# Reconstructions of toroidal current profiles for bootstrap current discharges in Wendelstein 7-X

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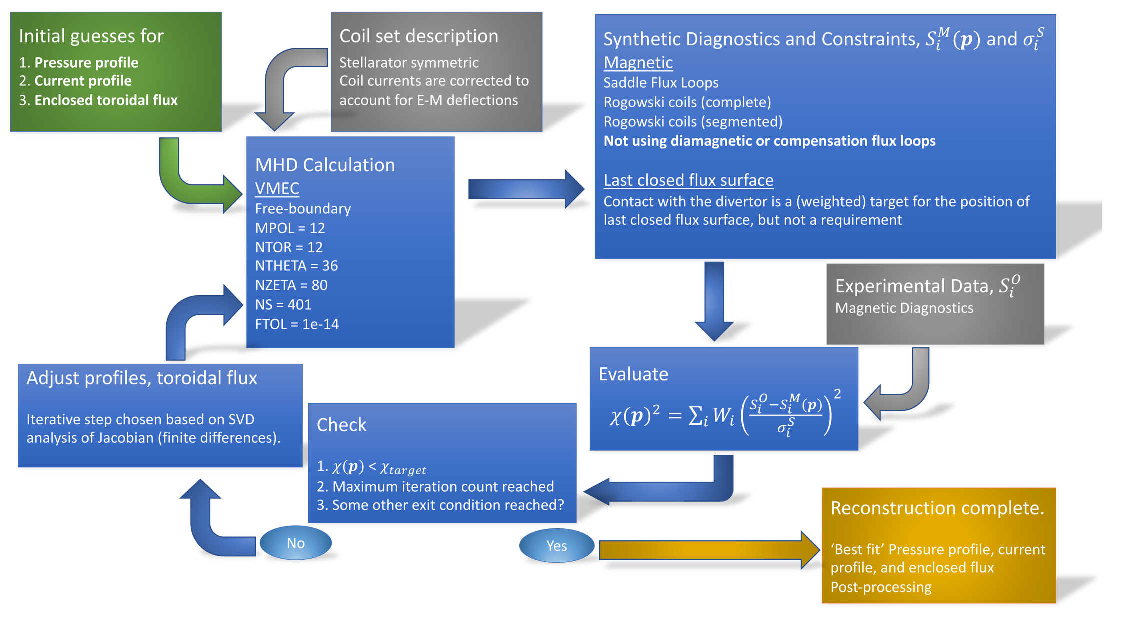
## Abstract

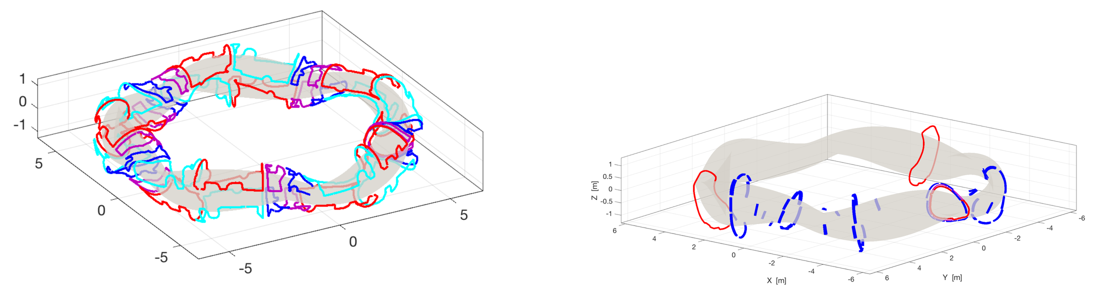
The reconstruction of the Wendelstein 7-X (W7-X) plasma equilibrium plays an important role in interpreting diagnostic signals and understanding the plasma. The reconstruction is iterative in nature, involving the repeated calculation of the MHD equilibrium and synthetic diagnostic signals and comparing these signals to measured signals. The parameters that describe the equilibrium (shape of the plasma, location of the boundary and profile information of the individual plasma species) are adjusted between iterations to find the best-fit of the measured and synthetic signals. These profiles are then used to interpret diagnostic information and for further physics analysis.

