Abstract

The reconstruction of the plasma equilibrium is a vital tool for toroidal fusion experiments to understand plasma performance and interpret diagnostic signals. The procedure involves solving the MHD equilibrium, computing synthetic diagnostic signals, and comparing these signals to measured signals. The parameters that describe the equilibrium are adjusted to match the synthetic signals to the measured ones. Information gained from the reconstruction includes the shape and location of the plasma and profile information regarding the plasma pressure, current, and individual plasma species which are subsequently used to interpret diagnostic information and for further analyses.

Constraints for plasma reconstructions at Wendelstein 7-X (W7-X) include magnetic diagnostics, Thomson Scattering, interferometry, electron cyclotron emission, soft x-ray arrays and x-ray imaging crystal spectroscopy. Treatments of edge constraints related to the edge rotational transform and divertor location are also presented. The MHD equilibrium solution is provided by VMEC, which assumes solutions with nested, closed flux surface. The current status and future plans for equilibrium reconstructions for W7-X are shown and discussed.

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Equilibrium Reconstruction Codes

The reconstruction is found be minimizing the cost function:

$$\chi(\boldsymbol{p})^2 = \sum_i \left(\frac{S_i^O - S_i^M(\boldsymbol{p})}{\sigma_i^S} \right)^2$$

S_i^O: Observed signals (measured diagnostic data)
$\boldsymbol{p}$: Parameters that describe plasma equilibrium
$S_i^M(\boldsymbol{p})$: Model predicted signals (synthetic model data)
σ_i^S: Diagnostic uncertainty

	MINERVA	STELLOPT	V3FIT	WAPID_FIT
MHD Solution	VMEC	VMEC	VMEC	None/Vacuum
Edgy Boundary	Fixed or Free	Fixed	Fixed or Free	Fixed
Magnetics	Yes (Mutual Inductance)	Yes (Virtual Casing)	Yes (Mutual Inductance)	None
Coil Currents	Yes	Yes	Yes	Yes
Interferometry	Yes	Yes	Yes	Yes
Thomson Scattering (T.S.)	Yes	Yes	Yes	Yes
X-Ray Imaging Crystal Spectroscopy (XICS)	Yes	Yes	Yes	Yes
Electron Cyclotron Emission (ECE)	Yes	Yes	Partial	No
X-ray Multi-Channel Tomography System (XMCTS)	Yes	Yes	Yes	No
CXRS	Yes	Yes	No	No

Plasma Fitting Parameters

- Pressure and current profiles may be parameterized by a variety of expressions (polynomials, splines, etc.).

Radial Coordinate: $s \equiv {}^{\psi}/_{\psi_{LCFS}}$ $\quad \psi_{LCFS} = PHIEDGE \quad I(s=1) = CURTOR$

$$P_{Total}(s) = am(0) \cdot \left[1 - s^{am(1)}\right]^{am(2)}$$

$$P_e(s) = f_{P_e} \cdot P_{Total}(s)$$

$$n_e(s) = SF(1) \cdot \left(b(0) + b(1) \cdot \left[1 - s^{b(2)}\right]^{b(3)}\right)$$

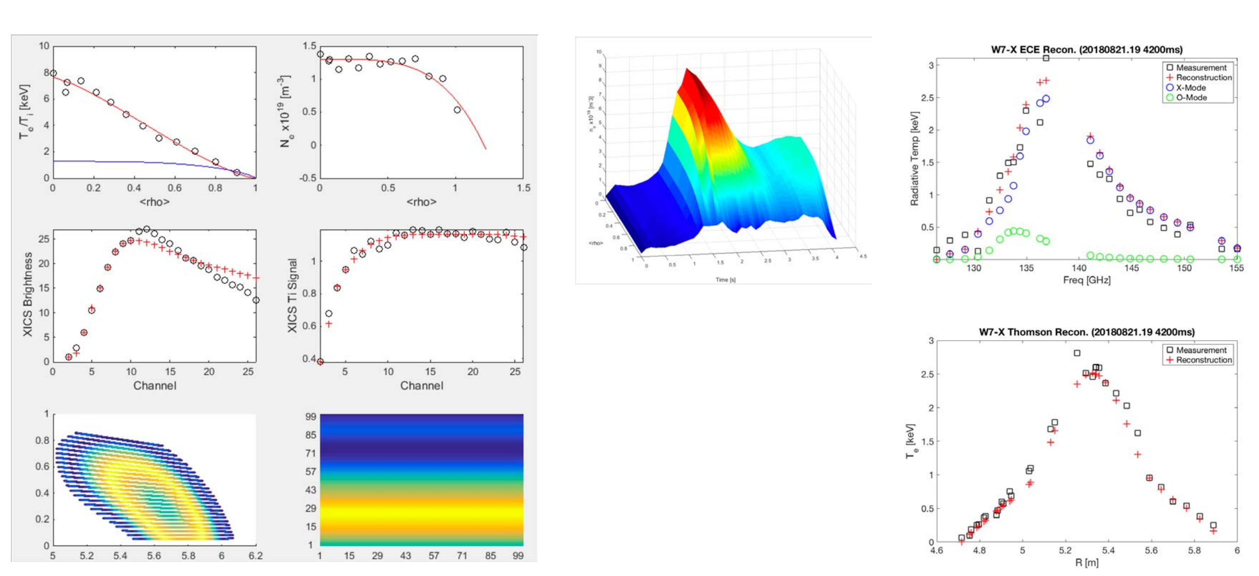
$$I(s) \propto ac(1) \cdot arctan\left(ac(2) \frac{s^{ac(3)}}{(1-s)^{ac(4)}}\right) + \cdots$$

