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Kinetic Equilibrium Reconstructions of Plasmas in the MAST Database and Preparation for Reconstruction of the First Plasmas in MAST Upgrade

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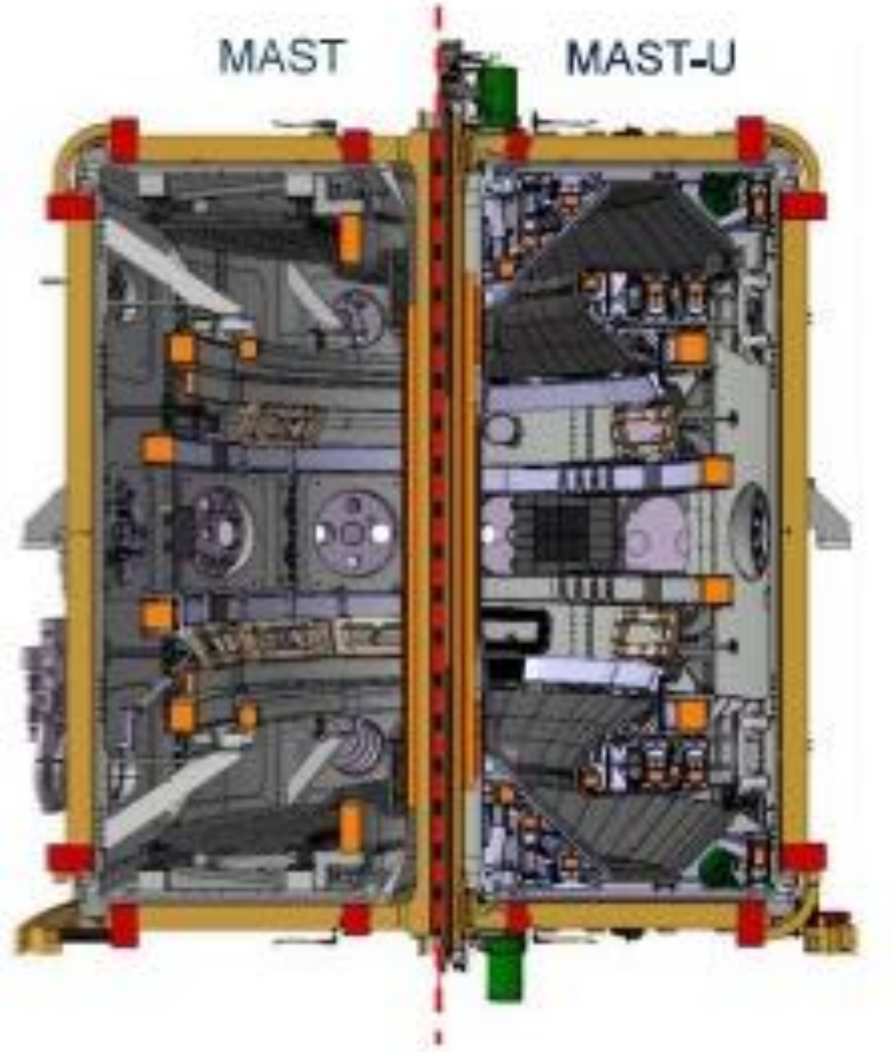
MAST-U is almost ready for first plasma; prep on MAST has readied equilibrium and stability tools

- Kinetic equilibrium reconstructions of plasmas in the MAST database are available
  - The VALEN 3D code is used to model currents in the conducting structure
  - Reconstructions with magnetics only, partial kinetic, and kinetic with MSE available
  - Kinetic reconstructions used for stability studies
- Reconstruction for the first MAST-U plasmas is ready
  - Again, a VALEN model is implemented and tested
  - Projected stability spaces have already been explored

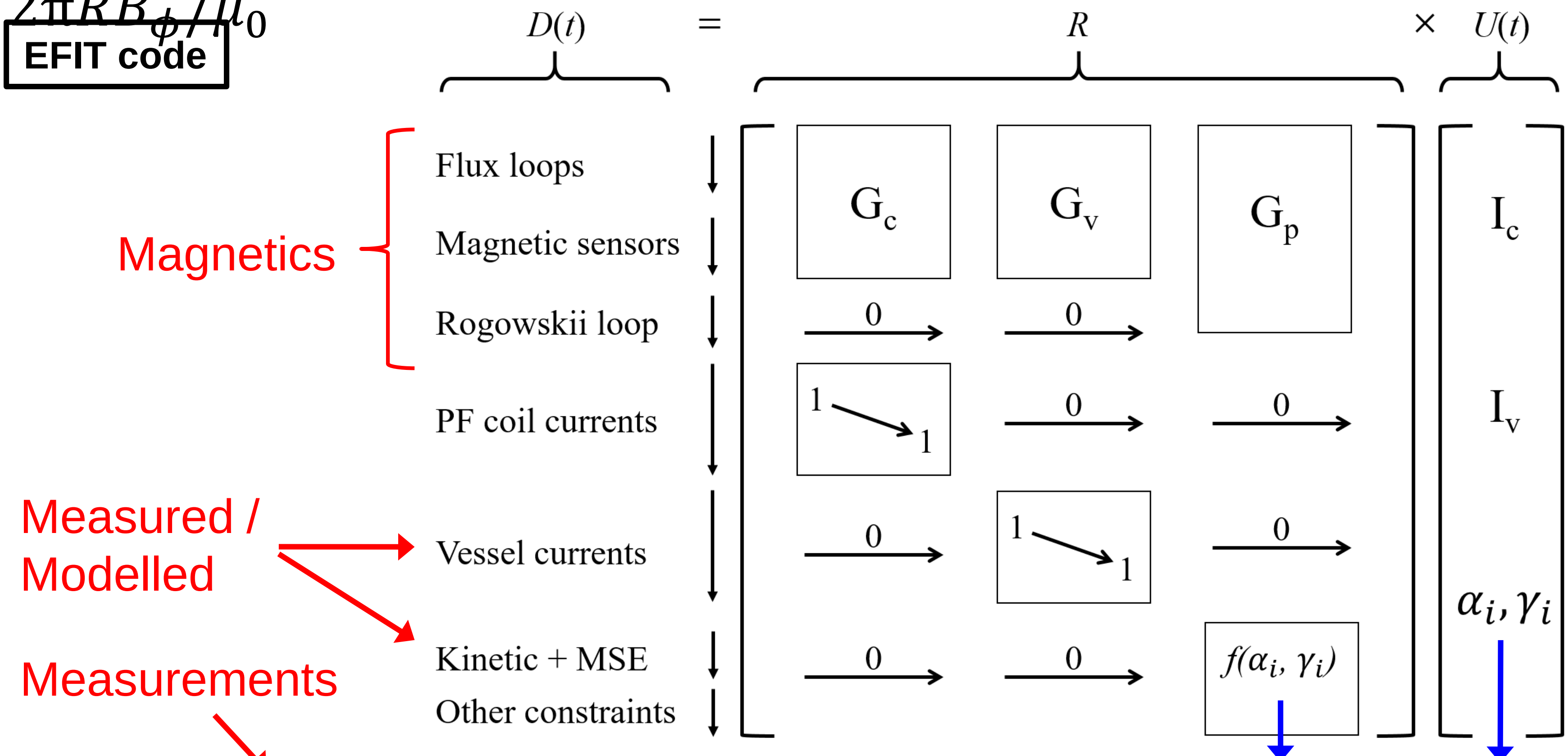
MAST-U is an upgrade of the Mega Amp Spherical Tokamak that has been years in the making



- New Super-X divertor
  - Important for this talk: new conducting structure close to plasma
- Increased TF, I_p, new PF coils
- During MAST operation, magnetics-only equilibrium reconstructions were routinely available, but not kinetic
  - Goal: make highest quality kinetic equilibrium reconstructions available for all of MAST-U operation

Equilibrium reconstruction solves the Grad-Shafranov equation while minimizing χ^2

$$\text{Grad} - \text{Shafranov: } \Delta^* \psi = -\mu_0 R^2 p'(\psi) + \frac{\mu_0{}^2}{4\pi^2} f f'(\psi),\ f = 2\pi R B_\phi / \mu_0$$



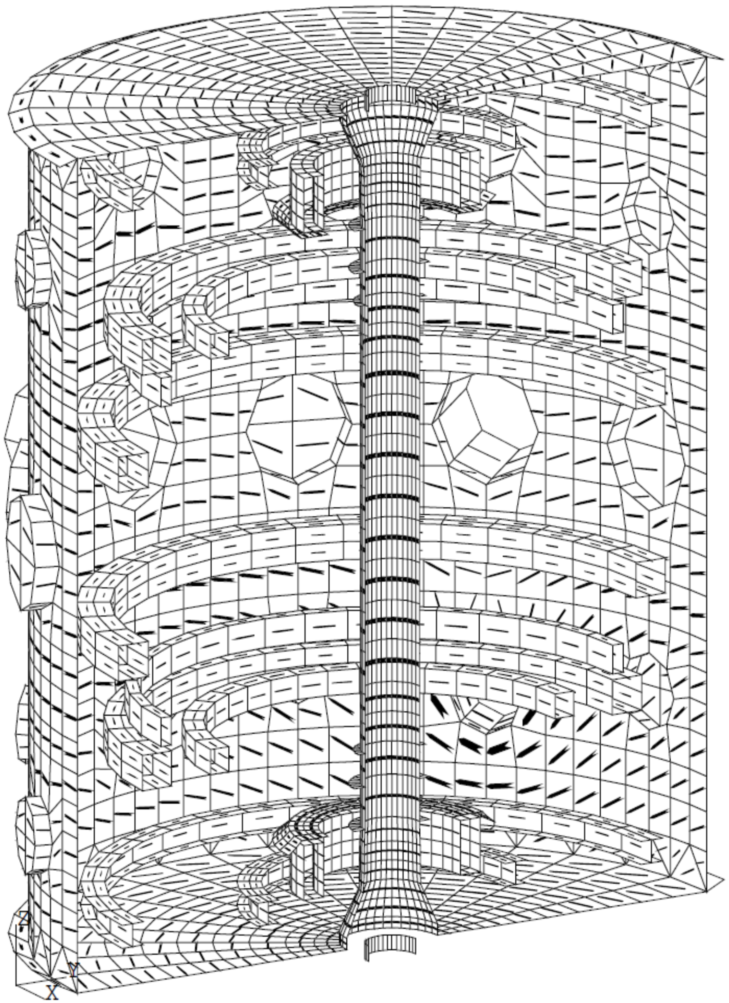
$$\chi^2 = \sum \frac{(M_i - C_i)^2}{\sigma_i{}^2}$$

