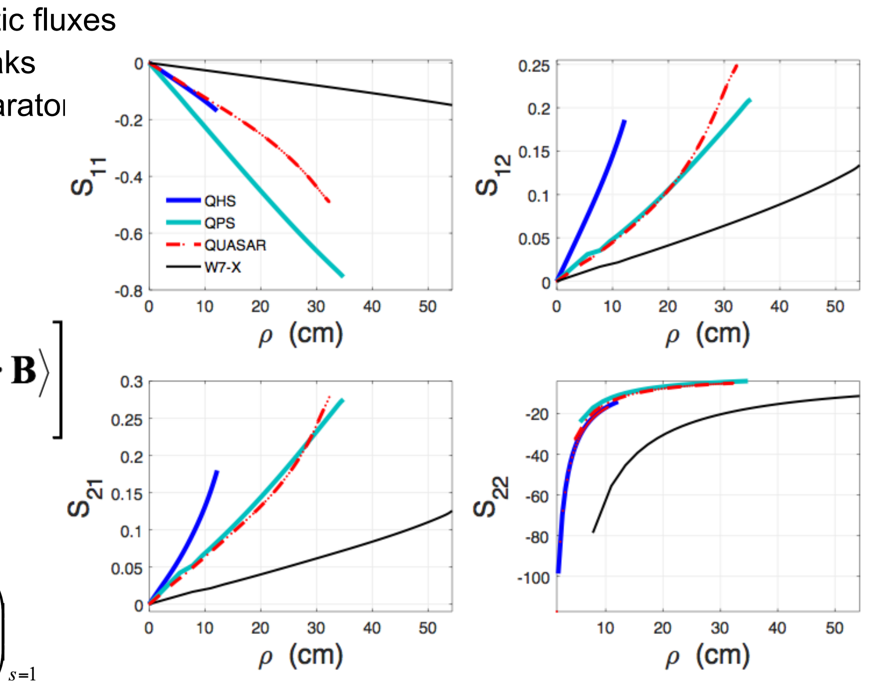
Boundary conditions

On axis: finite current density

$$\left.\frac{d\iota}{ds}\right|_{s=0}=0$$

@ LCFS :measurement

$$\iota|_{s=1}=\left(\frac{\mu_0 I}{S_{11}\Phi'}-\frac{S_{12}}{S_{11}}\right)_{s=1}$$



Next Steps

- Distribute magnetics analysis GUI
- Enable V3FIT as a Webservice
- Incorporate Thomson Scattering and ECE diagnostics into V3FIT reconstructions
- Investigate the effects of the enhanced relaxation due to 3-D effect in W7-X compared to axisymmetric modeling/scenario development
- ECH heating scans (OP 1.1) and dedicated experiments in OP 1.2 to test current relaxation and edge effects

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