or

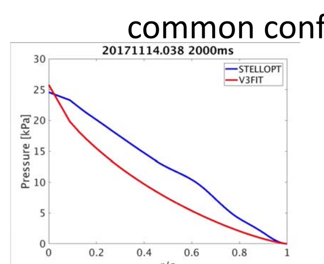
$$I(s) \propto ac(1) \cdot cos^2(\pi\,(x - x_i)/(2\,\Delta x)) + \cdots$$
$$x \in [x_i - \Delta x : x_i + \Delta x]$$
$$x = s \text{ or } \sqrt{s}$$

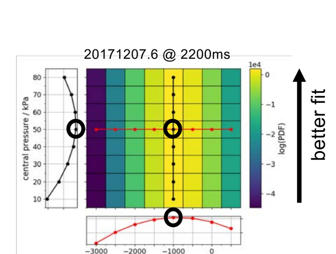
Recent Updates

- MINERVA: Mutual inductance algorithms implemented and tested
- STELLOPT: Interfaced to WAPID_FIT allowing improved initial guess for profiles
- V3FIT: XICS Diagnostic integration and BMW -> FLARE pipeline has been streamlined
- WAPID_FIT: Rapid fitting algorithm for profile reconstruction. Utilizes fixed boundary zero beta equilibria for lookup table generation



- Comparisons between MINERVA, STELLOPT and V3FIT are underway
  - Common set of diagnostic definitions and magnetic configurations established.
  - Field coil coordinates with EM-loading effects available for several common configurations.

