Use of Integrated Models to Support Machine Assembly

Simon McIntosh
Xue Bai
Yuri Gribov
Simon Pinches
Richard Pitts
Alberto Loarte

ITER Organization

Friday 3rd July 2025

IIS2025 14th ITER International School

Integrated Modeling in Magnetic Fusion Plasmas

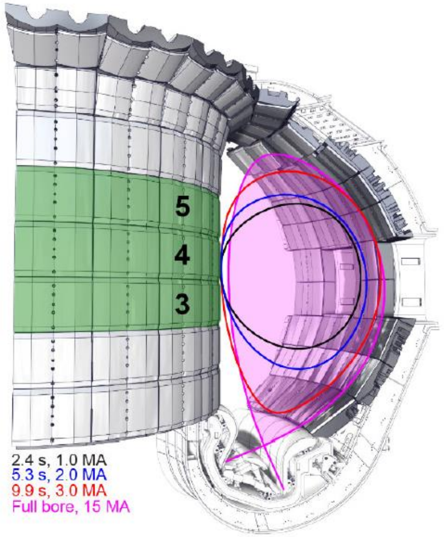
iter
china eu india japan korea russia usa

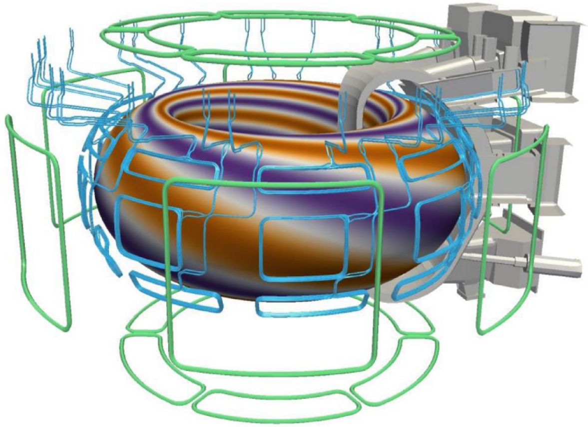
The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

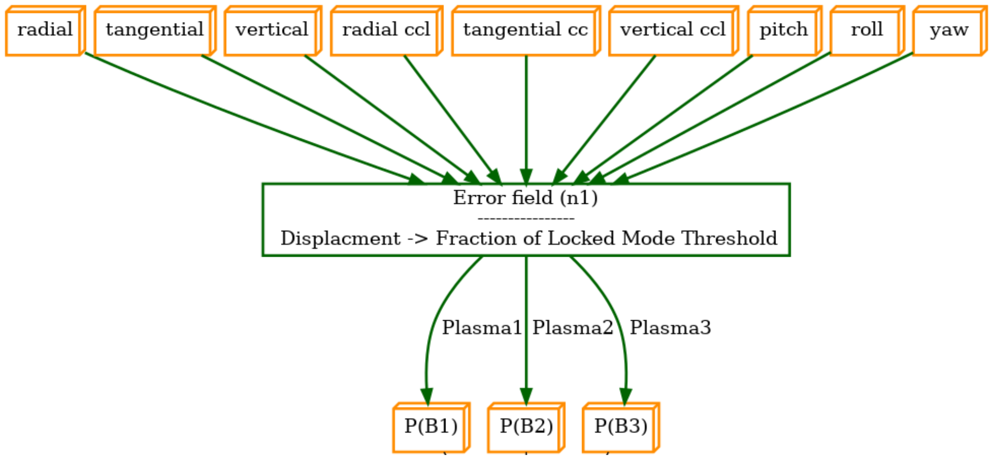
This presentation focuses on the development of ITER’s assembly strategy to ensure compliance with key physics limits.

All Models are Wrong…

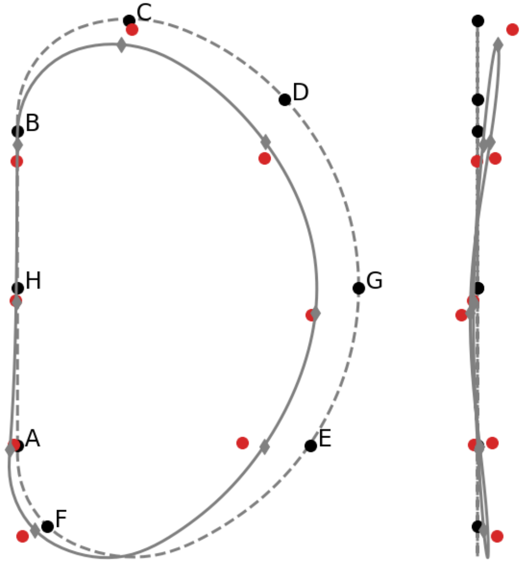
Physics Limits and Monte-Carlo trials

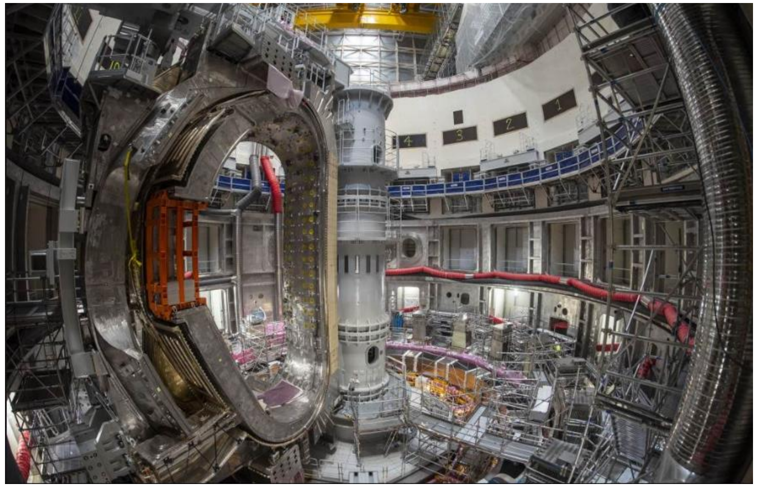






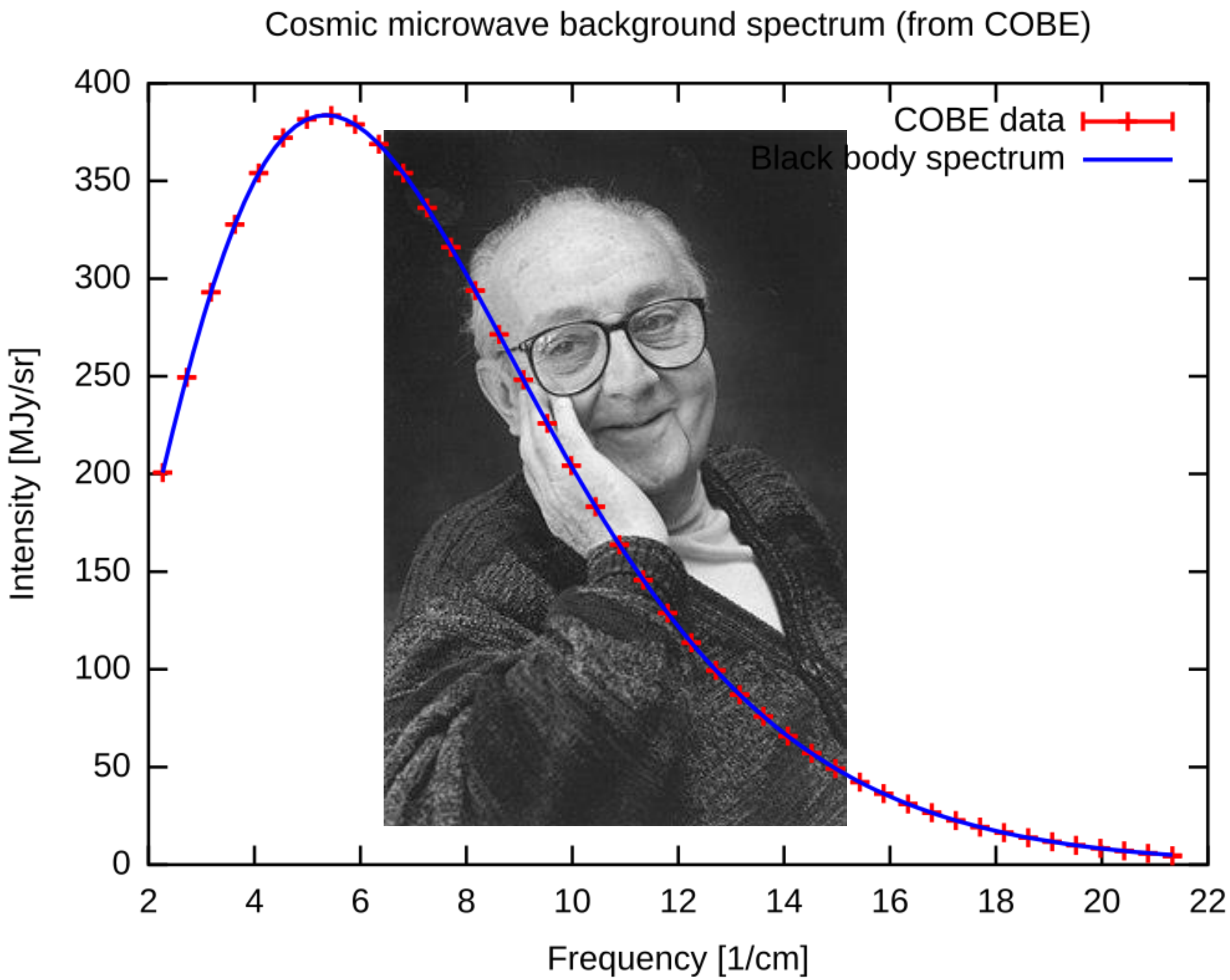
Gaussian Process alignment





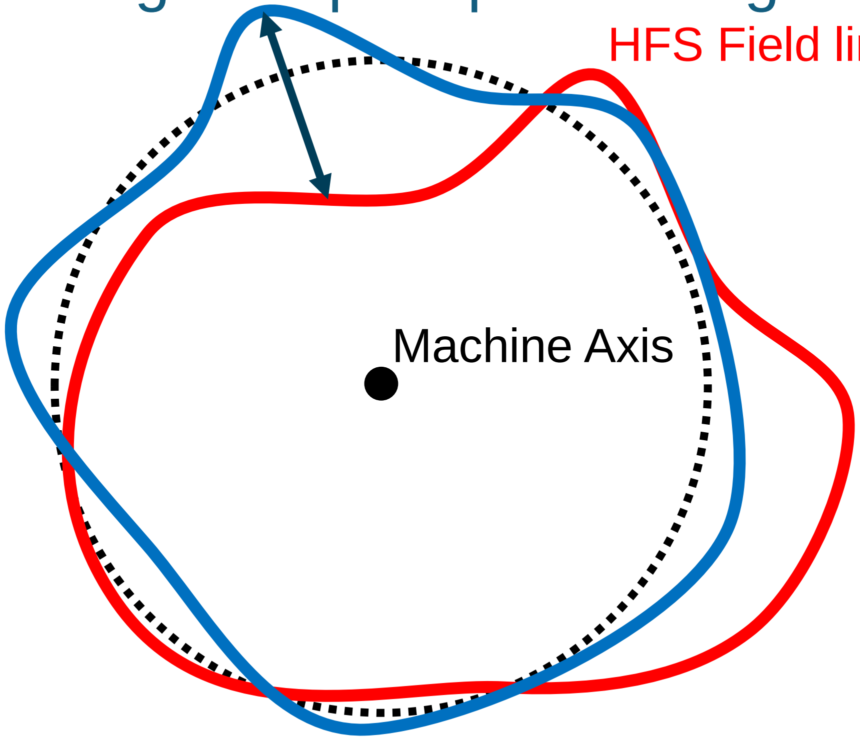
“All models are wrong, but some are useful”.

