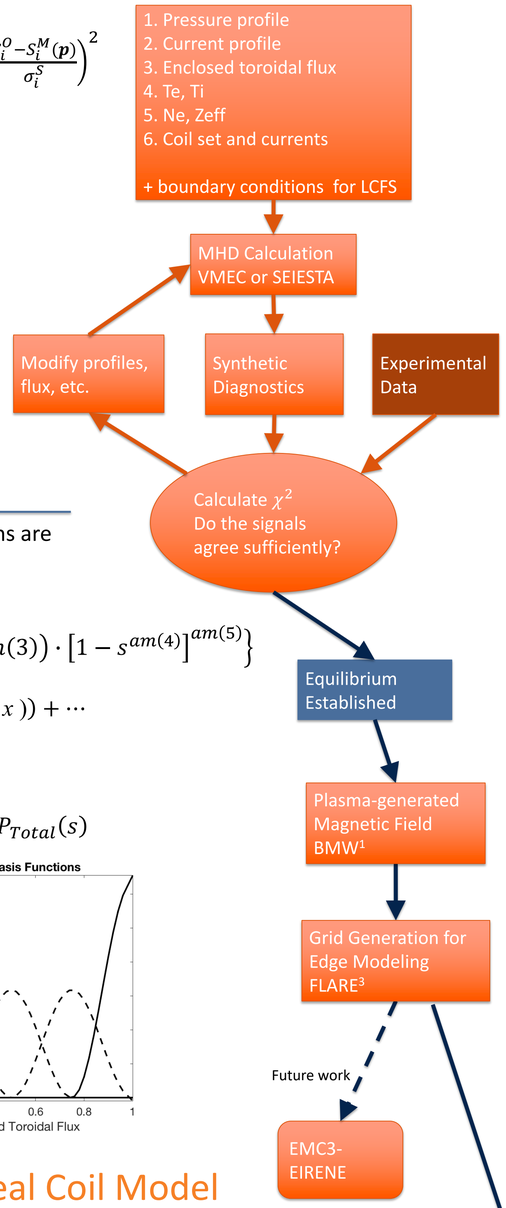
# Equilibrium Reconstruction Procedure

- Non-Linear Optimization procedure that determines the parameters of the MHD equilibrium (and other constraints) that are most consistent with experimentally observed signals and data
- Quasi-Newton Method with Singular Value Decomposition
- Cost function quantifies the level of agreement: $\chi(\boldsymbol{p})^2 = \sum_i W_i \left(\frac{S_i^O - S_i^M(\boldsymbol{p})}{\sigma_i^S}\right)^2$
  - $S_i^O$: Observed signals (measured diagnostic data)
  - $\boldsymbol{p}$ : Parameters that describe plasma equilibrium
  - $S_i^M(\boldsymbol{p})$ : Model predicted signals (synthetic model data)
  - $e_i(\boldsymbol{p})$ : Error vector
  - $\sigma_i^S$ : Diagnostic uncertainty
- Minimize the cost function, $\chi^2$ and quantify the uncertainty
  - $\boldsymbol{C}_{data} = \sigma_i \sigma_j \delta_{ij}$
  - $\boldsymbol{J}_{ij} = \frac{\partial e_i(\boldsymbol{p})}{\partial p_j}$
  - $\left(\boldsymbol{C}_{param}\right)^{-1} = \boldsymbol{J}^T (\boldsymbol{C}_{data})^{-1} \boldsymbol{J}$




## Plasma Model

- Typical parameterization for profiles shown here. Additional options are available. VMEC variable labels and indices are used.

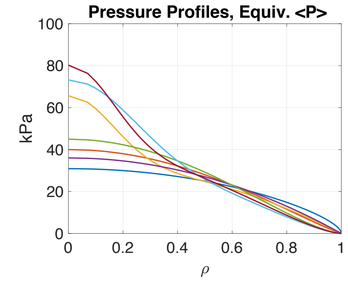
Radial Coordinate: $s \equiv {}^{\psi}/_{\psi_{LCFS}}$ $\quad \psi_{LCFS} = PHIEDGE$

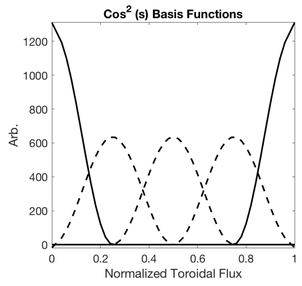
$$P_{Total}(s) = PRES\_SCALE \cdot \left\{am(3) \cdot \left[1 - s^{am(1)}\right]^{am(2)} + \left(1 - am(3)\right) \cdot \left[1 - s^{am(4)}\right]^{am(5)}\right\}$$