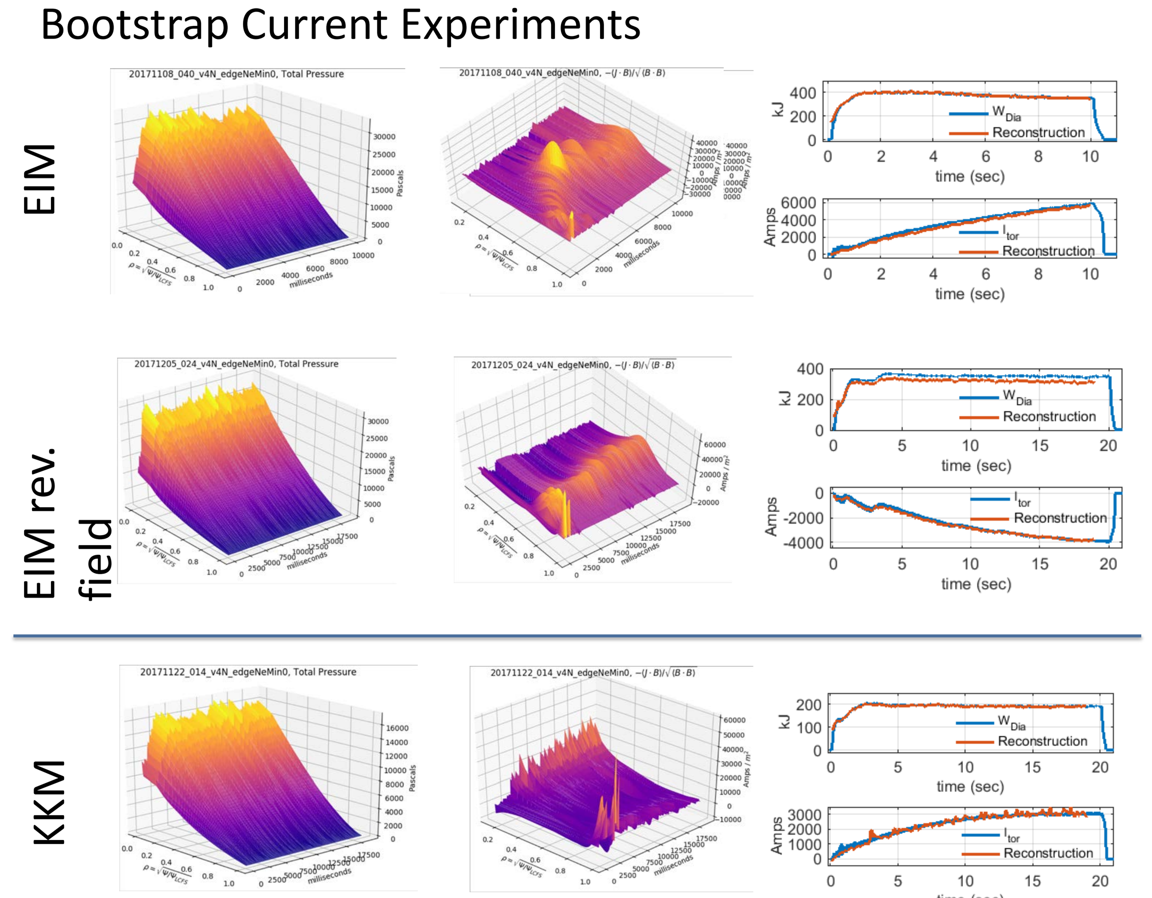




Bootstrap Current Experiments

- Long pulse experiments are necessary to determine the steady-state bootstrap current profile
- Shielding currents are induced which counter the BS and ECCD current
- They decay resistively on fast internal (skin) and slow external (L/R) timescales, leaving behind only the combination of BS and ECCD.
- Neoclassical transport modeling with SFINCS is underway; Time-evolution modeling to follow.
- Several long-pulse shots completed with a variety of operating power, density and wall conditions