Calculations

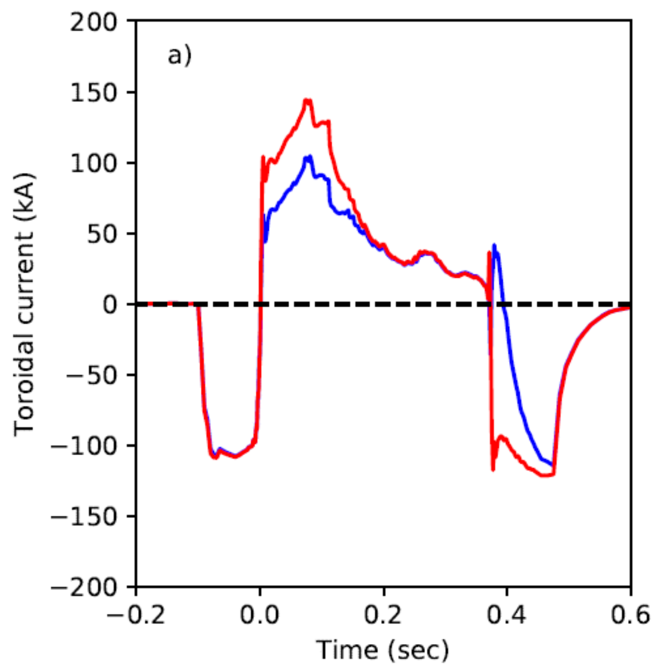
Constraints, for example:

$$p'_{(\psi_n=0)} = 0 \quad ff'_{(\psi_n=1)} = 0$$

A 3D, non-axisymmetric wall model of MAST was created in the VALEN code

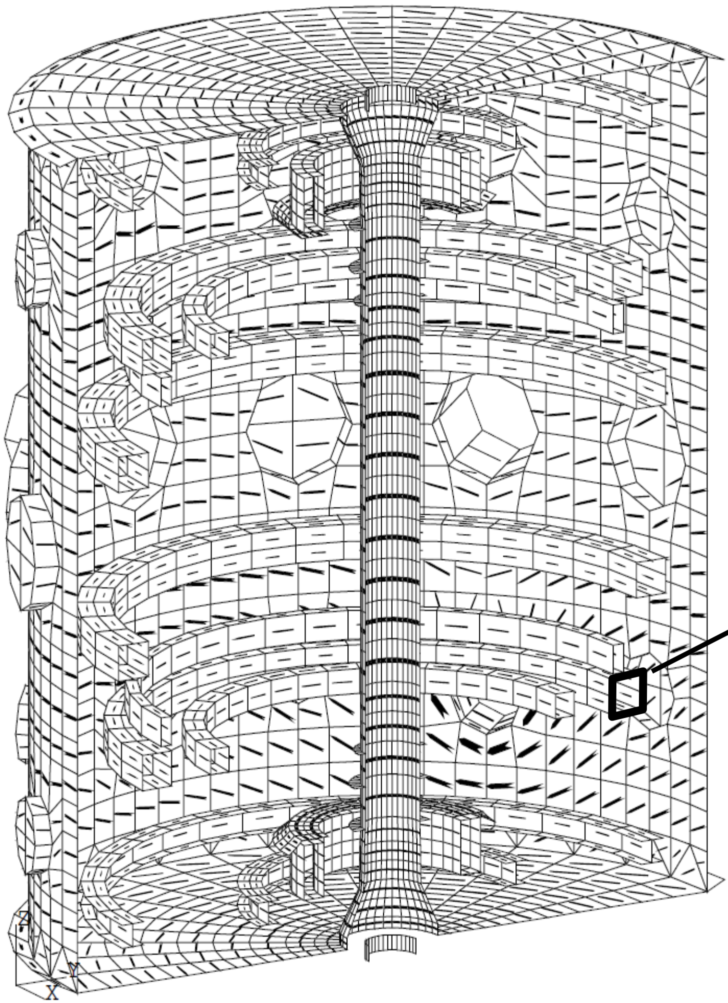


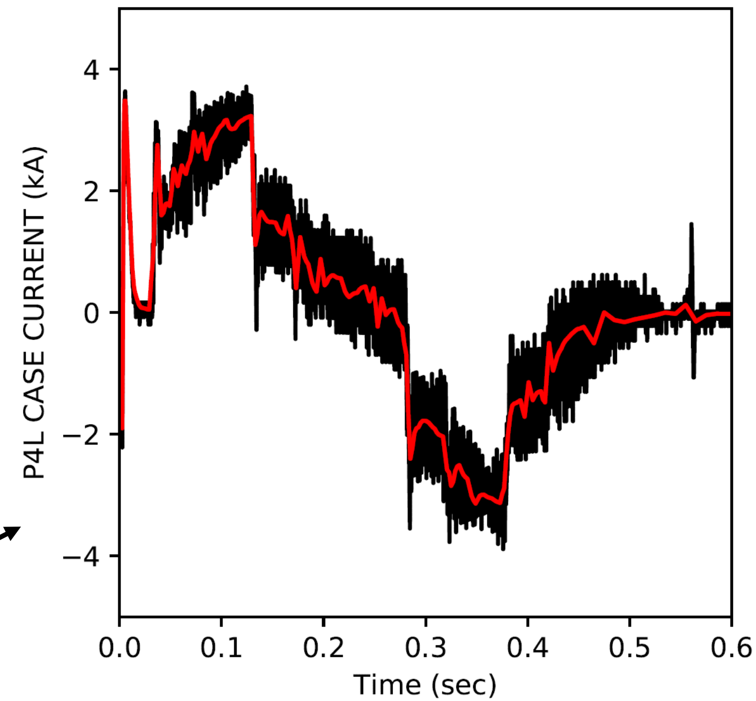
- VALEN splits a thin-shell into finite elements which are each mutually coupled to all other elements
- Shown are induced eddy currents during plasma discharge 23822



Total induced toroidal current in the MAST conducting structure with and without plasma current

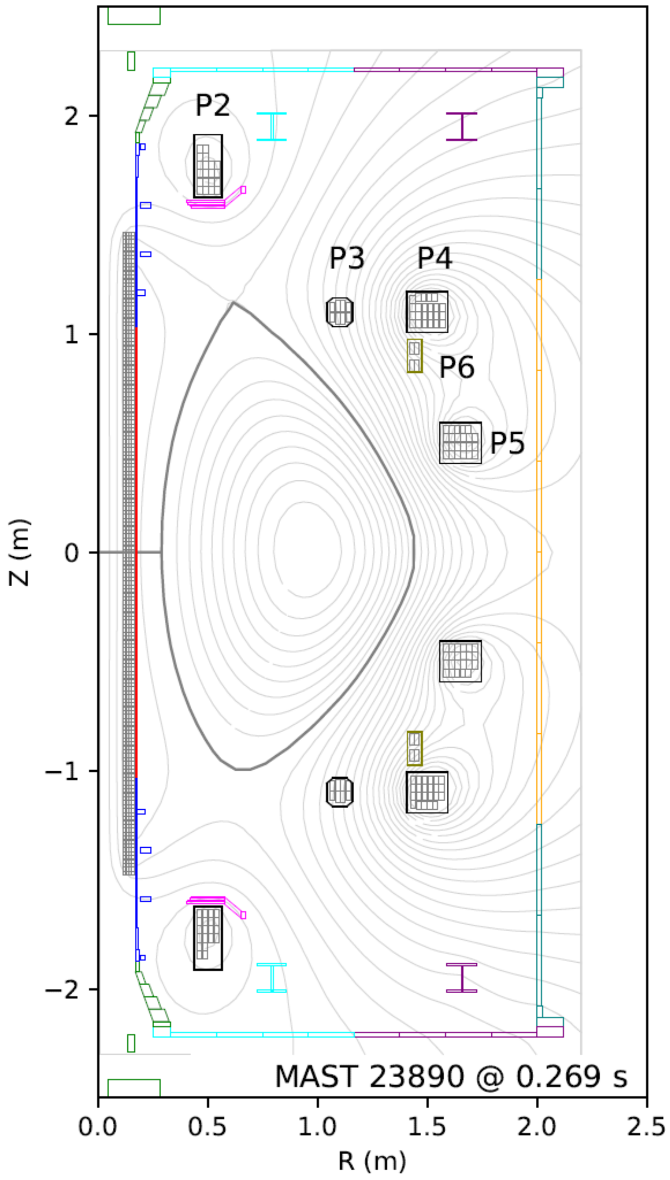
Coil case currents were measured in MAST, providing a good comparison to the VALEN model