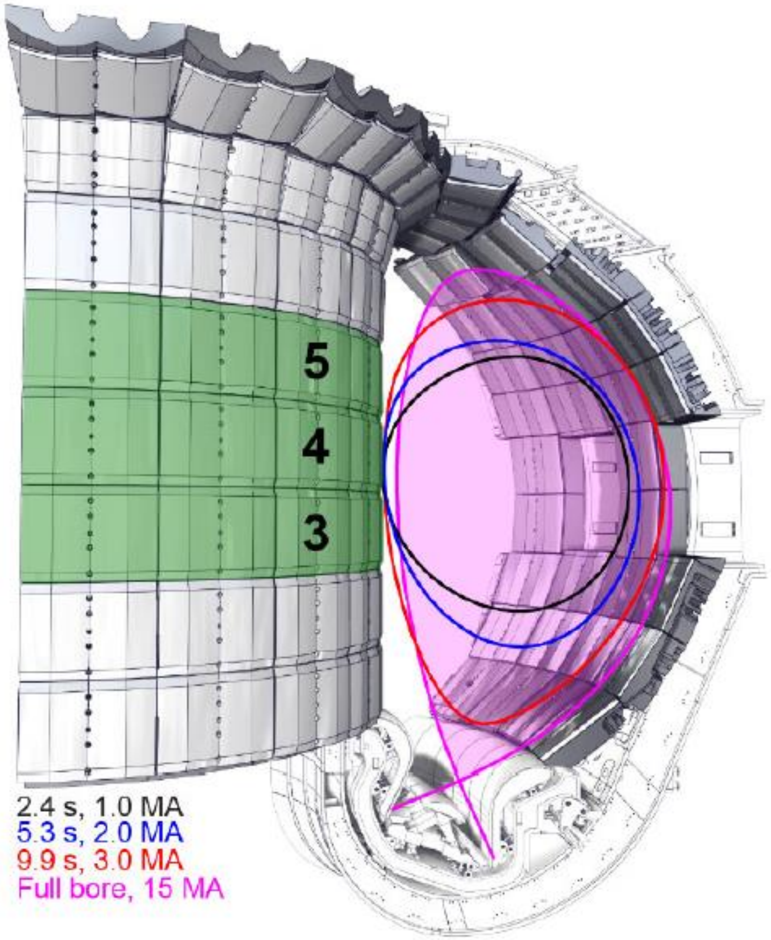
George Box



Field line deviations with respect to the first wall generate high start-up heat loads.

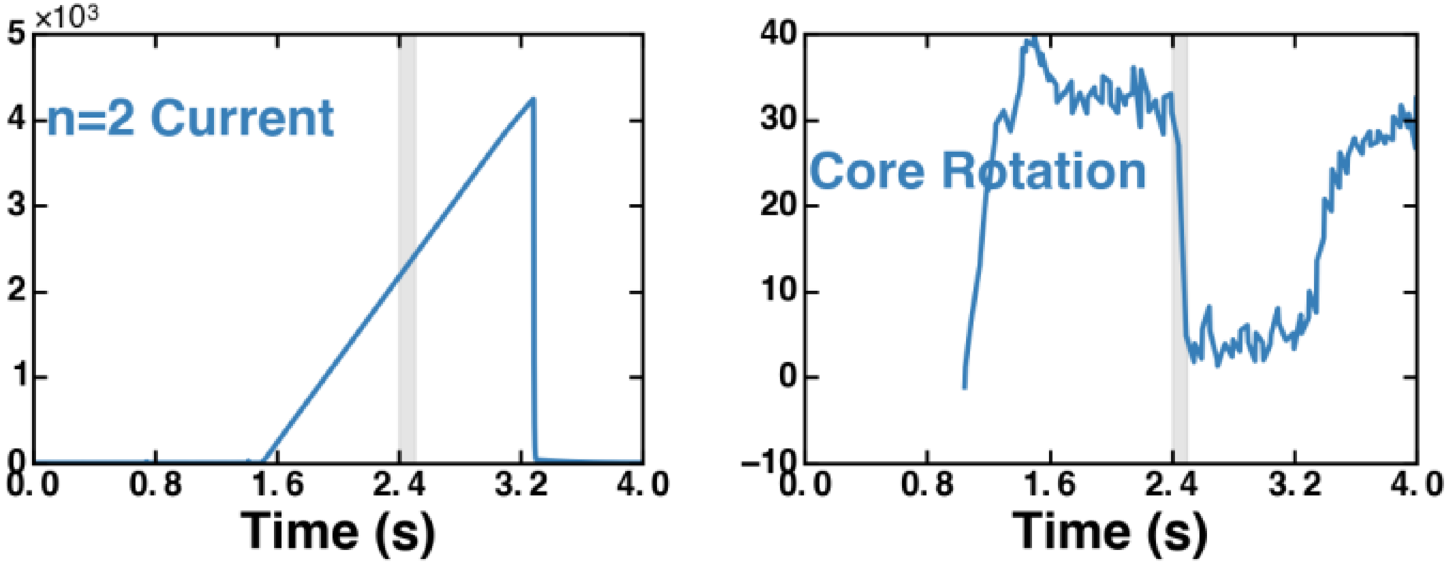
Field lines and first wall should be approximately concentric and circular with a long wave peak-peak misalignment $H <$ 6mm .

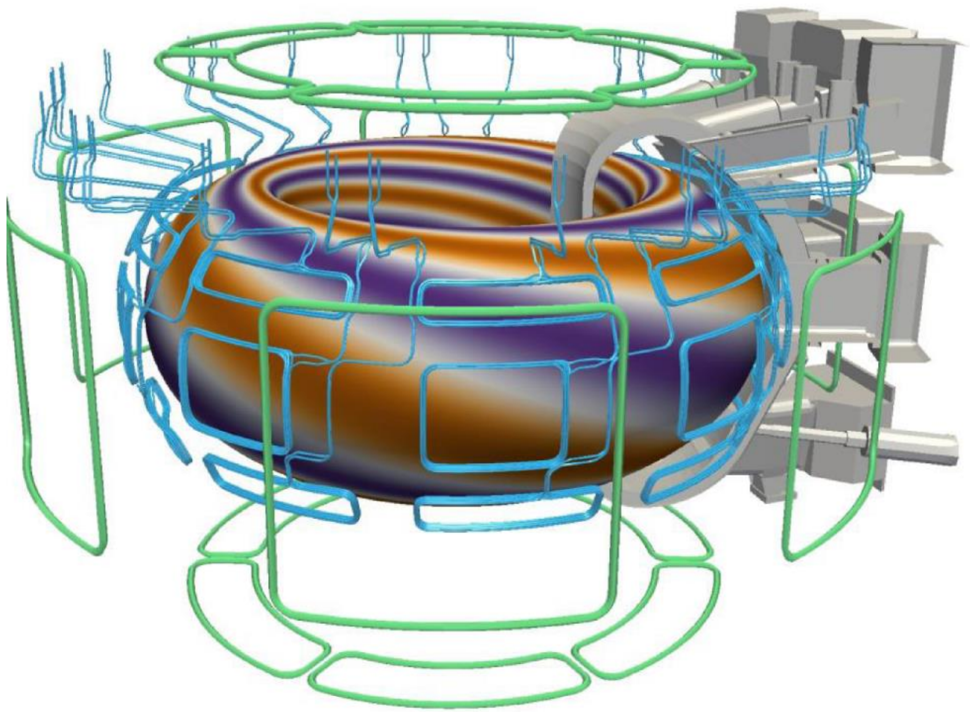




Error fields slow plasma rotation and increase disruptivity.

Overlap error field limits are defined via a semi-empirical scaling for n=1 & n=2 modes (GPEC) .

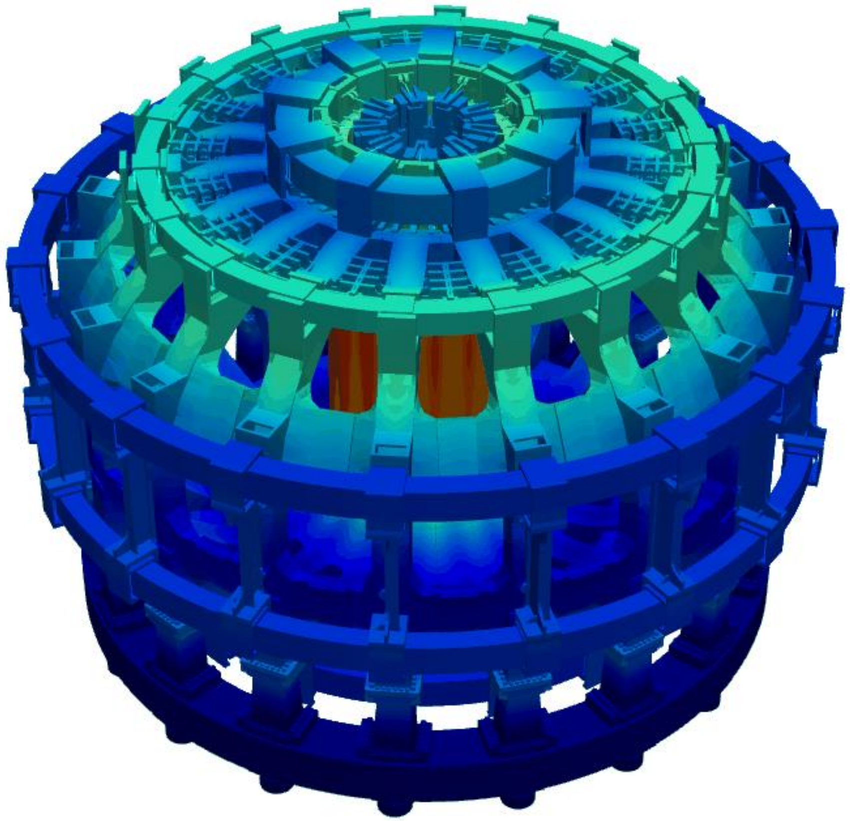


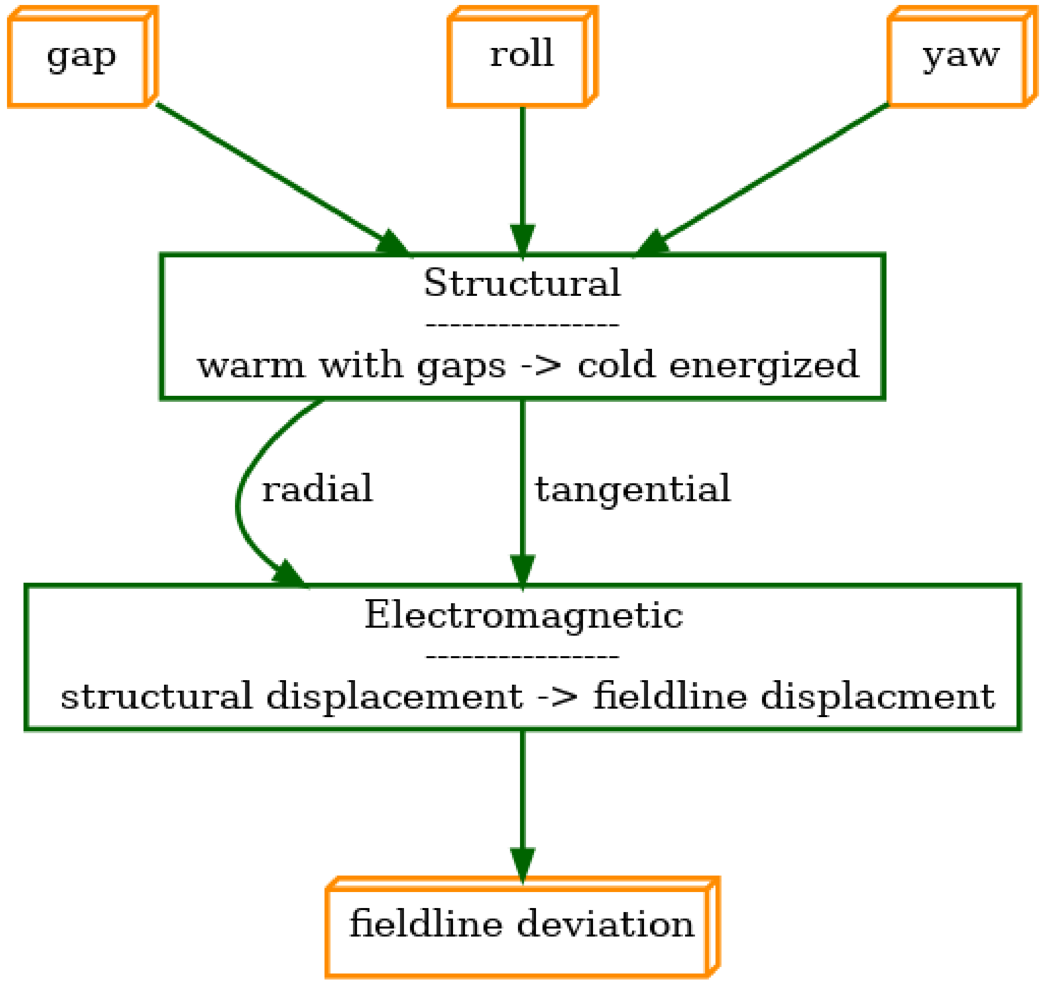


DIII-D L-mode discharge (Logan et al., 2020)

The machine is assembled in a warm discharged state but is operated in a cold active state with currents flowing in the coils.