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

$$I(s=1) = CURTOR$$

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

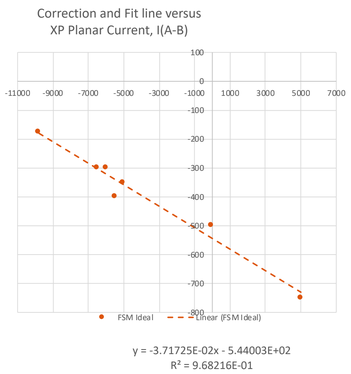



## Iota Correction with Offset Current in Ideal Coil Model

Table 1: From "Otte_OP12_W7-X_Workshop_iota-correction.pptx" (2019, May)
Processed FSM resulting in offset current I(A,B) for "ideal coil" model

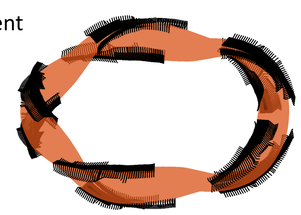
| Configuration | $I_{(1-5)}$, Amps Non-planar Coils | $I_{(A-B)}$, Amps Planar Coil Current | $I_{Offset}$, Amps, (in the Model) |
|---|---|---|---|
| EEM+261 "OP1.1 Limiter" | 12800 | 5000 | -750 |
| EIM+252 "Standard" | 12989 | 0 | -500 |
| FOM001+252 | 13602 | -5000 | -350 |
| FOM003+252 | 13664 | -5500 | -400 |
| FPM001+252 | 13725 | -6000 | -300 |
| FPM002+252 | 13797 | -6500 | -300 |
| FTM+252 "High iota" | 13725 | -9790 | -175 |

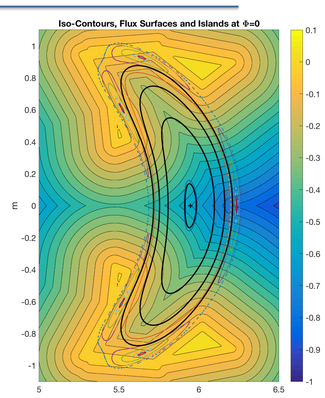



- Two-point linear fit for **Iota Scan experiments**: $I_{Offset} = -0.03320\ I_{(A-B)} - 500$

## Boundary Constraints

- Edge Transform: Targeting an $\iota_{LCFS} = 0.97$ for the equilibrium works well for (5/5)-island-limited configurations, 1.168 for (5/4)-island configuration
- Limiter iso-surface: The LCFS is a specified distance from nearest in-vessel component.
  - The 5/5-island chain in standard configuration (EIM) is iso-surface ≅ -0.06
  - Divertor structure is the limiting in-vessel component



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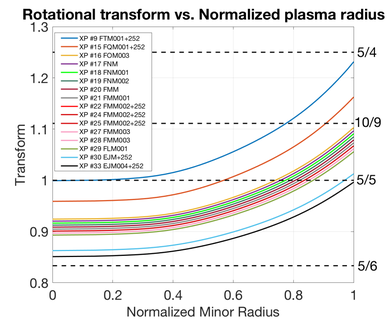
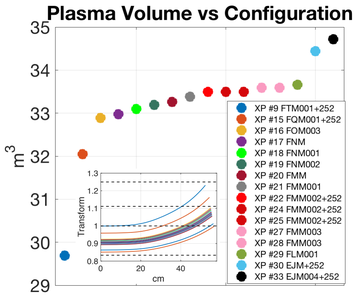
## Iota Scan

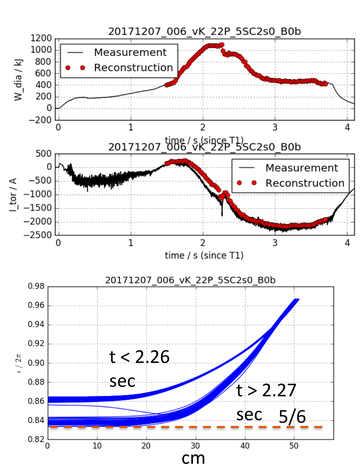
- Experimental configuration scan of rotational transform in W7-X
- Proximity of rational transform values investigated for confinement changes
- Edge boundary conditions vary (island, limited)
- Plasma radius and volume are reduced with increased transform
- Vacuum Reconstructions based on a *limited* plasma column – Plasma 'expands' to touch the divertor
- Size of plasma based on Poincaré plots is smaller; Edge stochasticity is not captured by VMEC