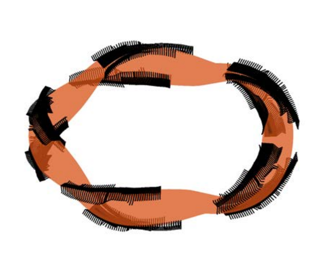
Bootstrap Current Experiments

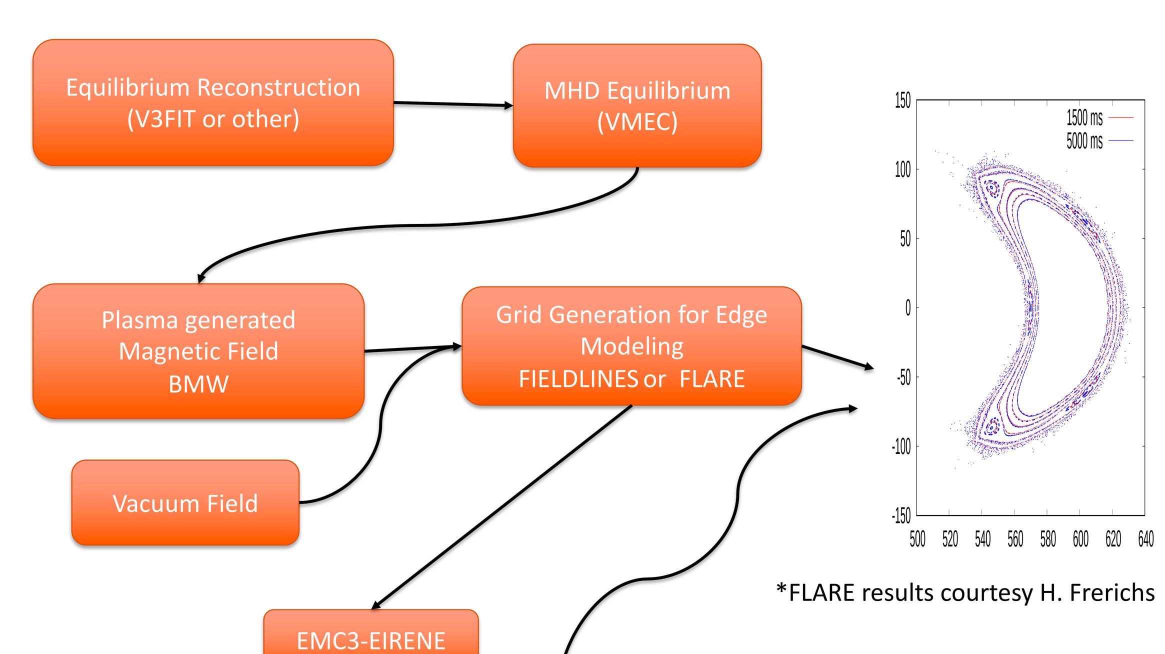


Edge & Divertor: Modeling and Experiments

Boundary Constraints

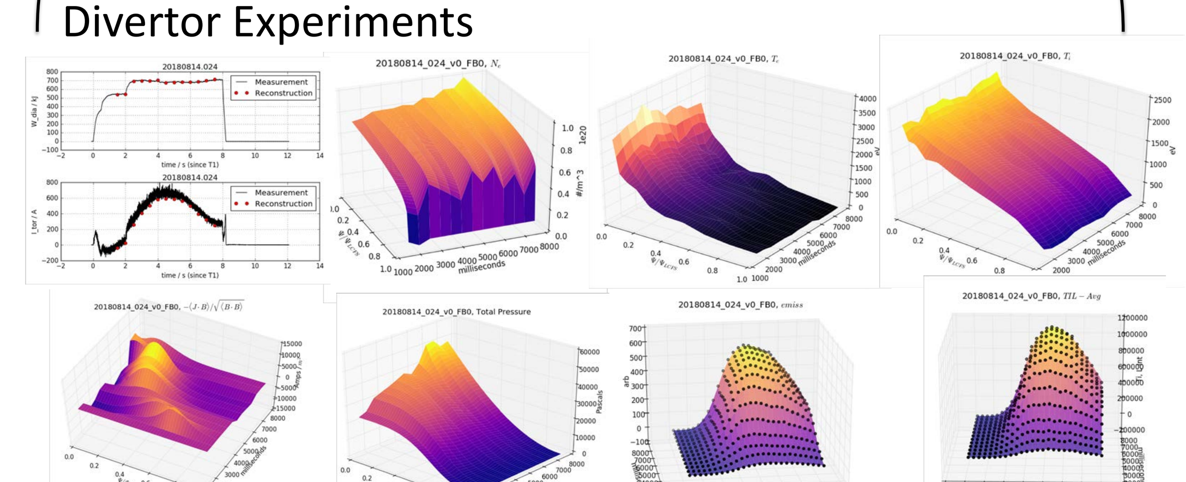
- Targeting an $\iota_{LCFS} = 0.97$ for the equilibrium works well for (5/5)-island-limited configurations, with and without control coils
- Limiter iso-surface: The LCFS is some distance from the nearest divertor/limiter component.
  - 5/5-island chain is highlighted
  - The iso-surface = -0.006 lies just inside of the 5/5-island chain