A single high-fidelity analysis pipeline takes ~4 weeks.

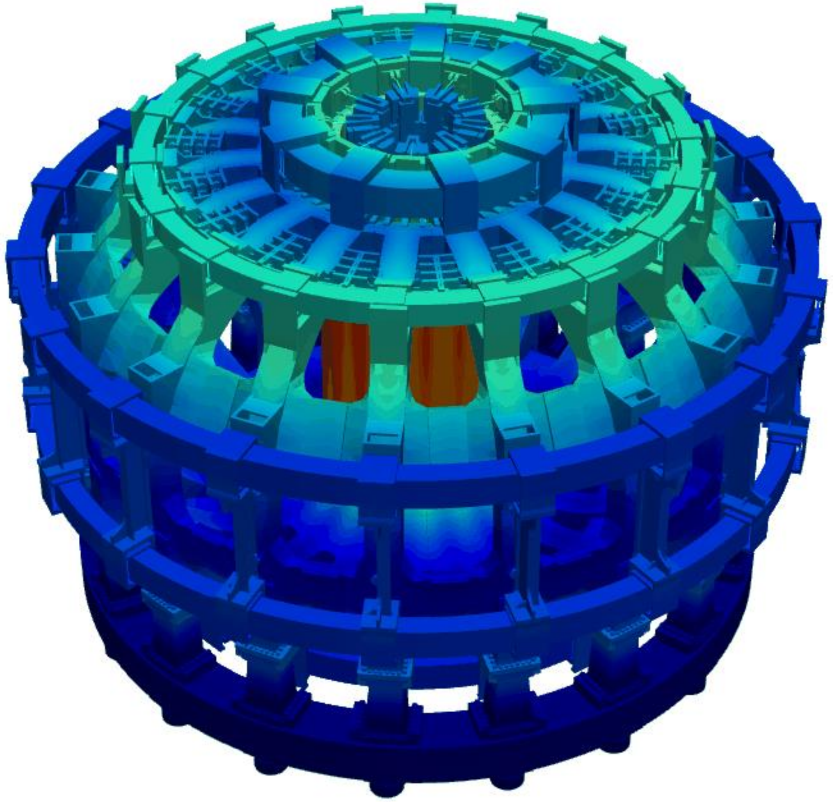




iter

Coil energization aligns the toroidal field coil vault.

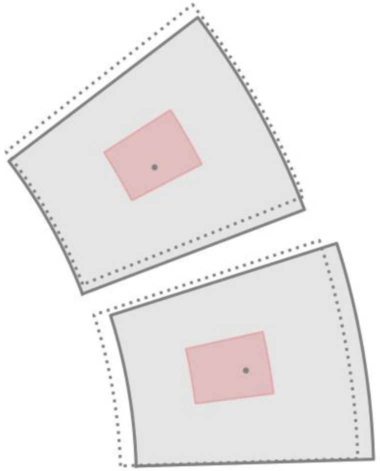
High-field and low-field sides of the TF coils are structurally decoupled.

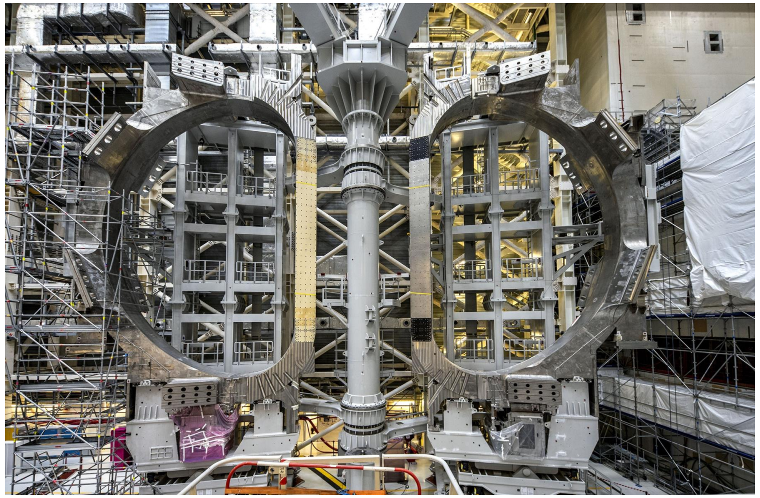


magnification x50

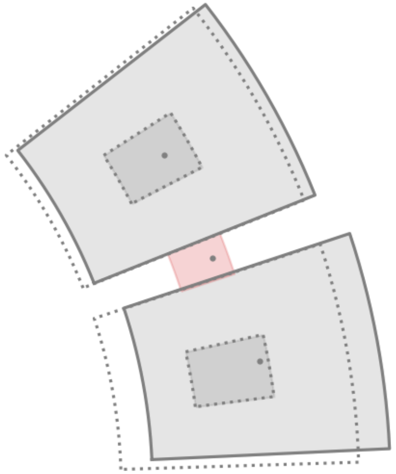
Component alignment is governed by targets and tolerances.