Here, the predicted evolution of toroidal current profiles is compared to reconstructions constrained by magnetic diagnostics. The initial pressure profiles are based on profile estimates from Thomson Scattering, interferometry, and x-ray imaging crystal spectroscopy. The presence of the 5/5 island-chain is ignored by the VMEC MHD calculations, and the last-closed flux surface is targeted (but not constrained) to touch the divertor plates. A prediction of the time-evolved current density profile for one case has been performed with the transport simulation of the poloidal flux using the NTSS-code. Comparisons to reconstructions are made at 'early' and 'late' time slices during the bootstrap discharges. The sensitivity of the reconstructions to the current density profile and its parameterization, and its dependence on diagnostic constraints and initial profiles are characterized. The outlook and future plans for the application of V3FIT reconstructions to W7-X plasmas are also discussed.

## Reconstruction Workflow




## Magnetic diagnostics



**Left**: 4 types of stellarator symmetric saddle coils for each of the 5 field periods. The plasma LCFS is shown in grey.

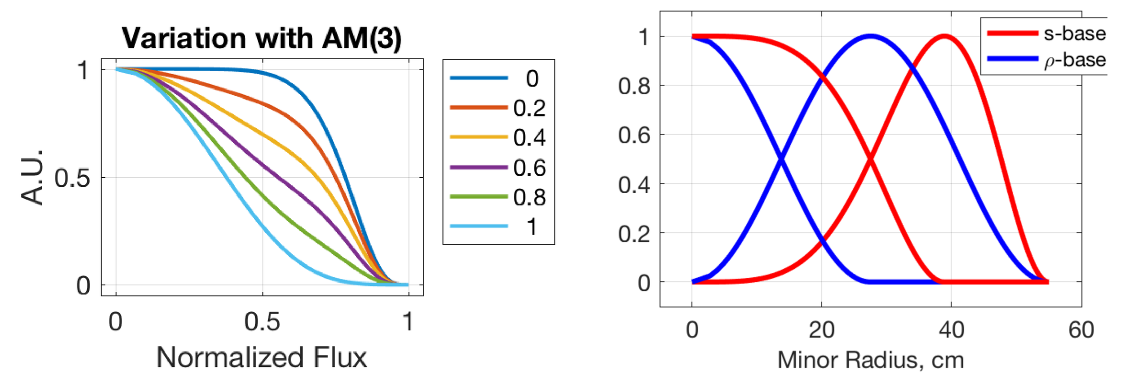
**Right**: Segmented Rogowski coils (in blue) measure $\int \mathbf{B} \cdot dl$ and provide good poloidal coverage over 2 field periods.

**Experimental Uncertainties** (Wb or T)

Saddle Loops: (Type 1: 4e-5, Type 2: 5e-5, Type 3:7e-5, Type 4: 2.5e-5)

Rogowski Coils, Segmented: 1e-5, Complete: 5e-5

## Profiles and Basis Functions




**Pressure profiles** (left) use a two-two-power parameterization:

$$\frac{P(s)}{P_0} = \left((1 - AM_3)\left(1 - s^{AM_1}\right)^{AM_2} + AM_3\left(1 - s^{AM_4}\right)^{AM_5}\right)$$

- Free Parameters: $P_0$ and $AM_3$
- Constants: $AM_1 = 1.0$, $AM_2 = 4.5$, $AM_4 = 4.0$, $AM_5 = 4.5$

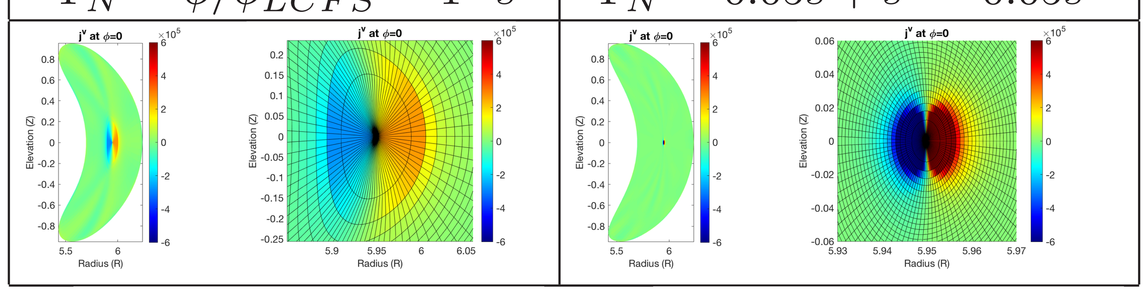
**Current density basis functions and profiles**