*FLARE results courtesy H. Frerichs

Divertor Experiments

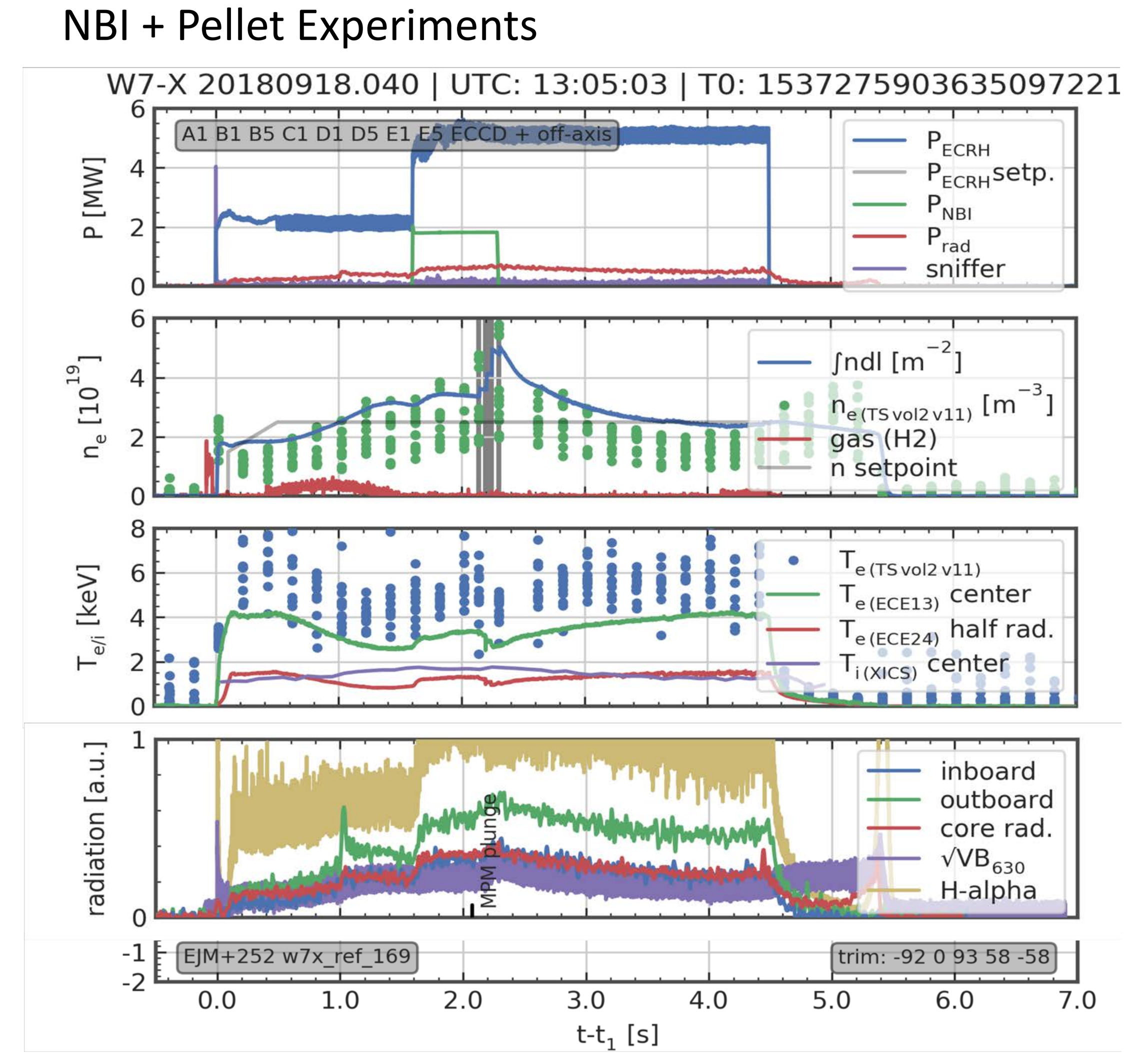


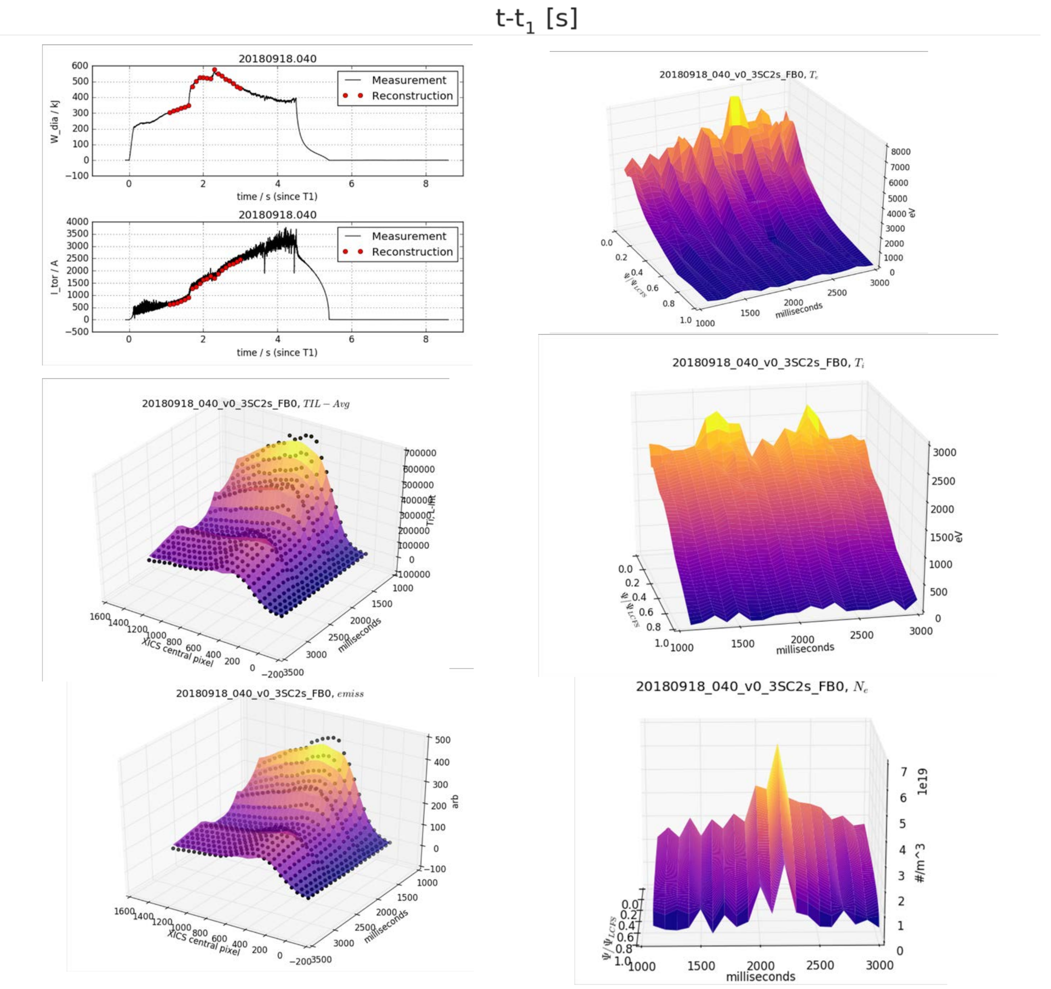
- A next natural step is to automate/streamline the V3FIT -> BMW -> FLARE -> EMC3-EIRENE interface for W7-X