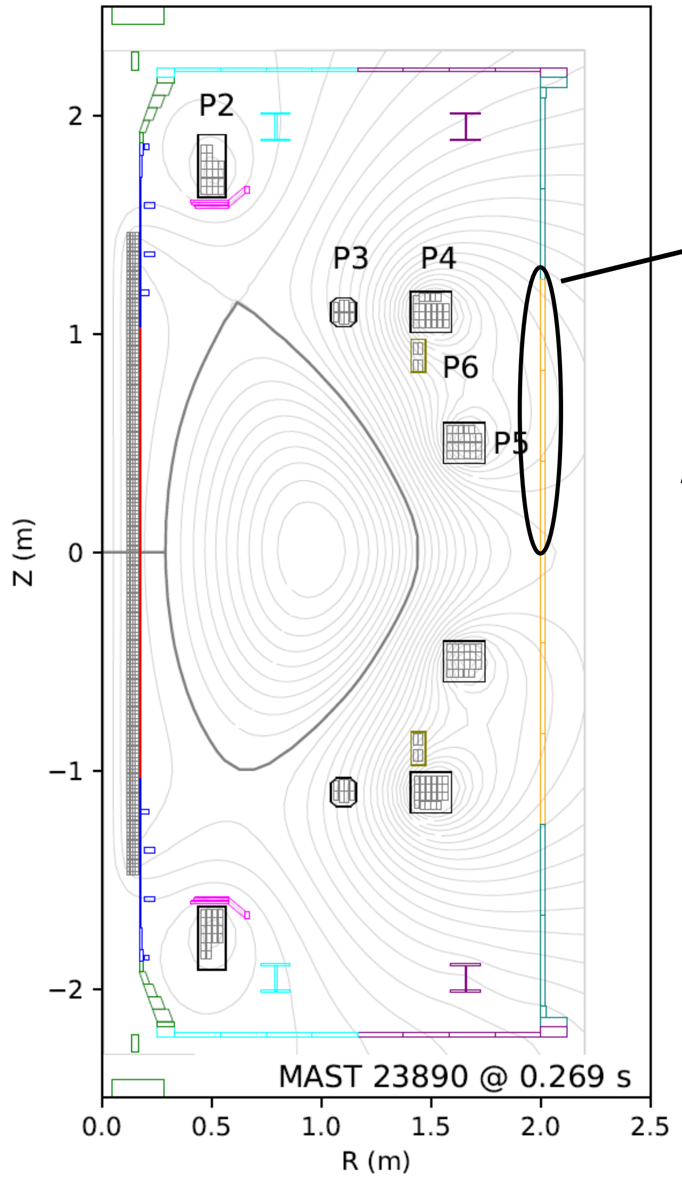
- Example: measured and VALEN modelled induced currents in the lower P4 coil case match
  - Shown for poloidal field coil test discharge 23588

Currents in other vessel structures are not measured, but are needed for good reconstruction

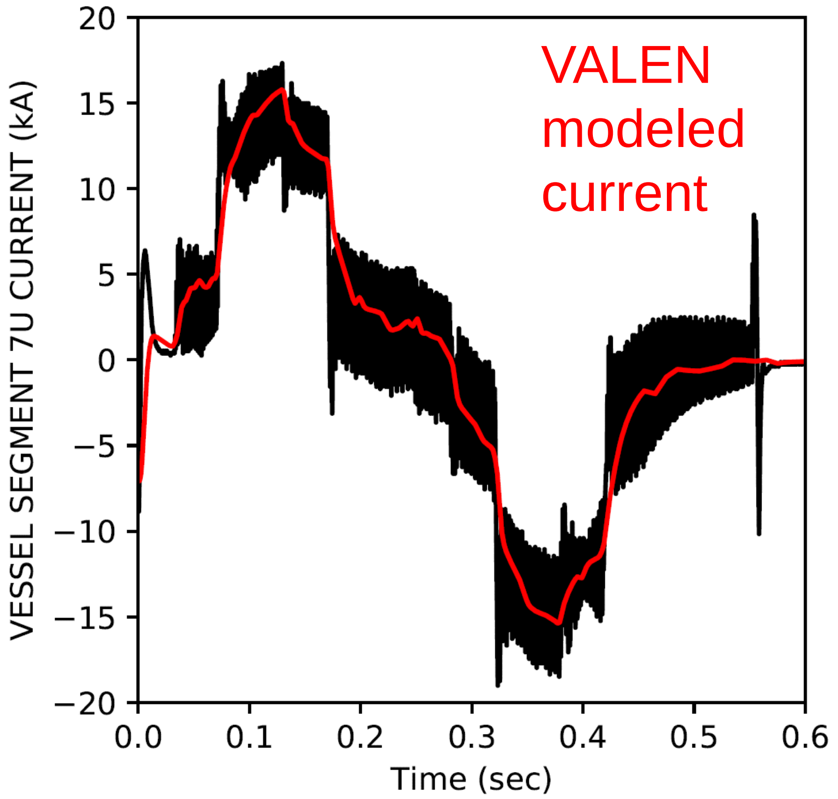


- The conducting material was grouped into 18 structures for EFIT equilibrium reconstruction
- The VALEN 3D model is also grouped in post-processing to give the modelled axisymmetric-equivalent toroidal currents in these structures
- Nearby loop voltage measurements are identified, and by comparing VALEN currents to measured voltages, effective resistances of the structures are determined

Currents in other vessel structures are not measured, but are needed for good reconstruction



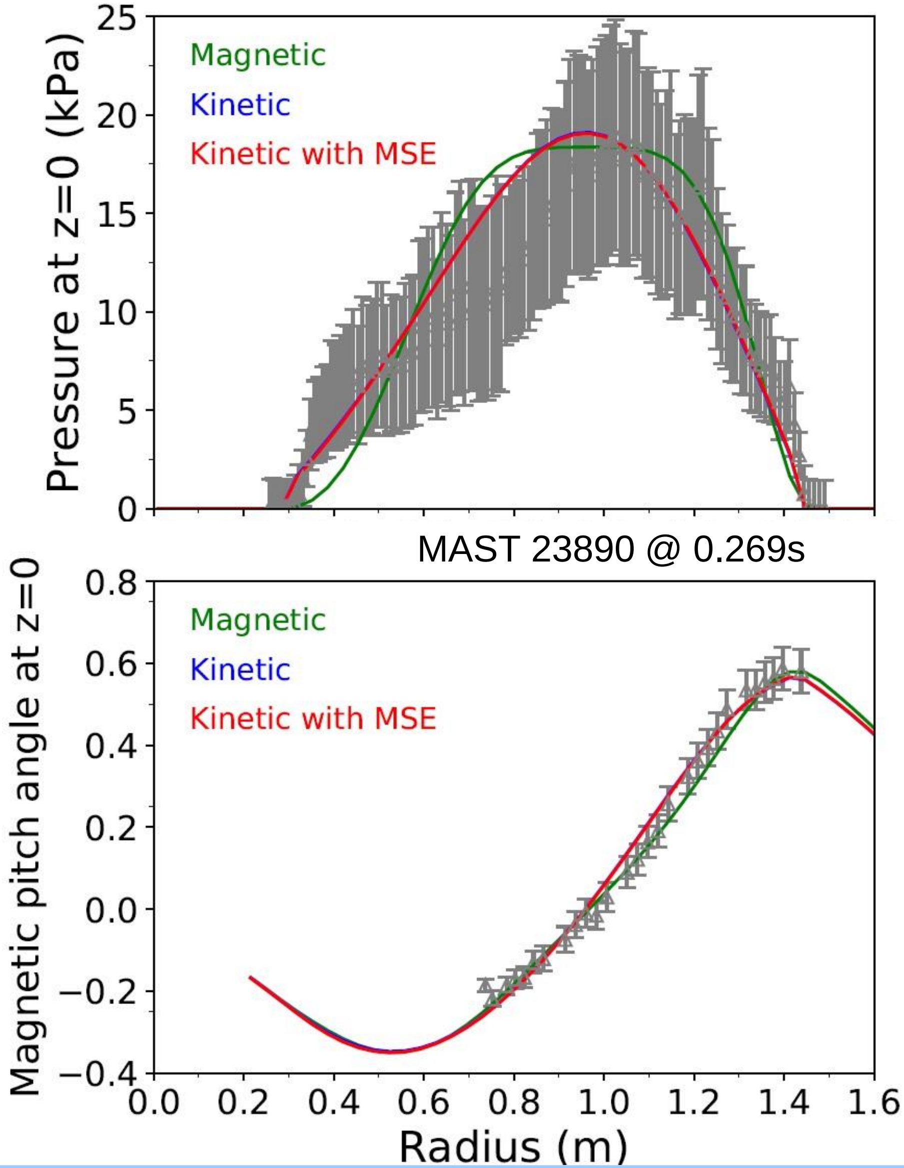
Measured loop voltage / determined effective resistance



- The effective resistances and measured voltages give an inferred current to use in the reconstruction

Reconstructions with various levels of diagnostic inclusion are possible

- Magnetics only
- Partial kinetic
  - Includes magnetics plus available pieces of the pressure profile: n_e, T_e, n_i… with models for the other pieces
- Kinetic with MSE
  - Includes above + magnetic pitch angle
- Kinetic with MSE and rotation
  - We plan to do this in EFIT, but also stay tuned for Luca's talk…

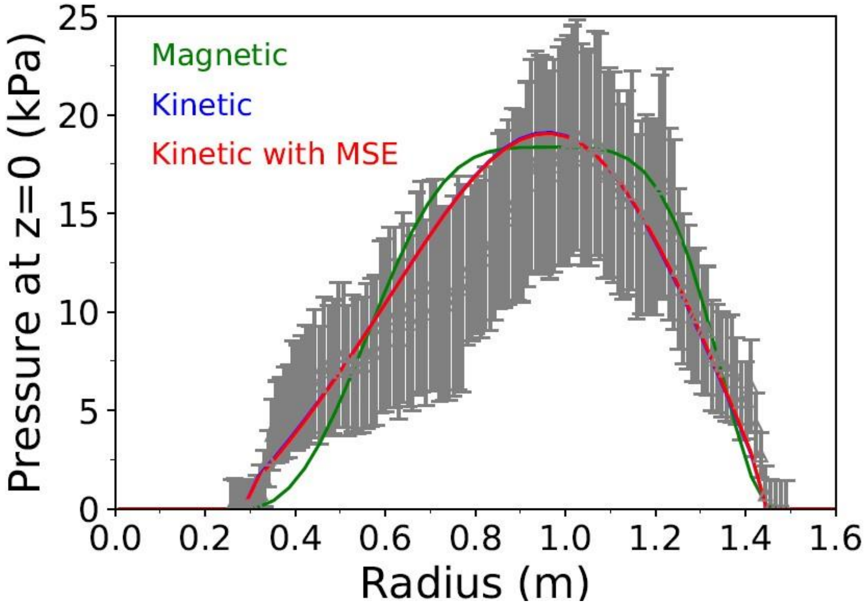


Equilibrium fit functions have been optimized for good results in a wide range of MAST plasmas