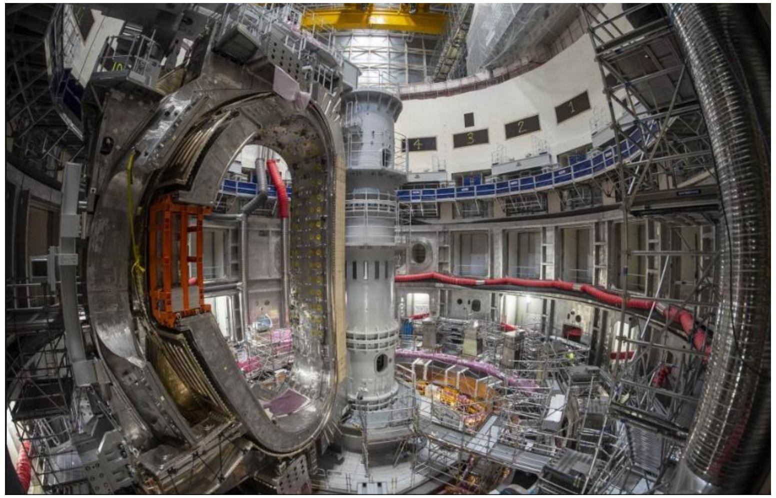
Subsector assembly tool



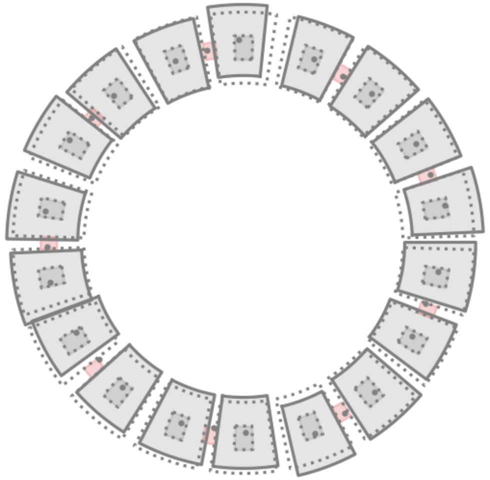


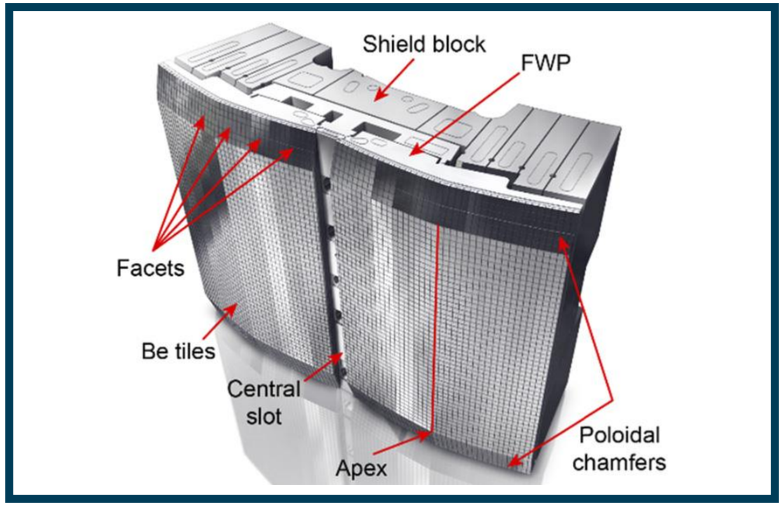
In-pit sector alignment





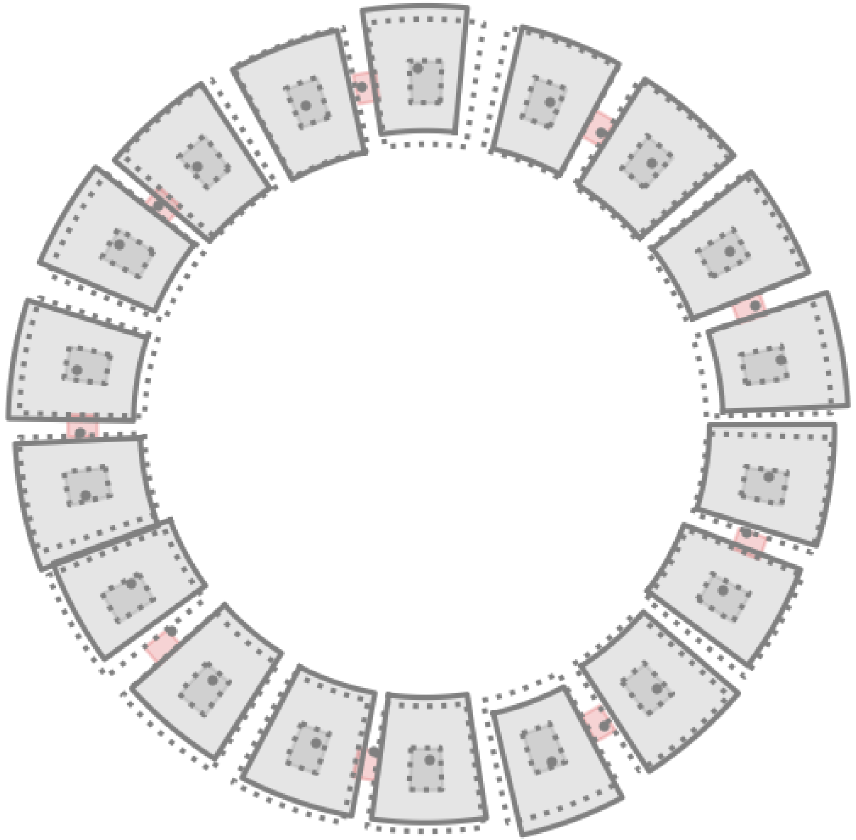
Torus closure & coil energization

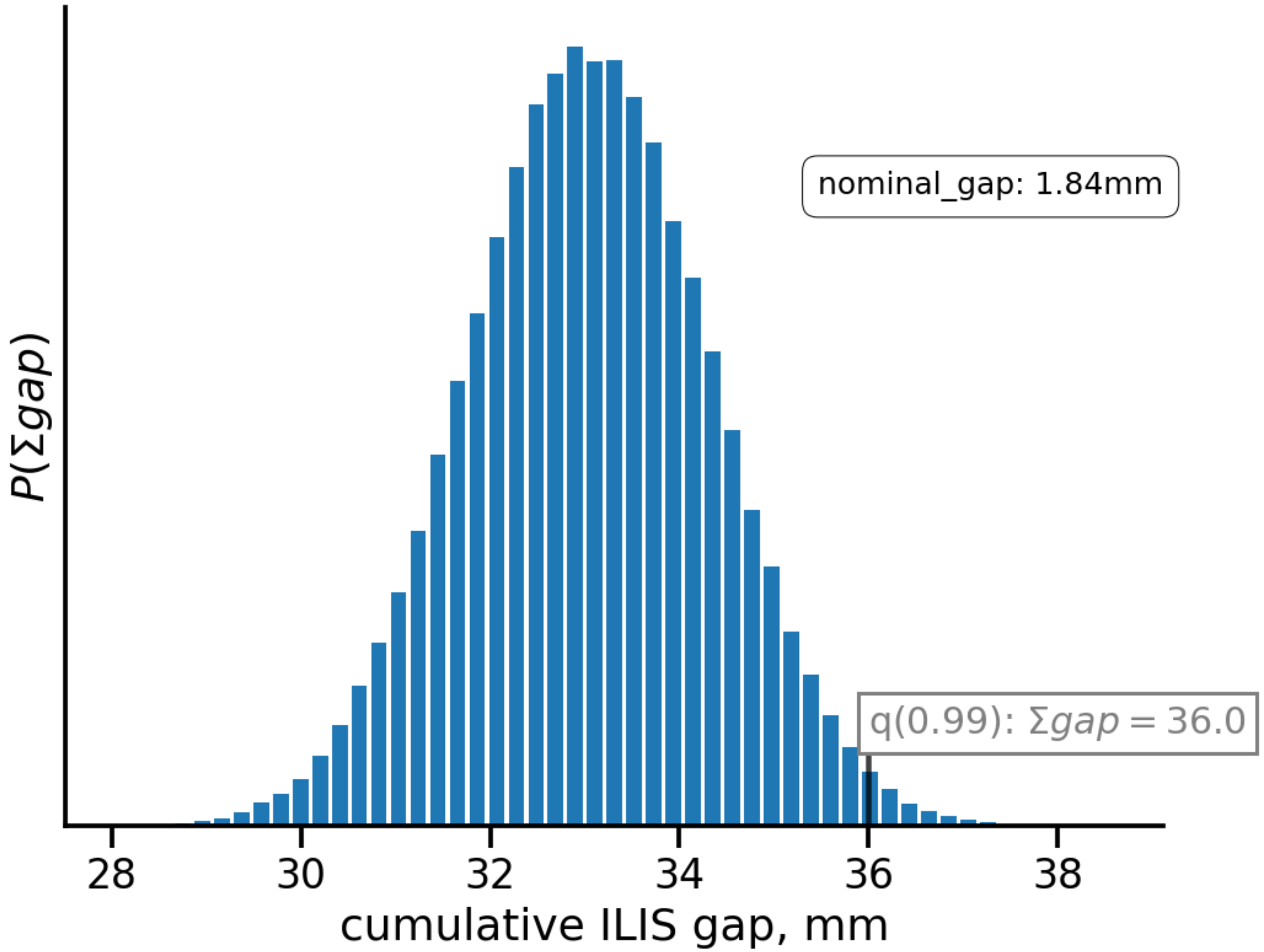




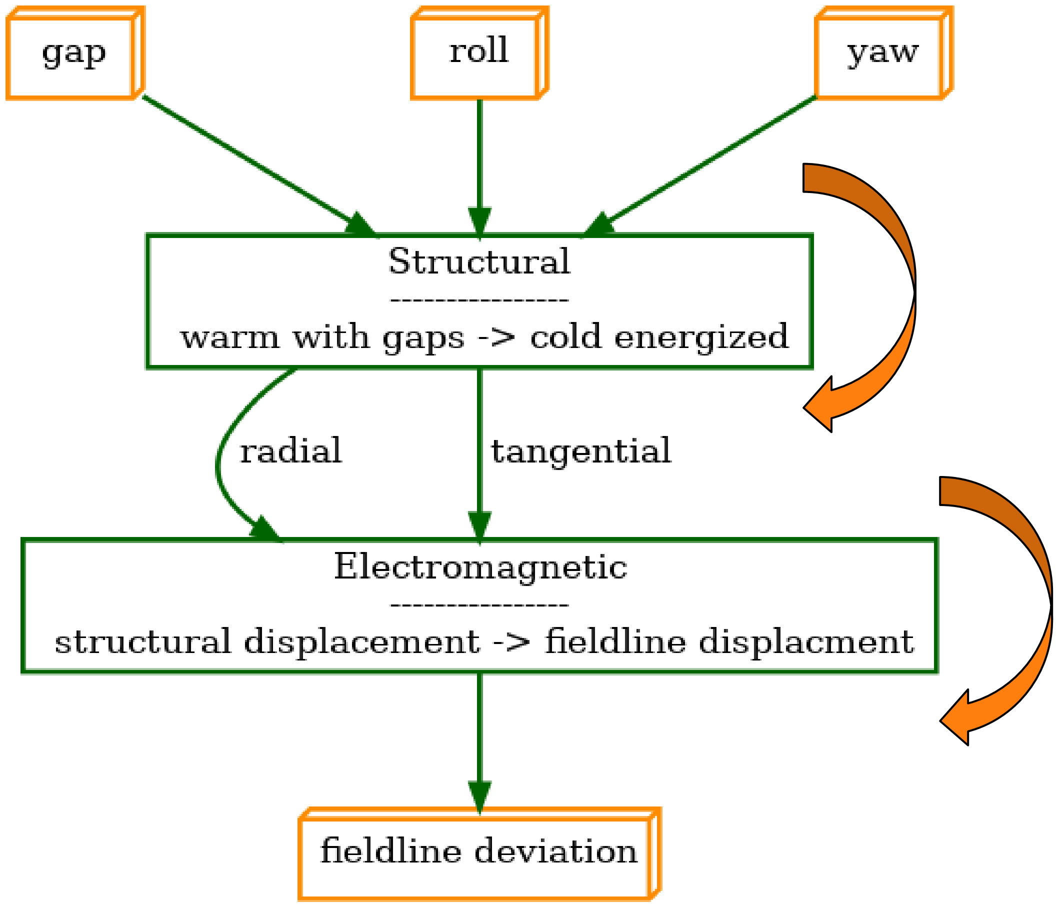
Cumulative ILIS gap limit is incompatible with reference ILIS gap.

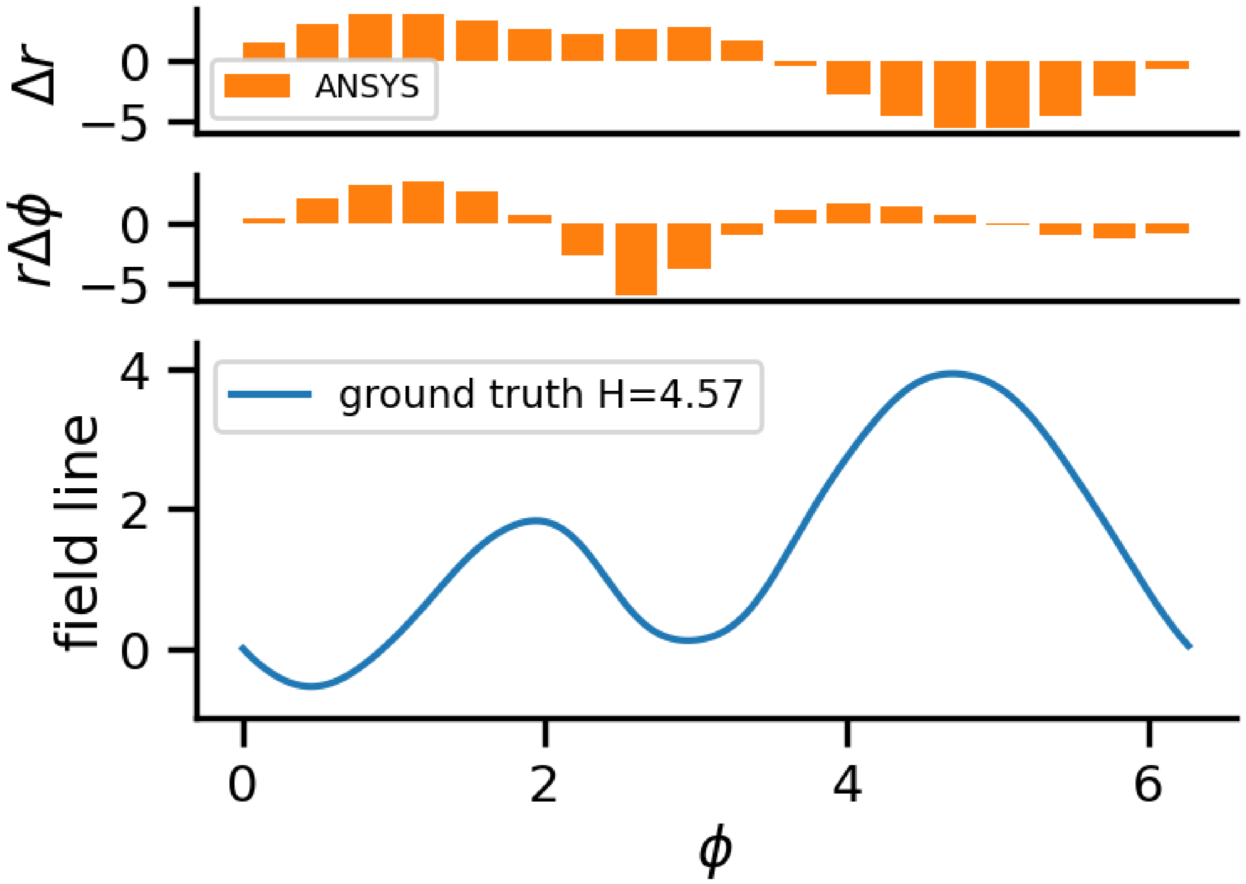
A cumulative gap limit <38mm is exceeded in 50% of all trials with a reference ILIS gap of 2mm .





Structural and electromagnetic models map warm coil assemblies to field line displacements.



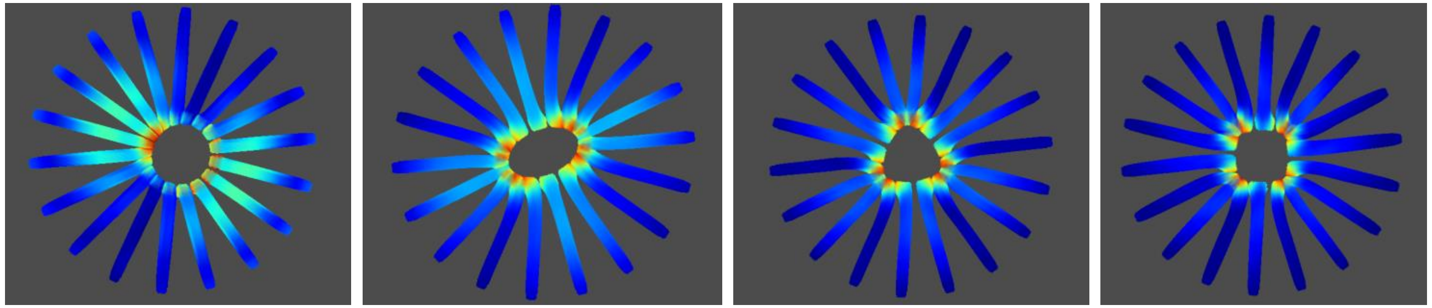


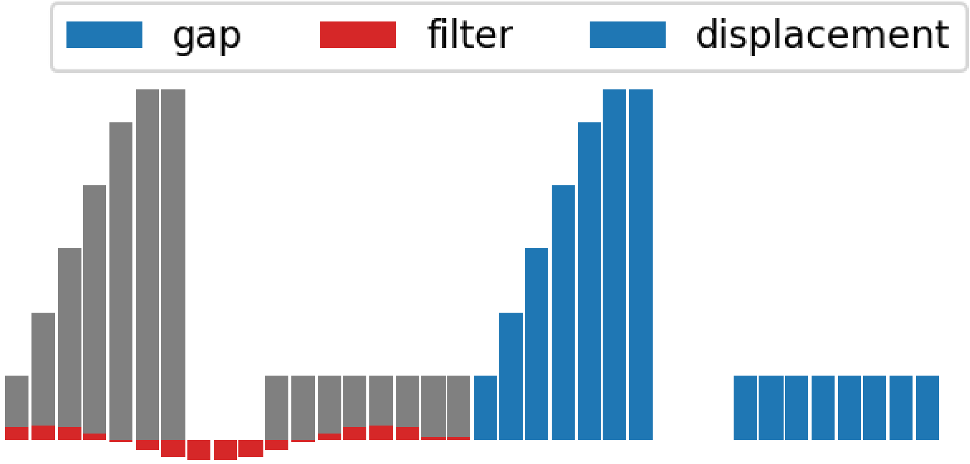
A transfer to the spectral domain permits the separation of excitation and response waveforms for structural and EM analysis.