Neutral Beam Injection and Pellet Fueling

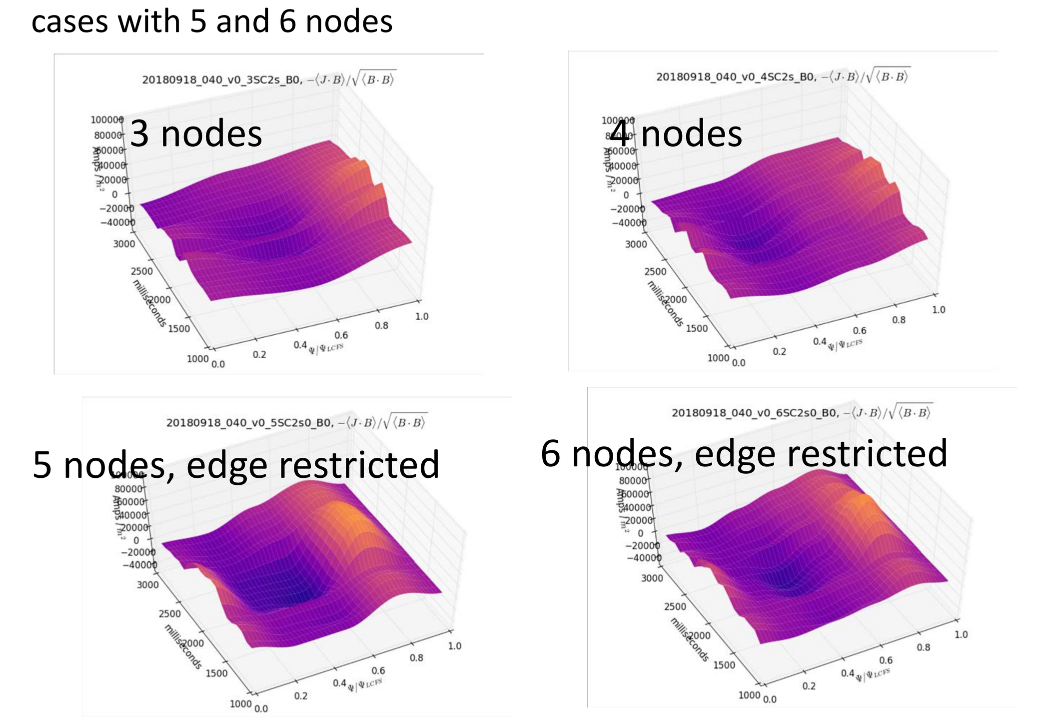
- Neutral Beam Injection experiments began in OP 1.2B
- Pellet fueling rapidly raises the core density of the plasma
- Testing new parametric model/basis functions of toroidal current density

NBI + Pellet Experiments

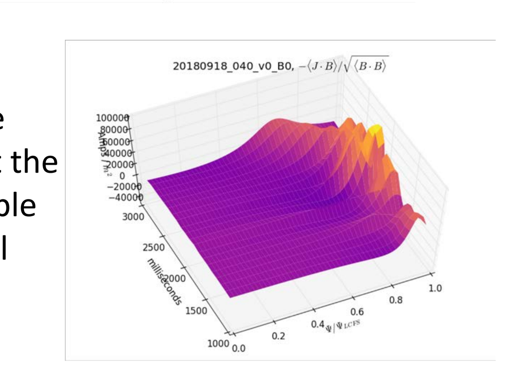




- New basis functions for current density: 'sum of cos-squared' profile
- Free parameters specify current density at equally-spaced (in 's') central points for smoothly-varying current density
- 3, 4, 5, or 6- nodes. The edge current density is held at zero for the cases with 5 and 6 nodes