- Magnetics only
  - Pressure gradients at axis and edge both zero
  - Simple polynomial representation:

$$\frac{\partial p}{\partial \psi} \approx \alpha_1 \psi_n (1 - \psi_n)$$

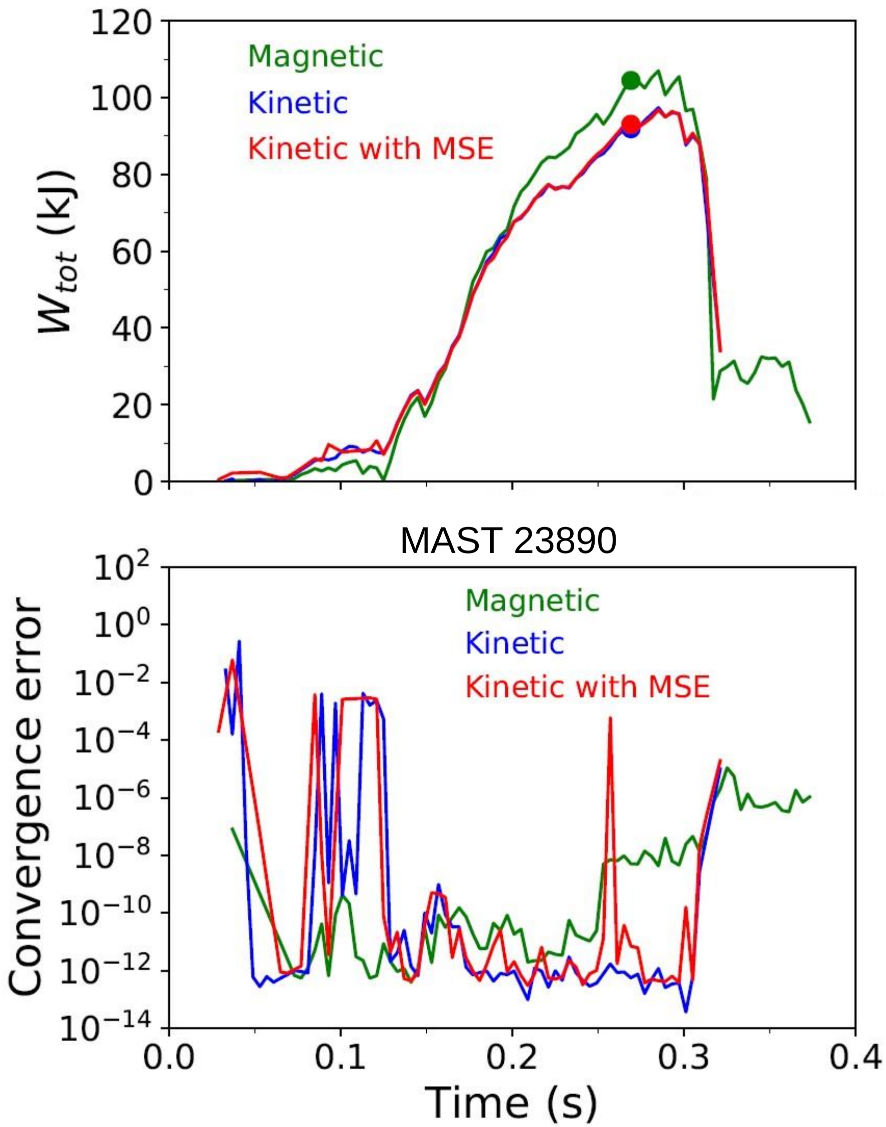
- Partial kinetic
  - More measurement constraints = more freedom to the fit
  - Fifth order *p'* polynomial with zero gradient at axis
  - *ff'* also fifth order, with zero value at axis, zero gradient at edge



MAST 23890 @ 0.269s

Convergence error is excellent in plasmas with sufficient stored energy

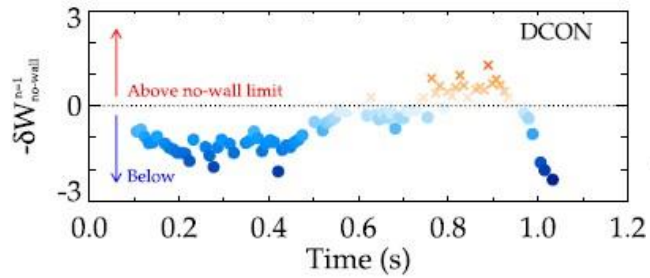
- Good convergence error is necessary for use of the equilibria in stability codes
- Clear differences between the magnetic and kinetic equilibria
- Adding MSE data, in this case:
  - Corroborates, but doesn't substantially change, the kinetic reconstructions
  - Occasionally increases the convergence error when pressure and pitch angle constraints don't perfectly agree

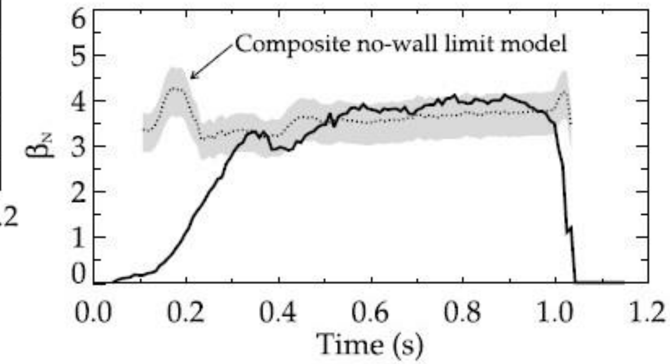


Kinetic reconstructions of the MAST database will be used for stability studies

- DCON ideal MHD calculations of beta limits require good reconstructions

NSTX: DCON -> DECAF reduced model

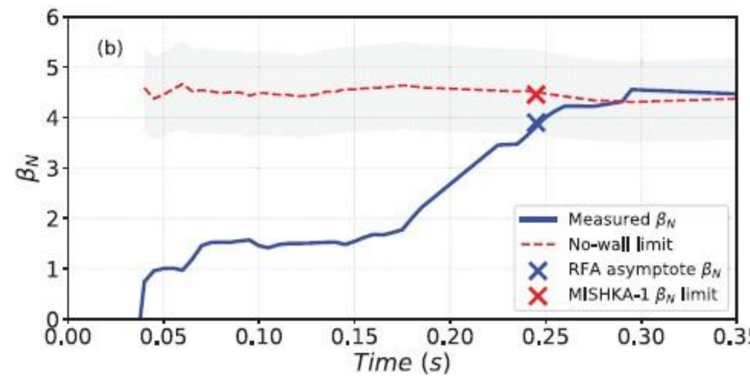




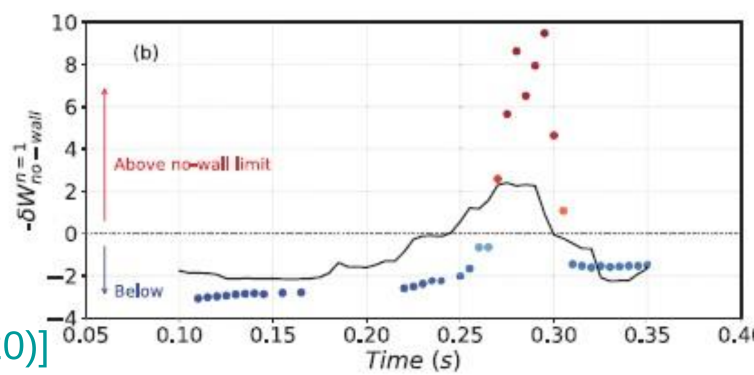
[J.W. Berkery *et al*., Phys. Plasmas **24**, 056103 (2017)]

- A RWM stability reduced model has been implemented in DECAF
  - Also, machine learning (coupled with physics) showed promise for initial studies training on NSTX and applied on MAST

MAST, ML emulation of DECAF model



and MAST, ML emulation of DCON



[A. Piccione, J.W. Berkery, *et al*., Nucl. Fusion **60**, 046033 (2020)]