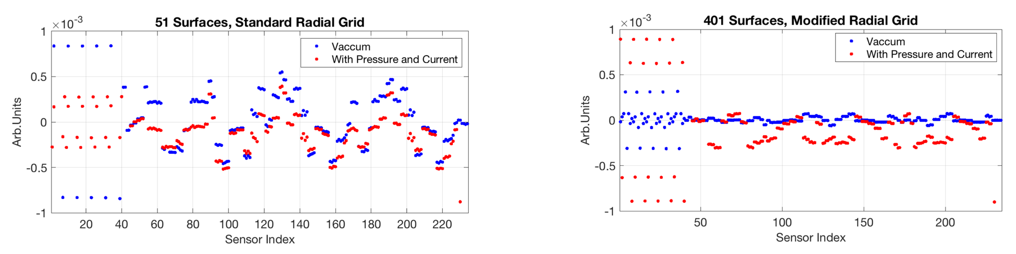
- Radial profile is specified by an analytic 'sum of $cos^2$' profiles with $AC_0 = N_{cssq}$ independent radial 'zones'.
- The profile shape is normalized according to the net toroidal current carried by the plasma. $CURTOR = \int_{s=0}^{s=1} ds 2\pi J(s)$.
- Radial coordinate can be $s = \Phi_{tor}/\Phi_{tor,LCFS}$ or $\rho = \sqrt{s}$.
- The coefficients $AC_1$ and $AC_2$ specify the relative magnitude of the local current density near the axis and near the mid-radius, respectively.
- Right: Demonstrating the difference between the s-based and $\rho$-based profiles on a common radial grid for $cos^2$-basis functions for $N_{cssq} = 3$.
- In both cases, the edge current density is restricted to be $j_{tor}(LCFS) = 0$ by restricting the $AC_3 = 0$.

## High Fidelity MHD Solutions

- A residual dipole current density exists near the magnetic axis (even at $\beta = 0$), rotates poloidally 1/field period, and contributes synthetic error to the magnetic signals.
- Increasing the number of surfaces and adjusting the grid spacing both reduce the residual on-axis current density and vacuum magnetic 'fingerprint'.
- The residual numerical noise can contribute to the synthetic magnetic response - minimizing this improves the reconstruction accuracy, precision, and robustness.

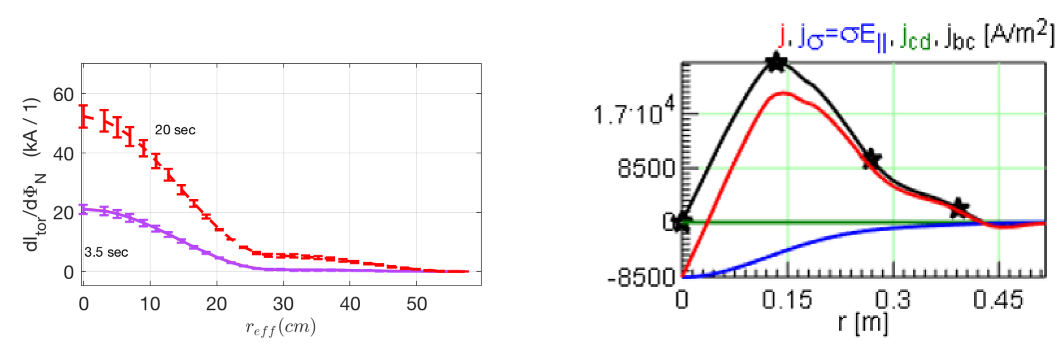
| Standard Grid, NS=51 $\Phi_N = \phi/\phi_{LCFS} = 1 \cdot s$ | Modified Grid, NS=401 $\Phi_N = 0.05s + s^2 - 0.05s^3$ |
|---|---|






## Time evolution modeling

- The reconstructions early/late in time display an expected behavior, if some residual ECCD current is present.
- **Left**: Reconstruction of toroidal current density @ 3.5 sec (purple) and 20 sec(red).
- **Right**: NTSS simulation of the bootstrap current @ 20 sec. Total toroidal current density in red.
- X-axis scaling difference of $\sim B_0$ due to normalization.