$$\{g \star h\}(x) = \mathcal{F}^{-1}\{G \cdot H\}$$

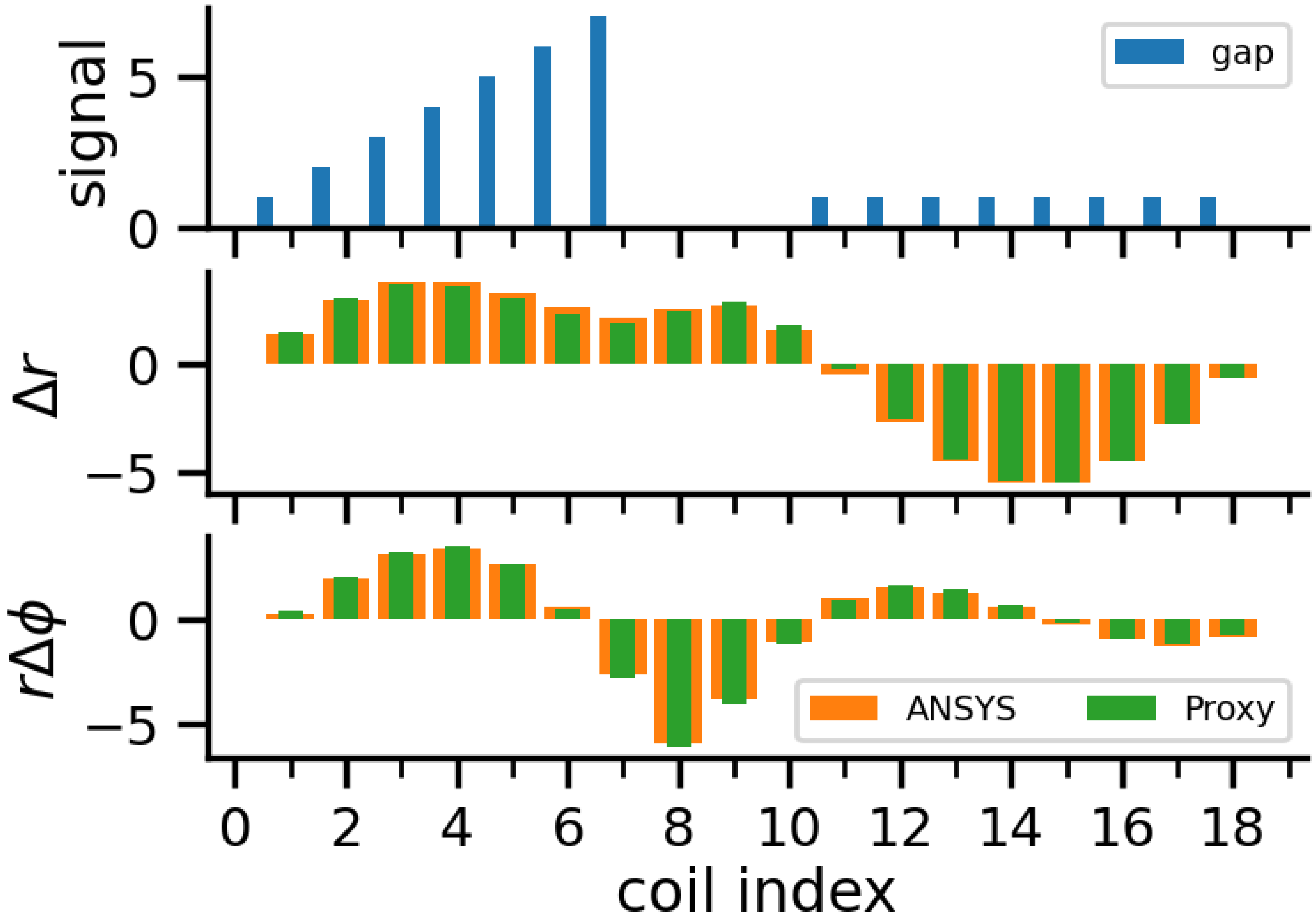
signal → FFT → Filter → inverse FFT → response

$$\text{Filter(k)} = \frac{\text{Response(k)}}{\text{Signal(k)}}$$

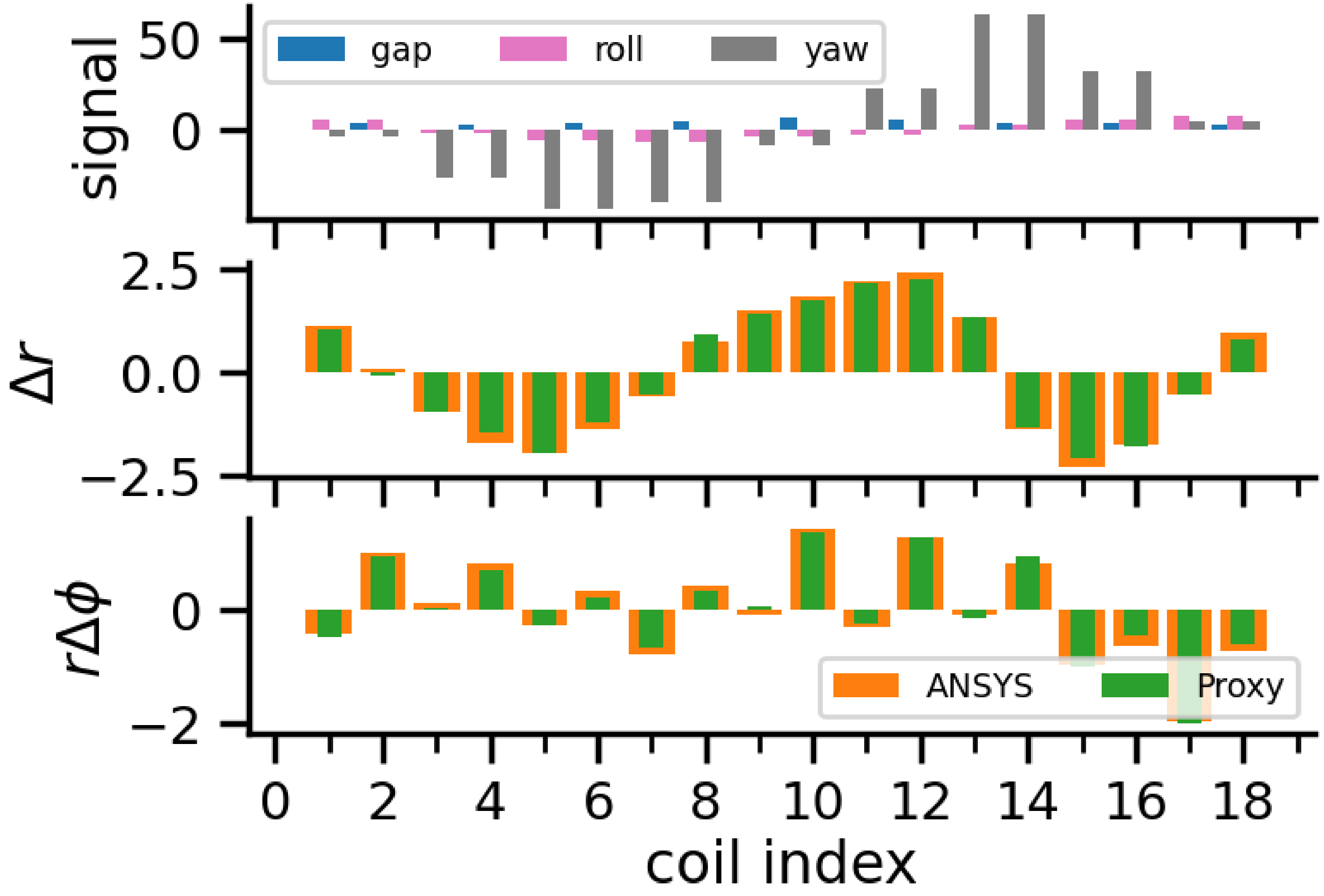




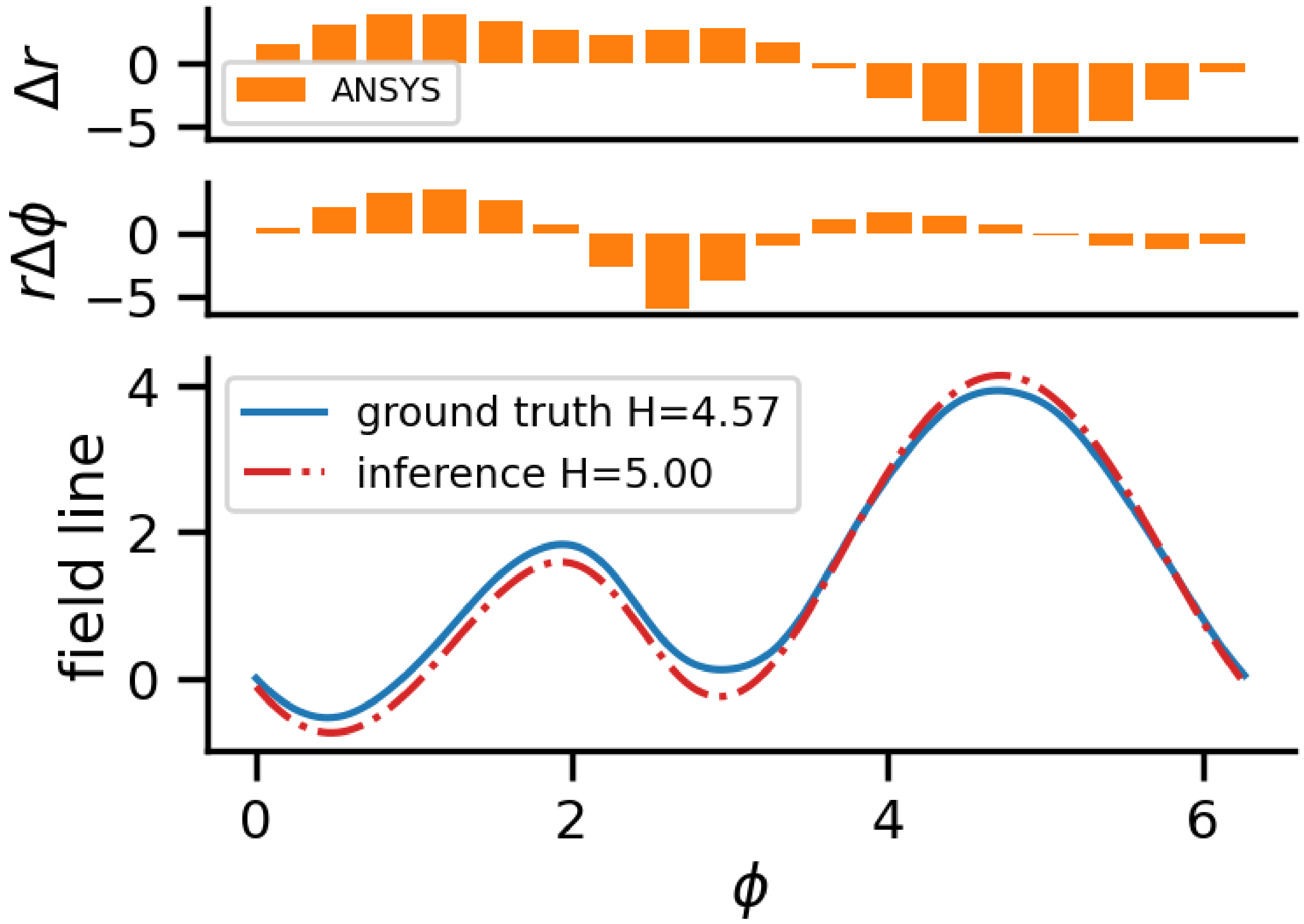
High-fidelity ANSYS simulations validate the structural proxy.