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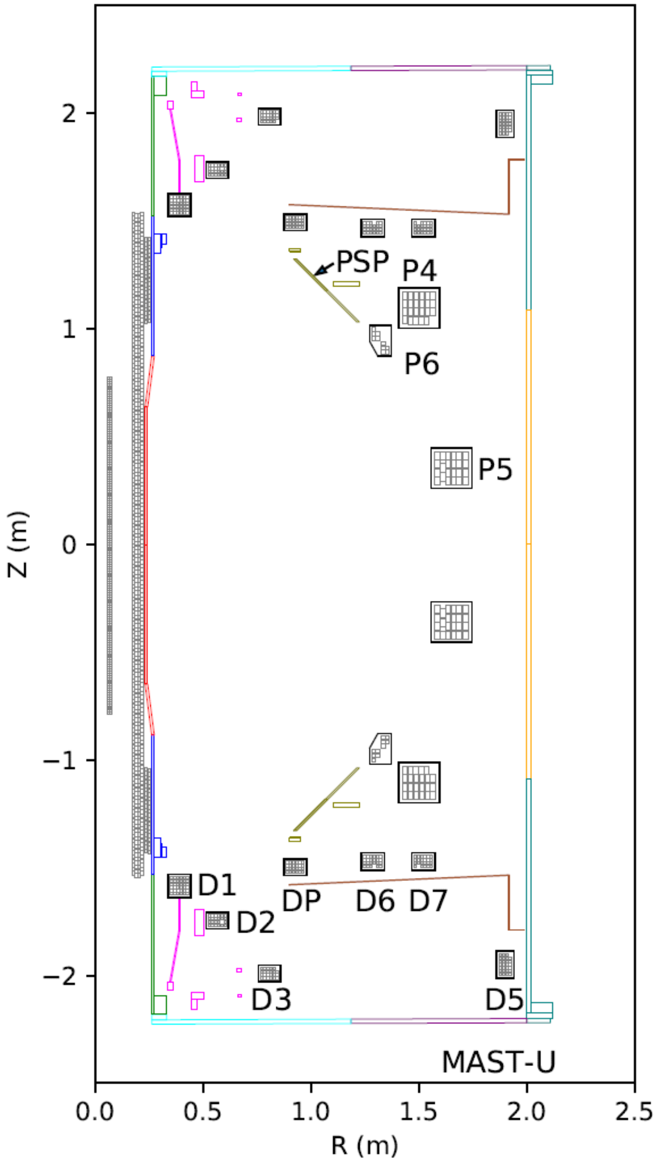
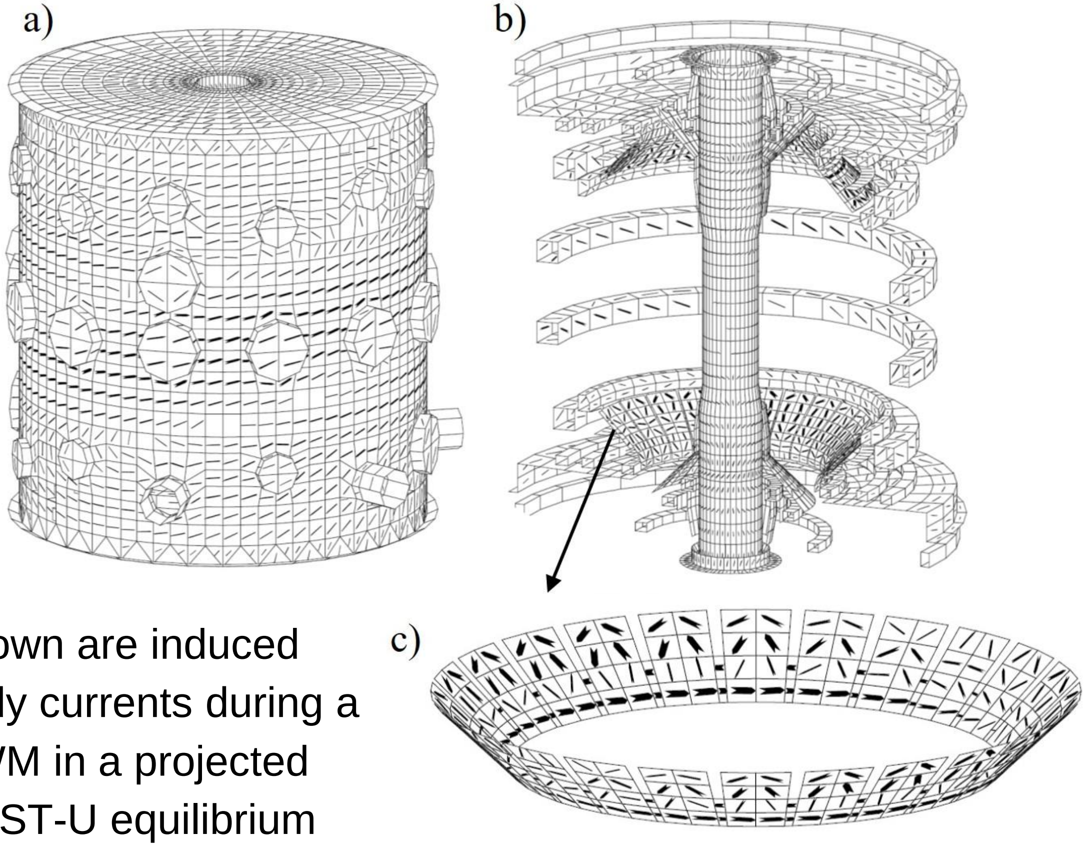
Preparations for the first MAST-U plasma equilibrium reconstructions are underway

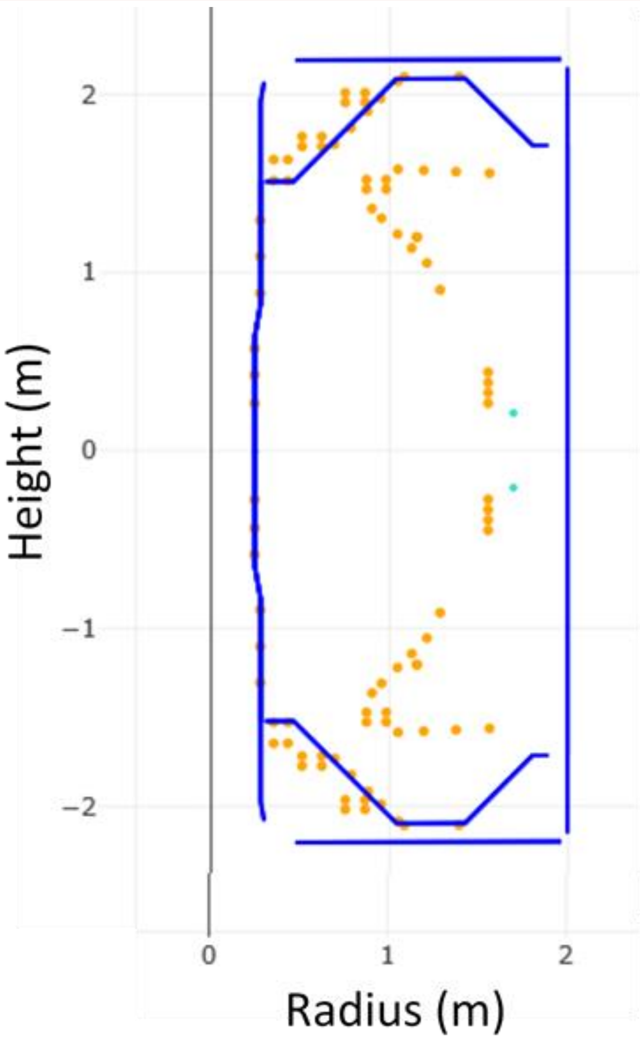


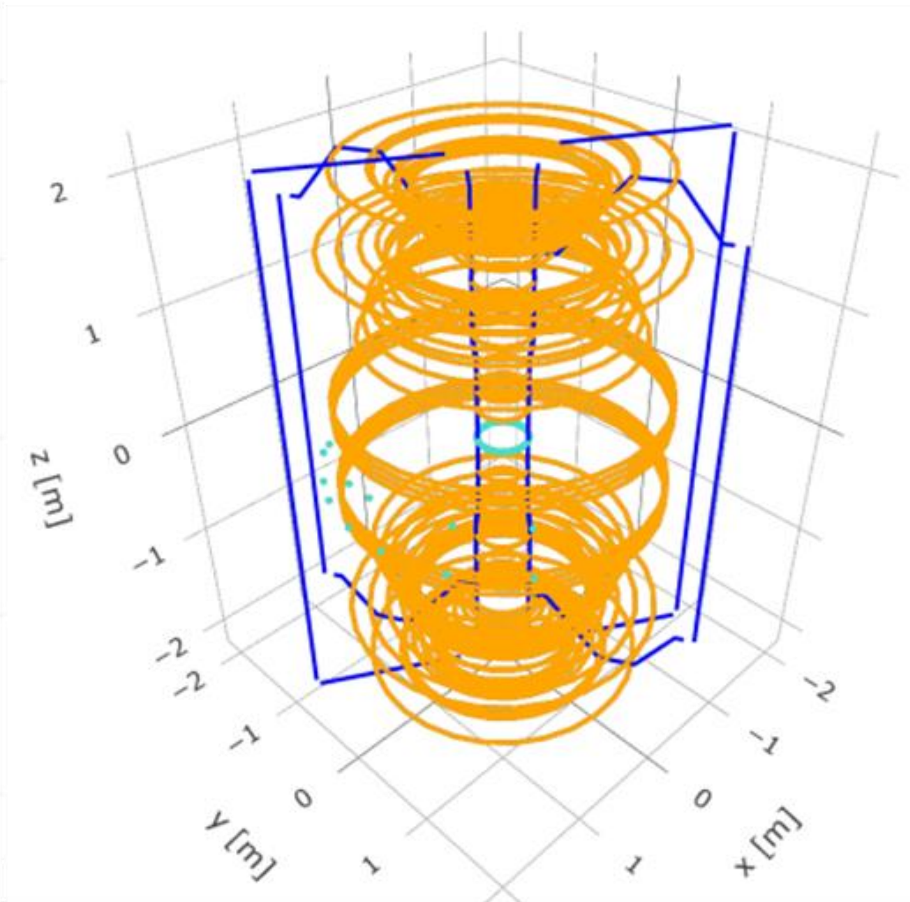
- The conducting material was grouped into 20 structures for EFIT equilibrium reconstruction