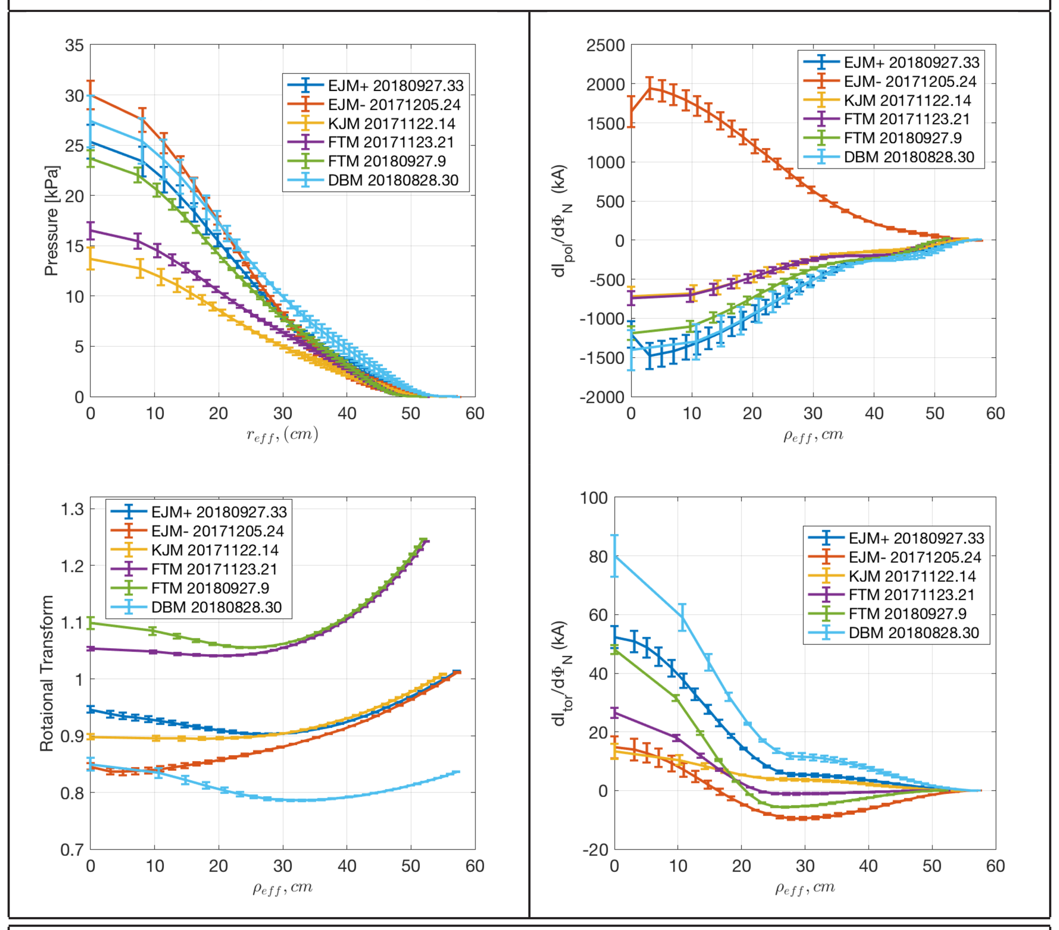

## Conclusion and Next Steps

- Pressure profile reconstructions are not very sensitive to the choice of basis function for the $j_{tor}$ profiles.
- Reconstructions of $j_{tor}$ with $\rho$-based $j_{tor}$ profiles provide reasonable results, if ECCD is considered.
- Limited agreement may be due to either restrictions in reconstruction model or because the diagnostics or not sensitive enough to distinguish between different profiles. Spectroscopy (i.e. XMCTS) may help differentiate between profiles. Future plans include using XMCTS in V3FIT.
- Neoclassical bootstrap current calculations are not performed for all XPs in this work - Although many cases are close to existing NTSS simulations.
- OP 1.2A data relies on XICS for $T_i$ measurements, and Thomson scattering does not have inboard coverage of the plasma cross-section.
- Only a few 'long-pulse' discharges available.