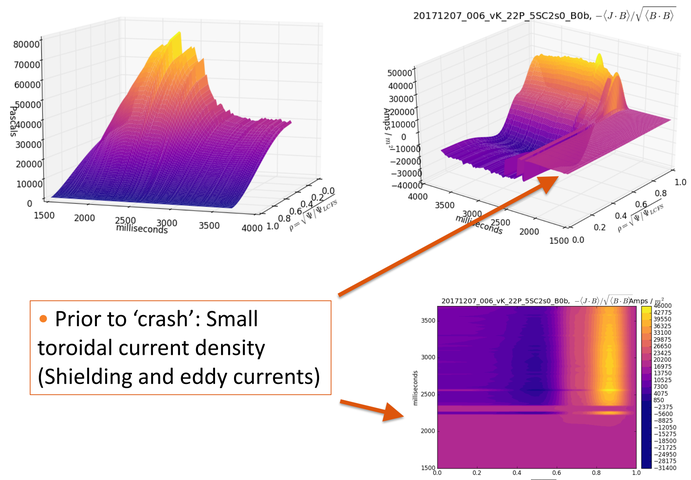



## High-Performance 20171207.006

- On-going analysis of record discharge in OP 1.2A
- Correct coil set model and current (iota correction) essential to the modeling
- Total stored energy and current agree well
- Pressure and current profiles based on magnetic reconstruction
- Transform approaches, but does not cross, the 5/6 rational value

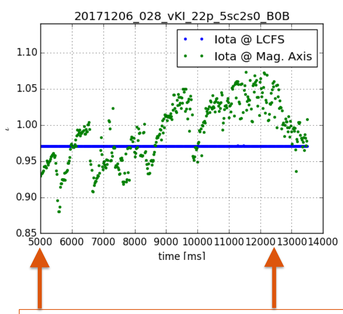


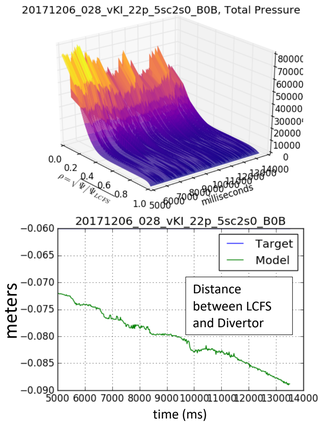

- Prior to 'crash': Small toroidal current density (Shielding and eddy currents)

## ECCD

- Electron cyclotron current drive used to control net toroidal current & current density profile
- Reconstructed edge transform constrained to iota=0.97
- Can drive large, centrally-peaked current profile which raises the core rotational transform

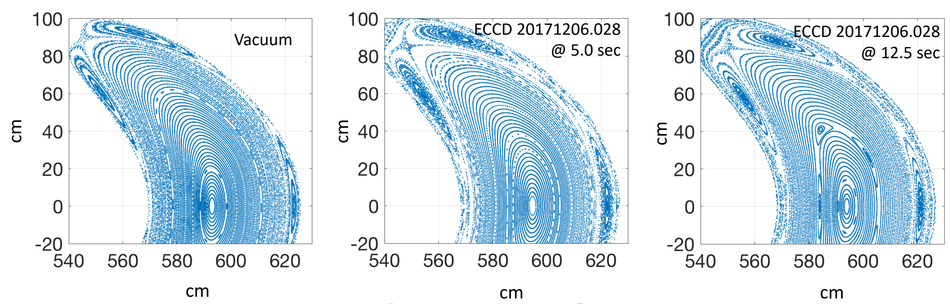



- Reconstruction at t= 5.0 sec and 12.5 sec used for field-line following calculations by FLARE




## Boundary Extension with BMW & FLARE

- Total fields, due to plasma currents and coil currents are calculated by BMW
- Poincaré plots generated by field-line following, with FLARE
- Cases Shown: Vacuum (left), ECCD @ 5.0 sec and 12.5 sec
- Edge 5/5-Island structure moves inward with increasing plasma current
- Initial result: Additional 5/5-island structure appears near Iota = 5/5 crossing. Analysis on-going




## On-going Activities and Future Plans

- Continued analysis of OP1.2 experiments (Bootstrap, Divertor, + )
- Diagnostic integration: Charge Exchange/Recombination Spectroscopy
- Sensitivity studies based on ECRH & ECCD modulation
- Neoclassical bootstrap current comparison