Shown are induced eddy currents during a RWM in a projected MAST-U equilibrium

Magnetic diagnostics have also changed between MAST and MAST-U





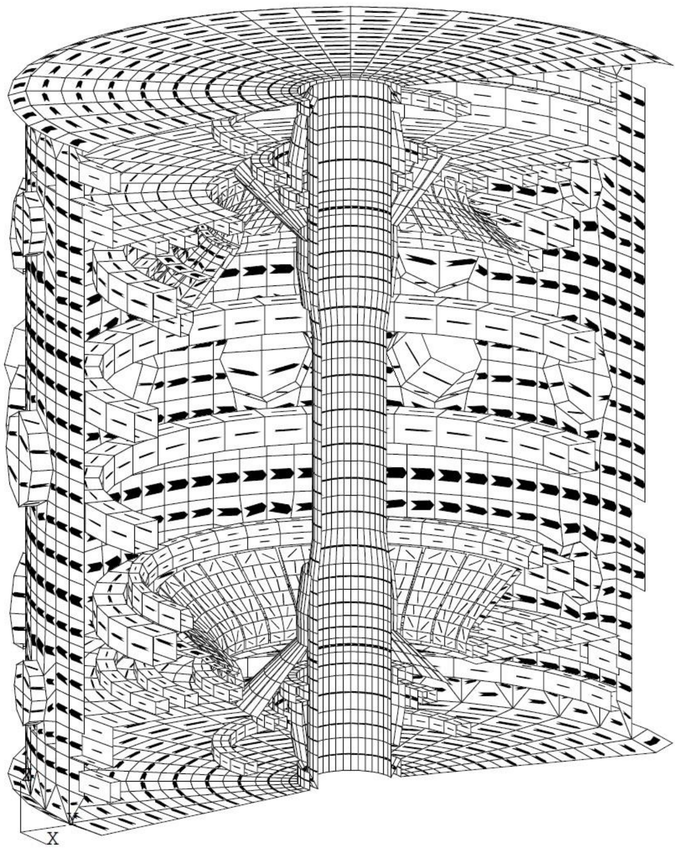
Flux loops

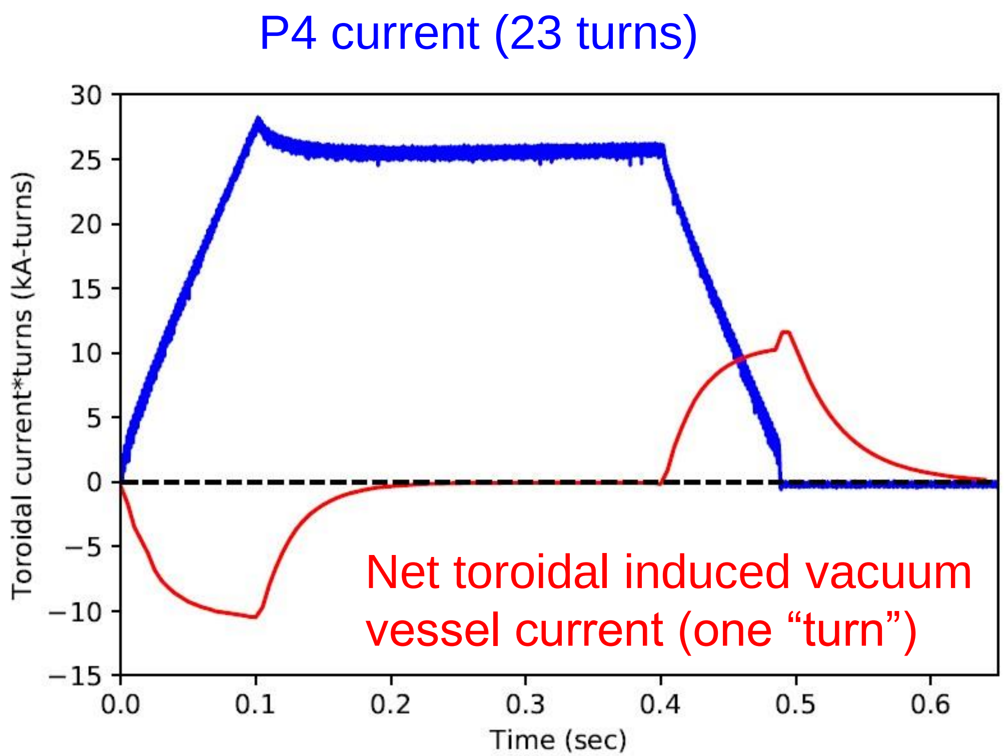
Mirnov coils

Rogowskis (also on coil feeds and cases)

- ❑ Only a partial set of the magnetics was acquired/identified for the first vacuum test shots

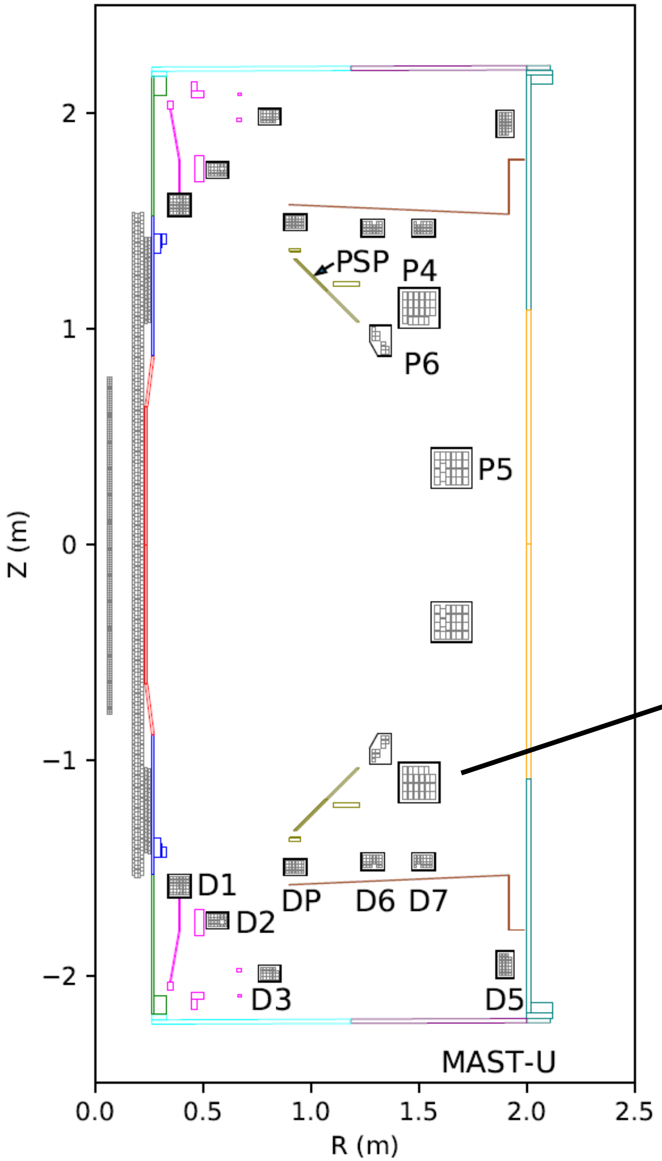
P4-only vacuum test shot 40315 was analyzed

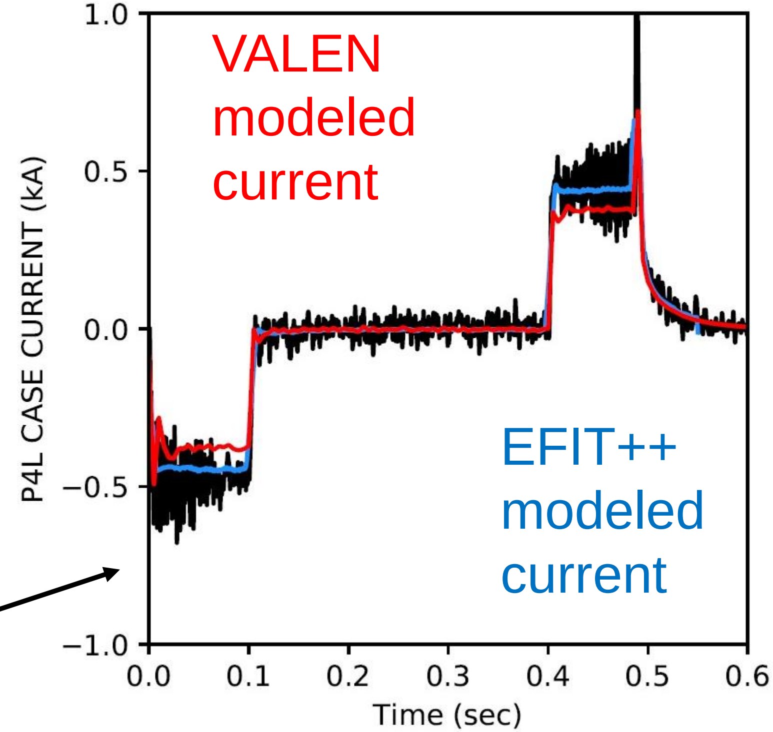




- Time-domain calculations were performed in VALEN using the experimental current in the P4 coil
  - Net toroidal currents in the conducting structure, and eddy current patterns were determined

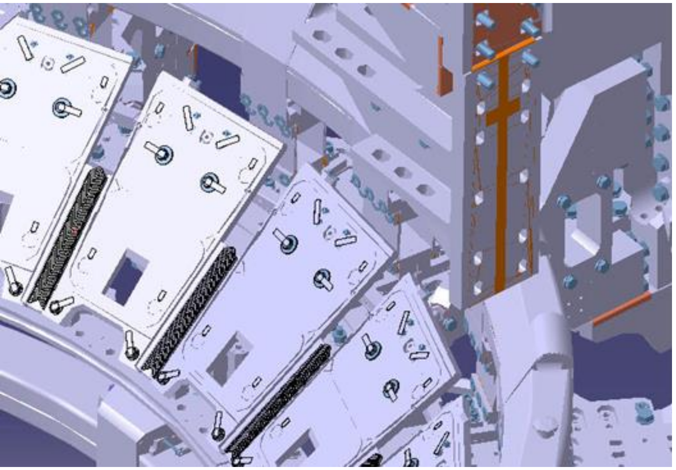
Comparisons to measured P4 coil case currents give confidence in the VALEN model

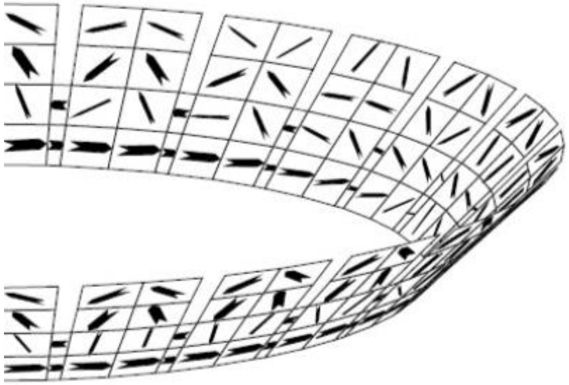




- Rogowski measurement of P4 feedthrough current subtracted from total current
  - With compensation and calibration, this gives the induced coil case eddy currents