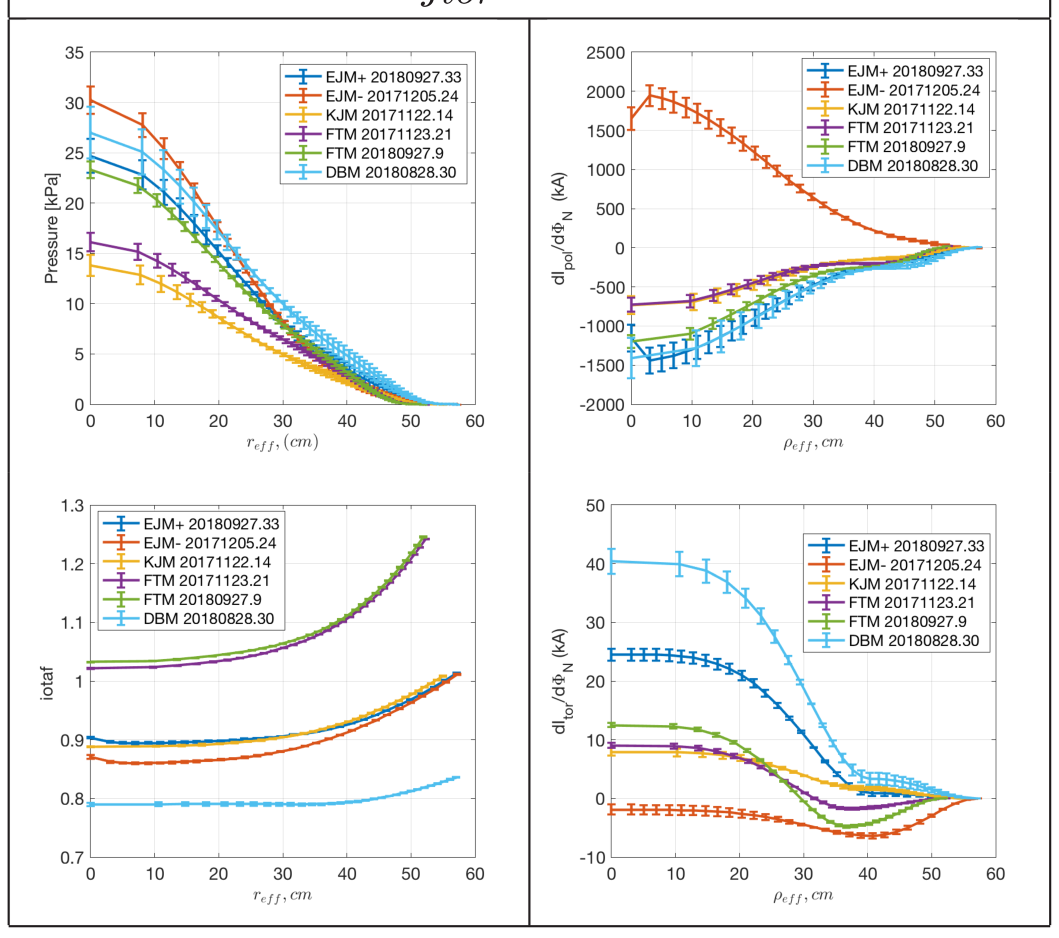
## Long Pulse Reconstructions

| | |
|---|---|
| EIM (+) | 20180927.033 @ t= 20.0 sec |
| EIM (-) | 20171205.024 @ t=18.0 sec |
| KJM | 20171122.014 @ t=16.0 sec |
| FTM (v1) | 20171123.021 @ t=22.0 sec |
| FTM (v2) | 20180927.009 @ t=22.0 sec |
| DBM | 20180828.030 @ t=18.0 sec |

$\rho$-based $j_{tor}$ reconstruction




s-based $j_{tor}$ reconstruction




## References

- **VMEC**: "Steepest-descent moment method for three-dimensional magnetohydrodynamic equilibria", Hirshman and Whitson, Phys. Fluids, **26** (1983).
- **V3FIT**: "V3FIT: a code for three-dimensional equilibrium reconstruction" J. D. Hanson, et. al., Nuclear Fusion, **40** (2009).
- "Uncertainty Analysis in 3D Equilibrium Reconstruction", M.R. Cianciosa, et. al., Fusion Science and Technology, **74** (2018).
- **NTSS**: "Neoclassical transport simulations for stellarators", Turkin, Y., et. al., Physics of Plasmas, **18** (2011).

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