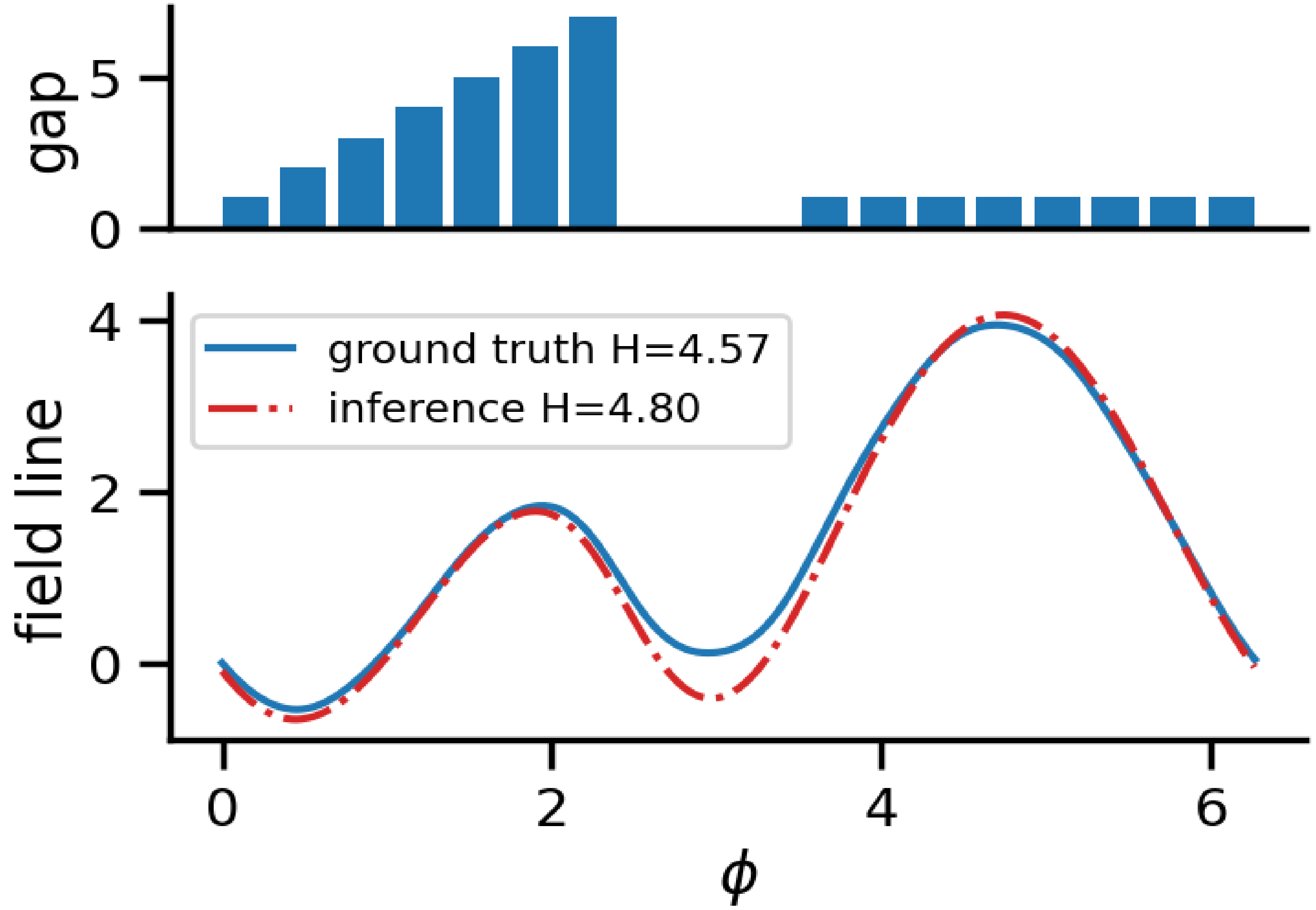
High-fidelity ANSYS simulations validate the structural proxy.



High-fidelity EM simulations validate the electromagnetic proxy.



Spectral filters accelerate single point solution time from 4 weeks to 50 micro seconds with an RMS error <5%.



A computational graph visualizes the mapping from mm to first wall heat flux limit.

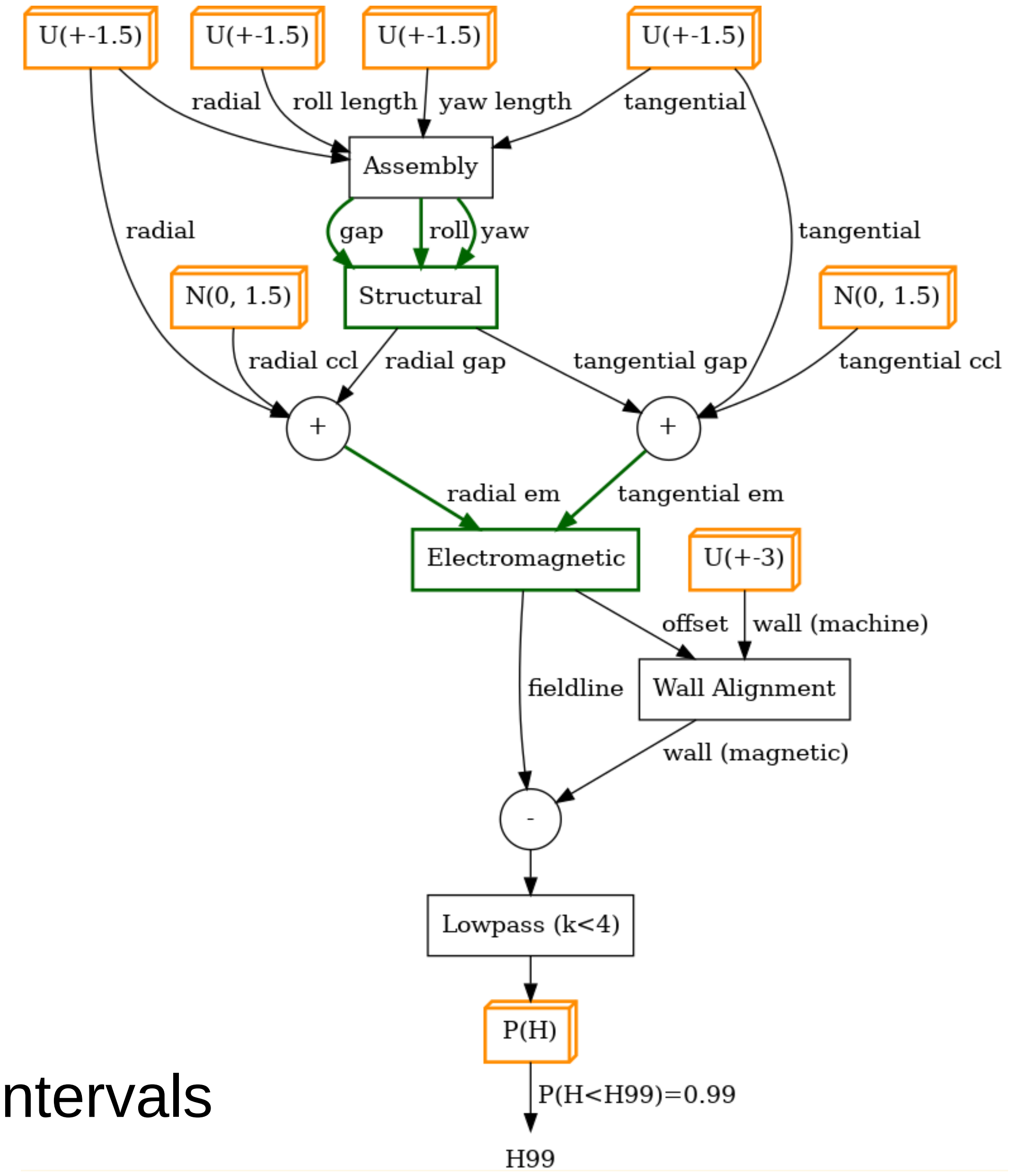
Seven input PDFs (orange):

1. Radial $\mathcal{U}(\pm1.5)$
2. Tangential $\mathcal{U}(\pm1.5)$
3. Roll Length $\mathcal{U}(\pm1.5)$
4. Yaw Length $\mathcal{U}(\pm1.5)$
5. Radial CCL $\mathcal{N}(0,1.5)$
6. Tangential CCL $\mathcal{N}(0,1.5)$
7. First Wall $\mathcal{U}(\pm3)$

Two models (green) implementing 8 filters

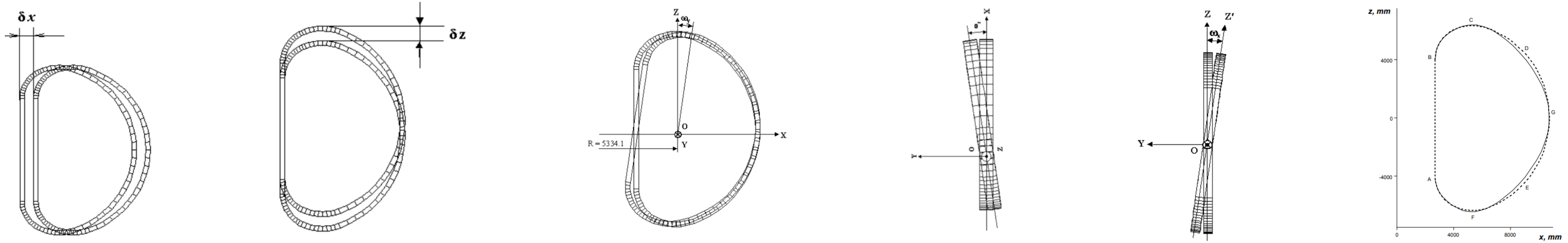
One output PDF P(H)

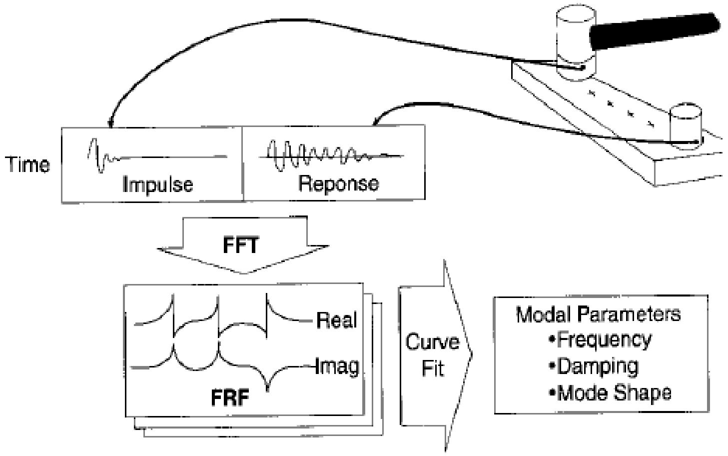
Estimates are presented as 99% prediction intervals



Large impulse response dataset provides overlap error field filter.