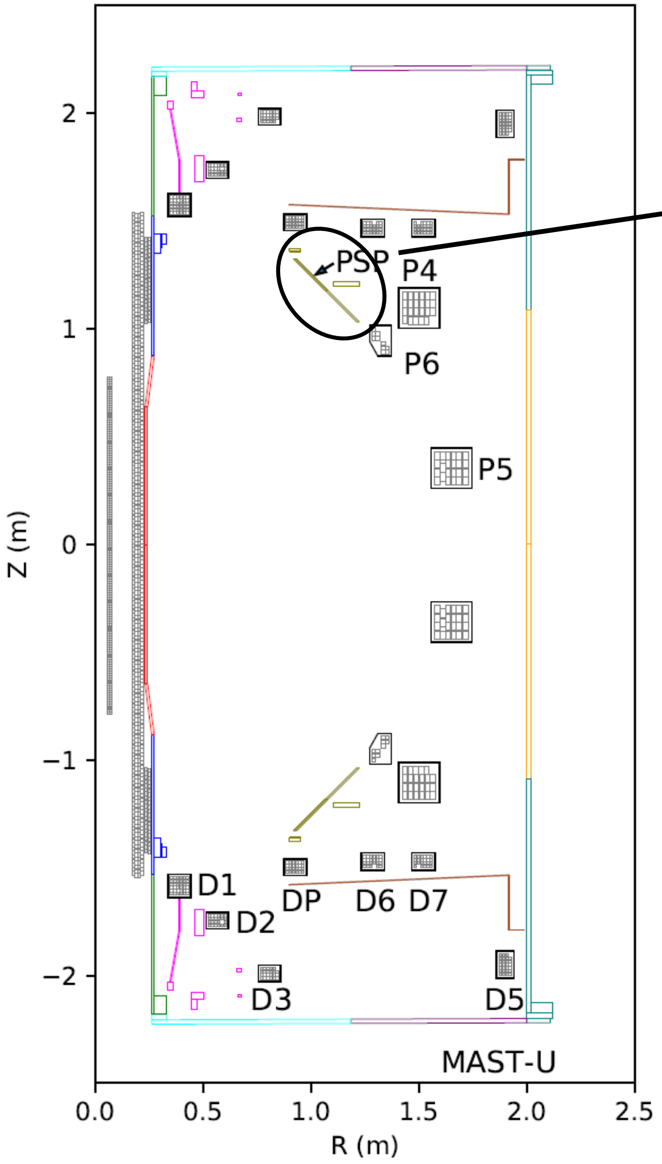
The passive stabilization plates are a new non-axisymmetric 3D structure close to the plasma



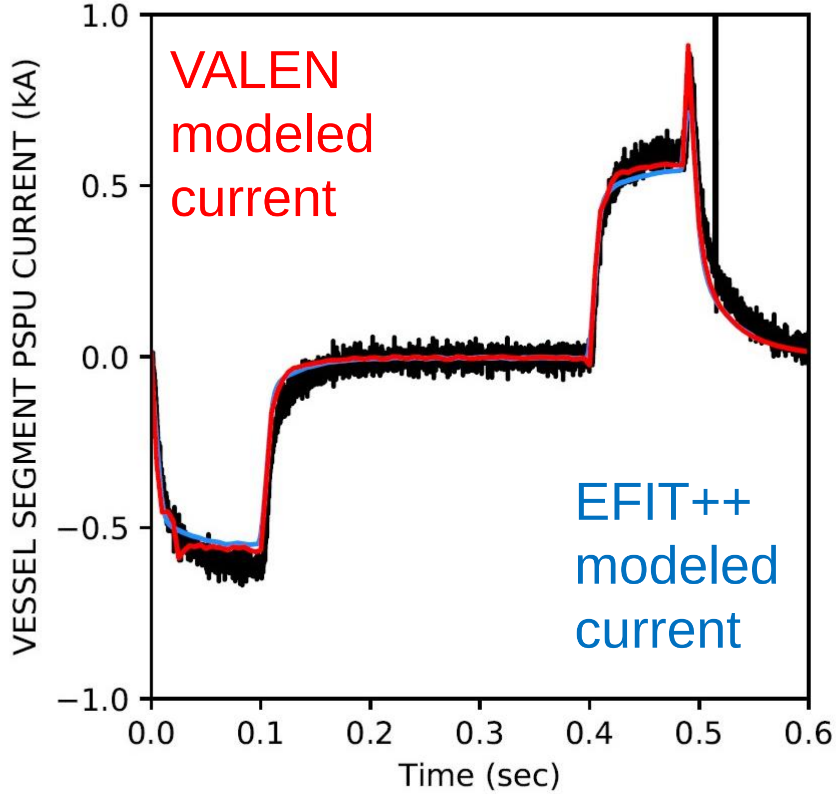


- The connections between the individual plates span only half the plates height
- The resistivity of those connections is modeled, but not precisely known
  - If there is notable extra resistance due to the mechanical joint from plate to plate, eddy currents will be more likely to circulate within each plate
  - If there is negligible extra resistance, the sum total of all plates will act as a complete toroidal conductive path
- This effect will be most important for periods of transient coil currents, less so at steady state

Initial effective resistances for the MAST-U vessel structures have been determined

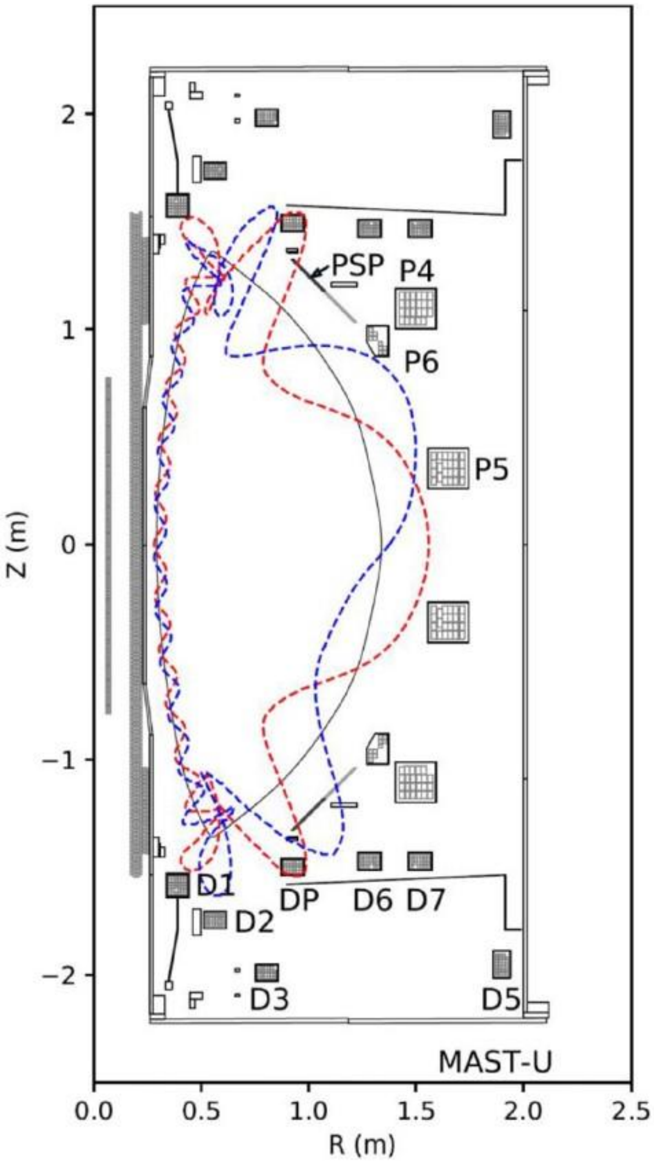


Measured loop voltage / determined effective resistance

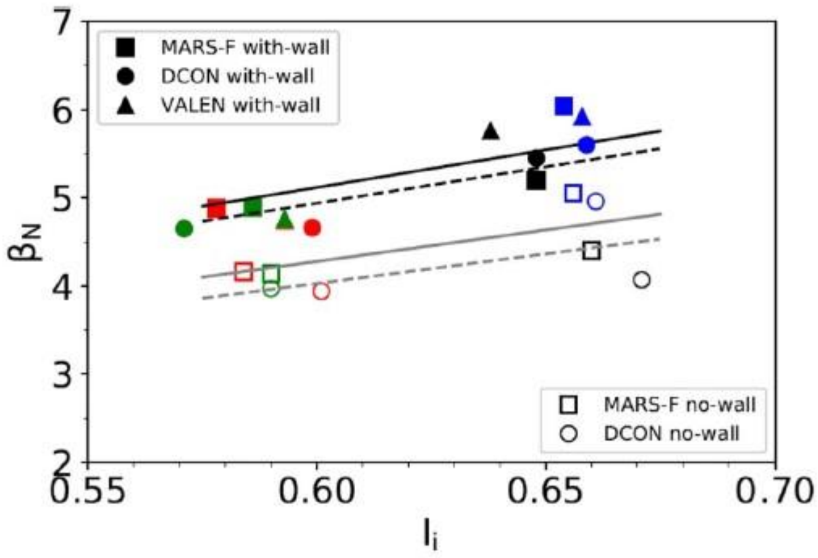


- The VALEN model is able to capture the response of the passive stabilization plates

Projected MAST-U equilibria were used to evaluate the ideal MHD stability space



- Exaggerated view of perturbation shows importance of PSP for wall stabilization
- Multiple codes give similar no-wall, with-wall beta limits
  - DCON, MARS-F and VALEN with different wall models tested on multiple projected equilibria



[J.W. Berkery, *et al*., accepted by PPCF (2020)]