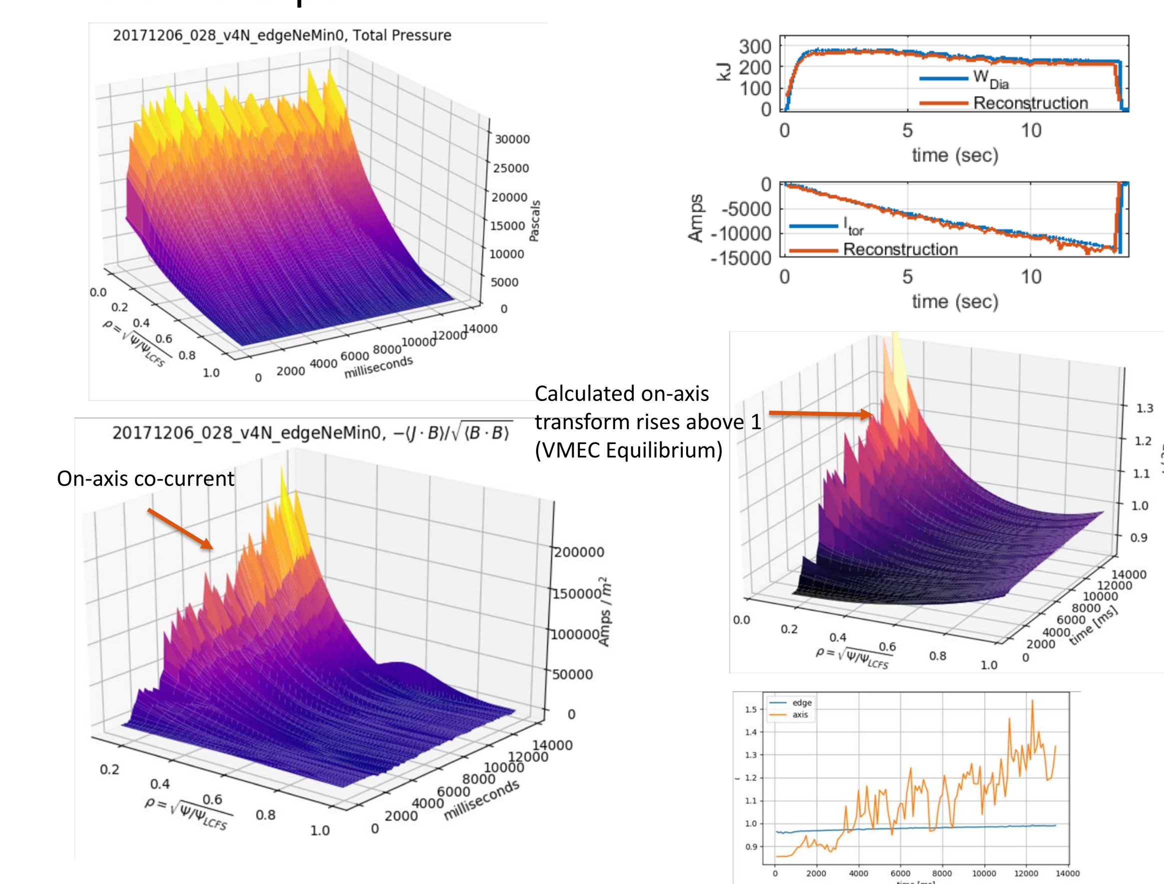
- Compare to 'sum of arctangents' profile (bottom right). Reconstructions suggest the sum of arctangent functions is not flexible enough to resolve the region of residual current driven by NBI.



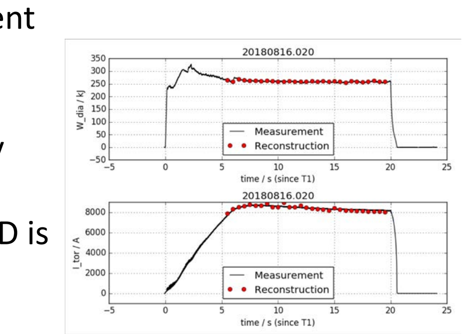
Electron Cyclotron Current Drive Experiments