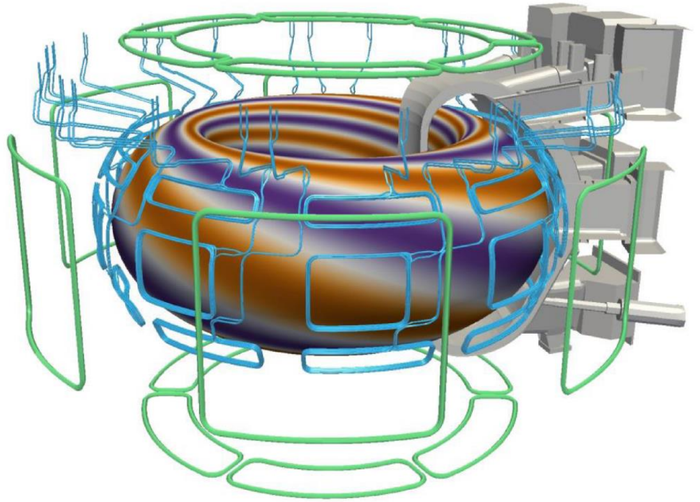
Impulses have a very board frequency response (that is, uniform for **all** frequency components).





signal → FFT → Filter → Response

$$\text{Filter(k)} = \frac{\text{Response(k)}}{\text{Signal(k)}}$$



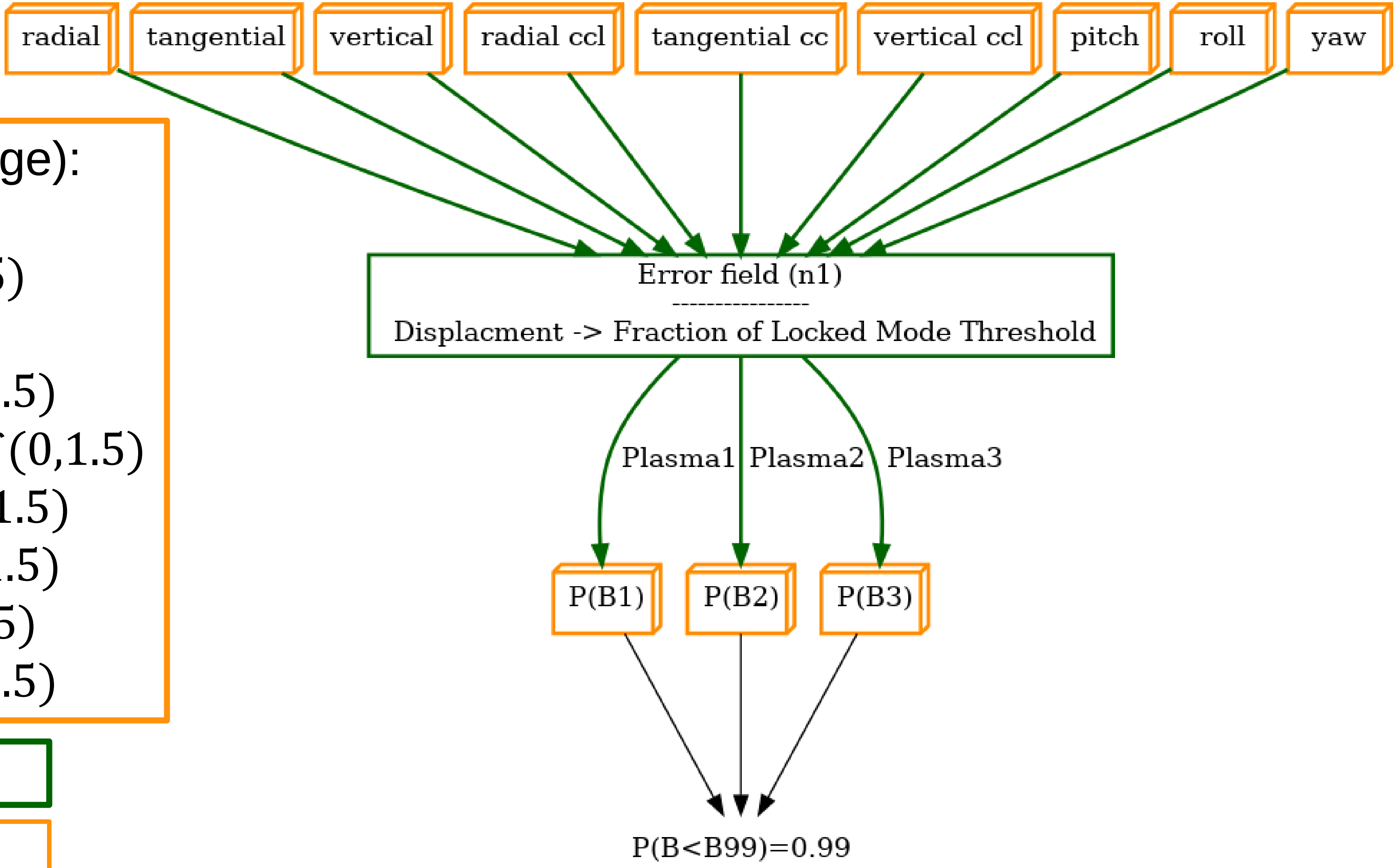
A computational graph visualizes the mapping from mm to the overlap error field limit.

Nine input PDFs (orange):

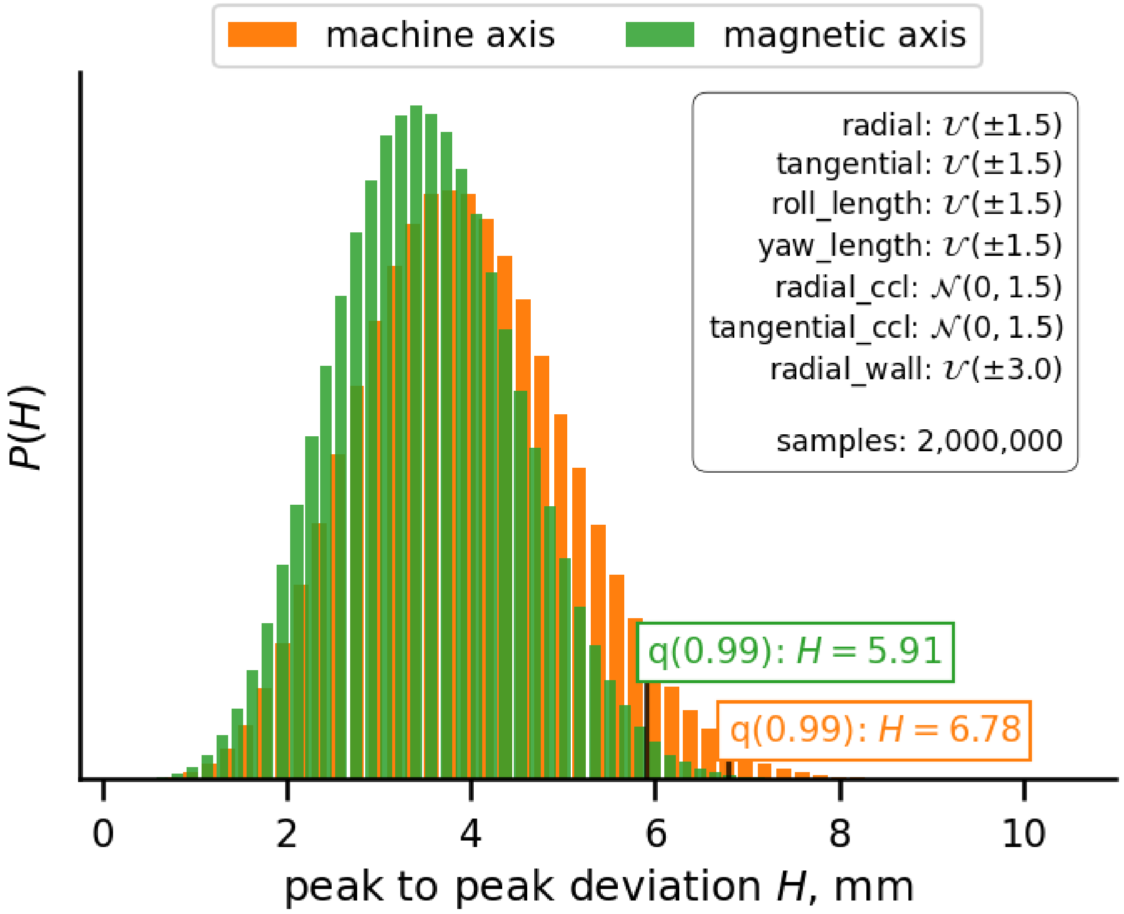
1. Radial $\mathcal{U}(\pm 1.5)$
2. Tangential $\mathcal{U}(\pm 1.5)$
3. Vertical $\mathcal{U}(\pm 3)$
4. Radial CCL $\mathcal{N}(0, 1.5)$
5. Tangential CCL $\mathcal{N}(0,1.5)$
6. Vertical CCL $\mathcal{N}(0,1.5)$
7. Pitch Length $\mathcal{U}(\pm 1.5)$
8. Roll Length $\mathcal{U}(\pm 1.5)$
9. Yaw Length $\mathcal{U}(\pm 1.5)$

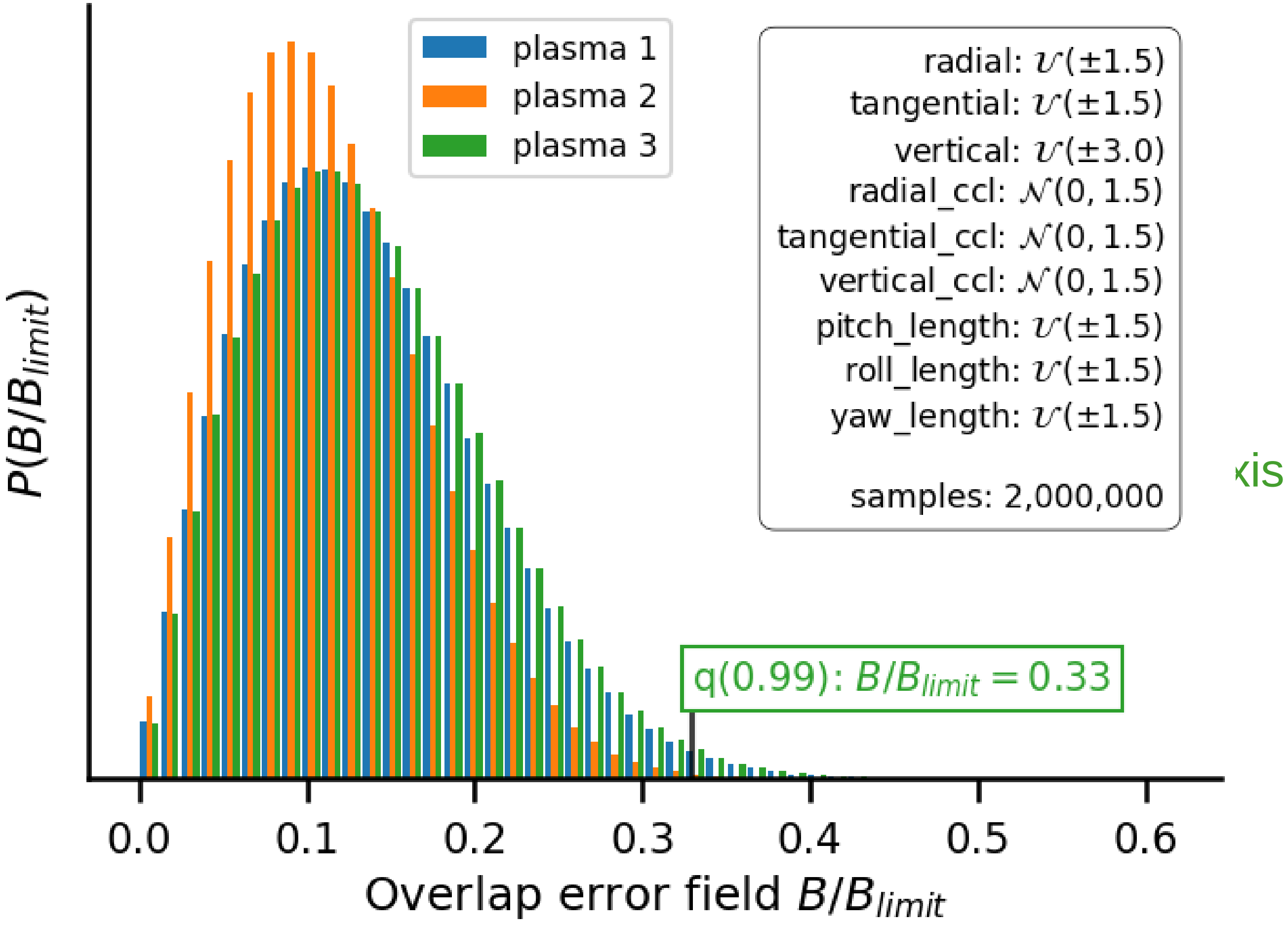
One model with 27 filters

Three output PDFs P(B)