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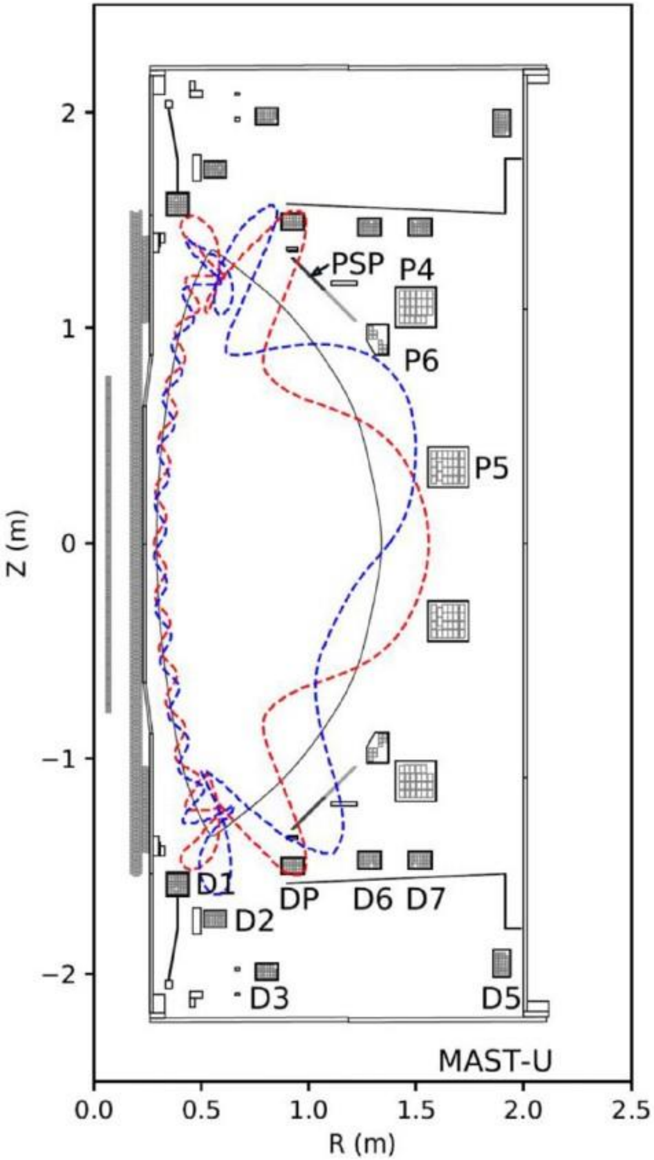
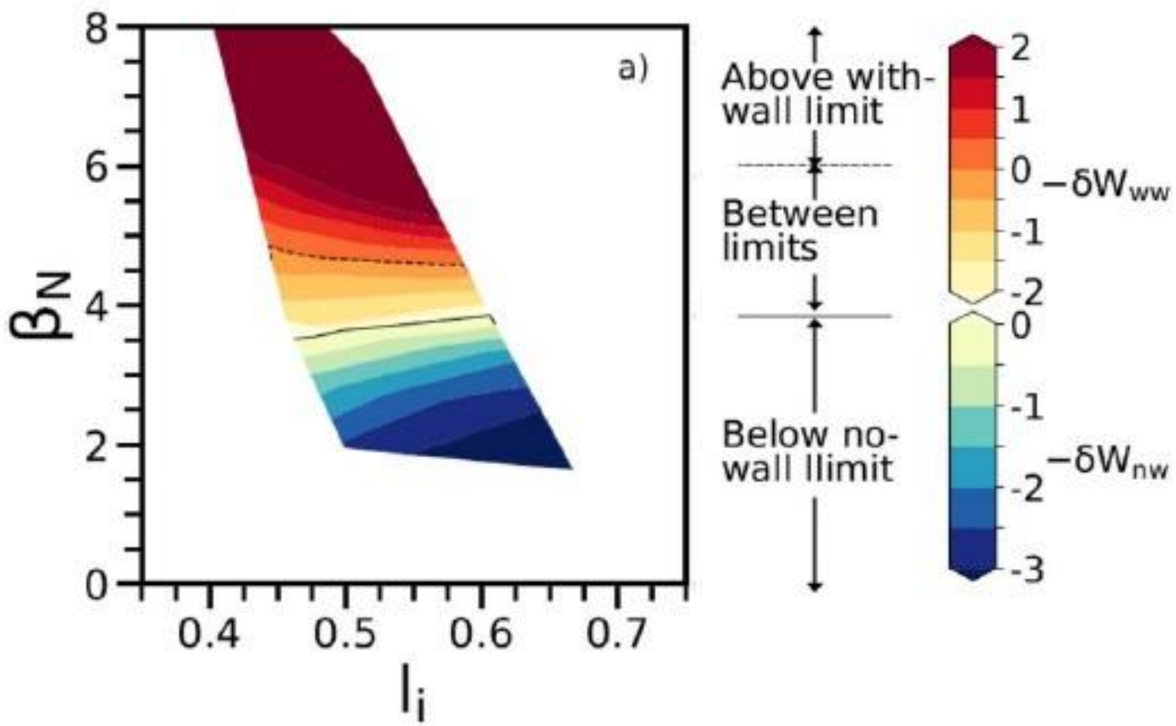




- Scans of pressure and q profiles map stable and wall-stabilized MAST-U regimes

[J.W. Berkery, *et al*., accepted by PPCF (2020)]

Conclusions

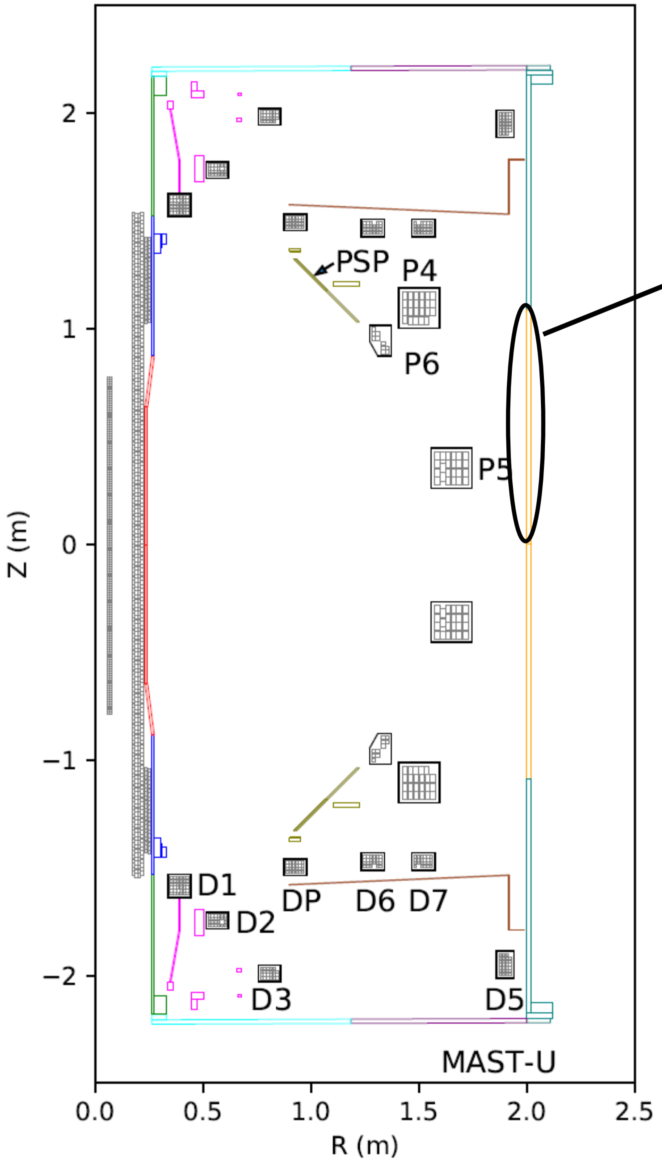
- Kinetic equilibrium reconstructions should be ready for the first MAST-U plasmas
  - The VALEN model of currents in the conducting structure is implemented and tested
- Reconstructions with magnetics only, partial kinetic, and kinetic with MSE have been tested in MAST
  - Good performance is obtained, with low error
- Stability studies using these equilibria have started
  - Initial results obtained for MAST with DCON, DECAF, and ML

    [A. Piccione, J.W. Berkery, *et al*., Nucl. Fusion **60**, 046033 (2020)]
  - Projected stability spaces for MAST-U have been explored

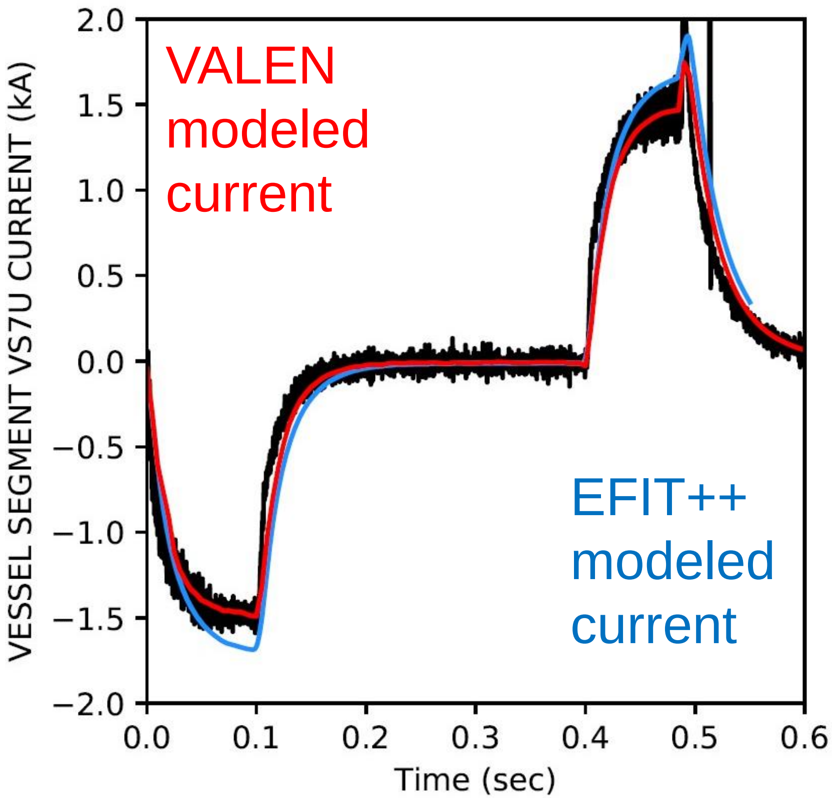
    [J.W. Berkery, *et al*., accepted by PPCF (2020)]

Extra slides

Initial effective resistances for the MAST-U vessel structures have been determined



Measured loop voltage / determined effective resistance



- The effective resistances and measured voltages give an inferred current to use in reconstructions