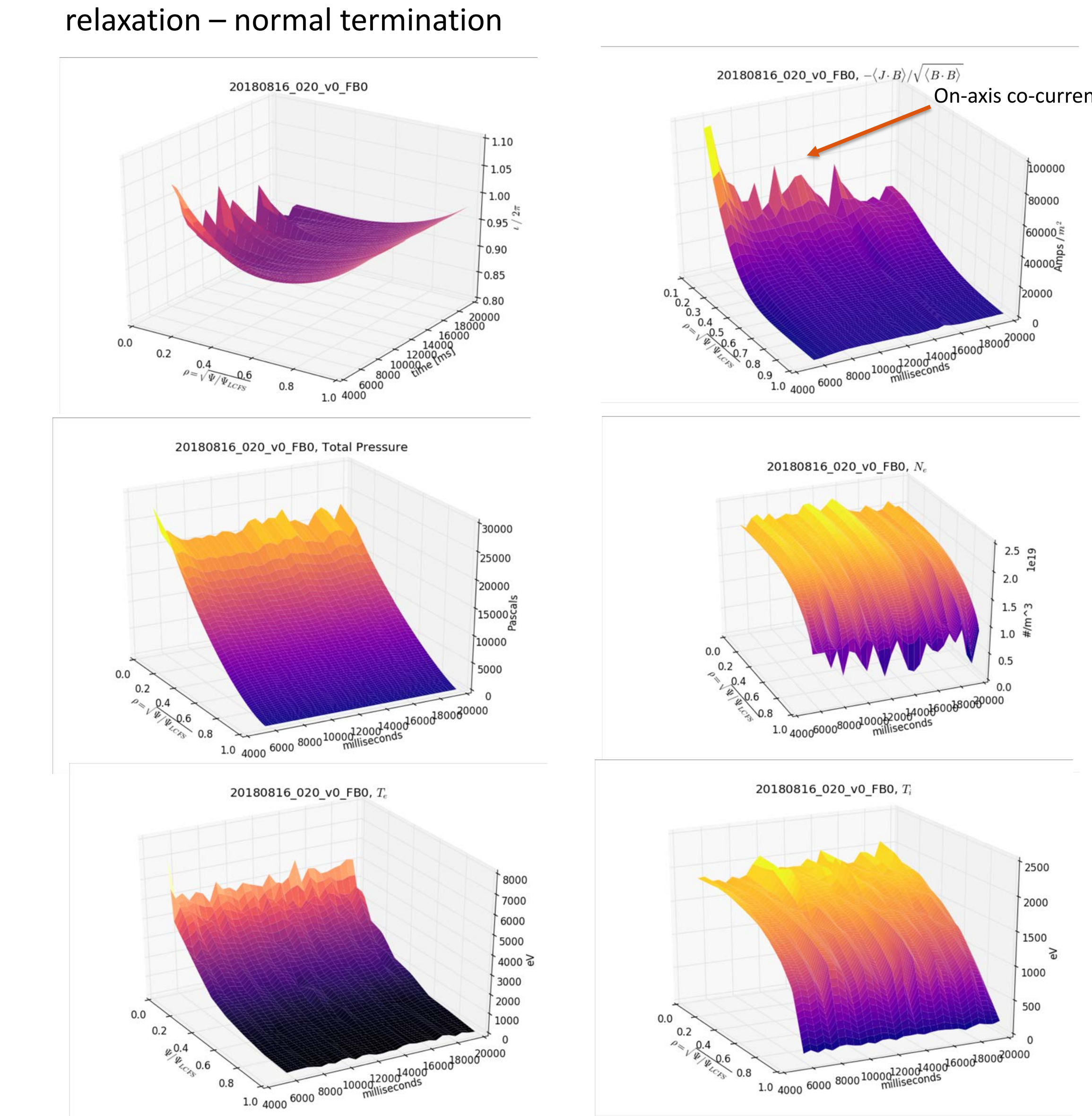
- Co- /Counter- and On-/Off-Axis ECCD available on W7-X.
- Further modeling required to accurately reconstruct the near-axis region during on-axis current density drive – qualitative/preliminary results to date
- Large-scale (plasma terminating) events, with precursors, happen at the largest driven net toroidal currents – iota ~ 5/5 assumed to play a role

Co-ECCD Experiments



- Current drive experiments to pre-inject current profile close to (net) bootstrap levels
- ECCD switch off just as steady-state level of current is reached. Current relaxes resistively (Fast internal / Slow external timescales)
- Rotational transform stays below 1 after ECCD is switched off
- Profiles are very quiescent during internal relaxation – normal termination





OP 2.0 : Long-pulse, High-Performance

- Understanding the sensitivity / Limits of the reconstruction with various diagnostic constraints and assumptions
- Effects of non-symmetric fields
- Couple the reconstruction to (Bootstrap, ECCD, NBI, Edge, + more) modeling
- On-going diagnostic integration and code benchmarking (XMCTS, TRAVIS)
- Eddy current modeling
- Sensitivity studies with ECRH & ECCD modulation
- Intra-code validation studies
- Automation of magnetic field calculations with finite beta
  - FLARE Integration
  - EMC3-EIRENE

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