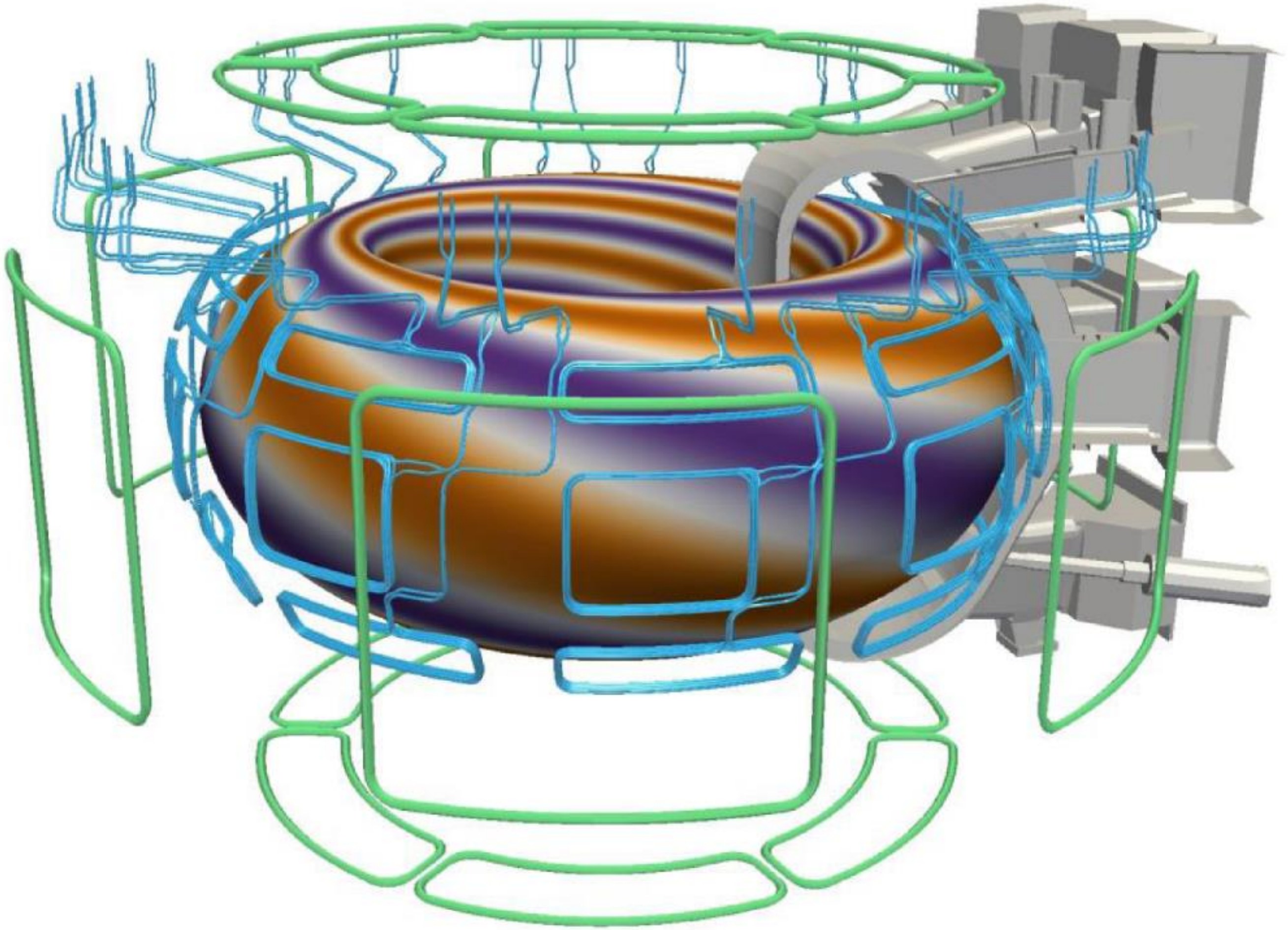
Large scale Monte-Carlo simulations highlight critical links between TF coil assembly tolerances and First Wall customization capacity.





Error field compensation will use two sets of axisymmetric coils.

Question: what are the PF and CS assembly tolerances given finite correction coil currents?



Including plasma response to external 3D fields is essential

$$\mathbf{B} = \mathbf{C}\,\boldsymbol{\phi}_x$$

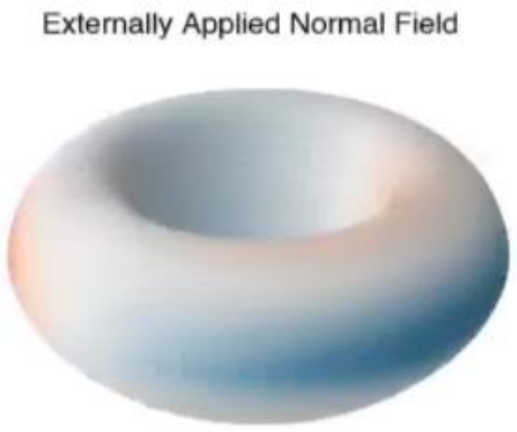
Resonant Response
Response Matrix
External fields

$$\mathbf{C} = U\Sigma\mathbf{V}^*$$

Response Matrix
Right Singular Matrix

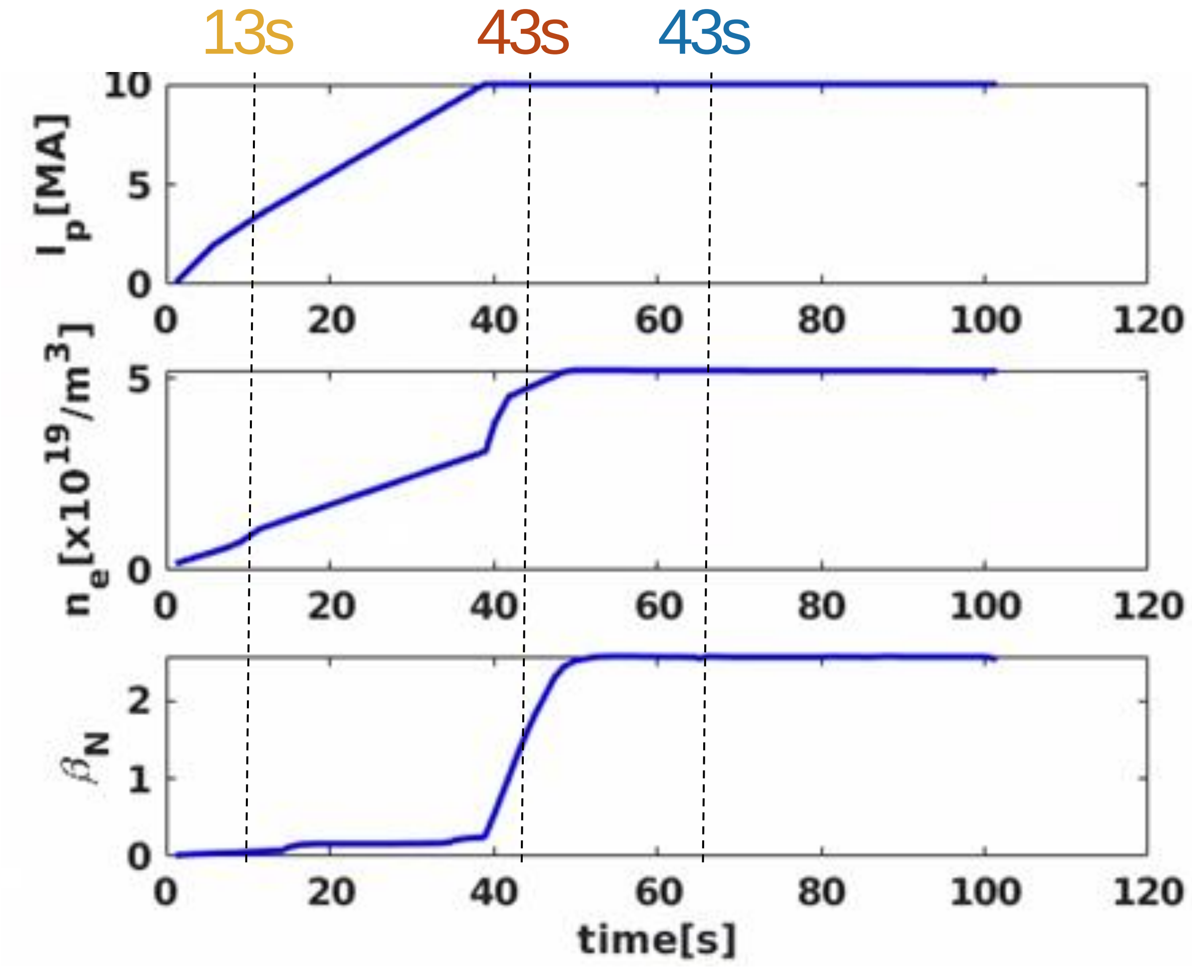
$$\boldsymbol{\delta} = \boldsymbol{\phi}_v \cdot \boldsymbol{\phi}_x$$

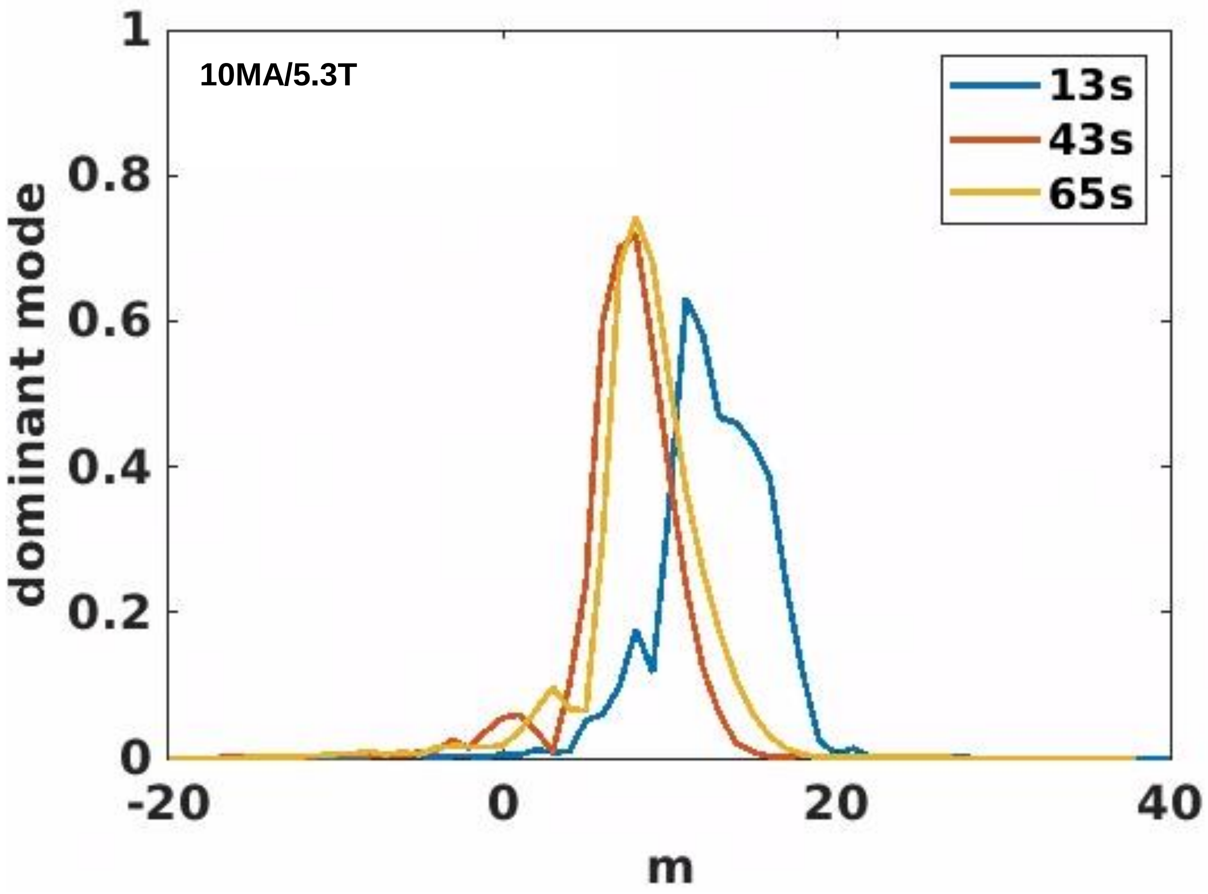
Overlap Error Field
Dominant Mode
External fields



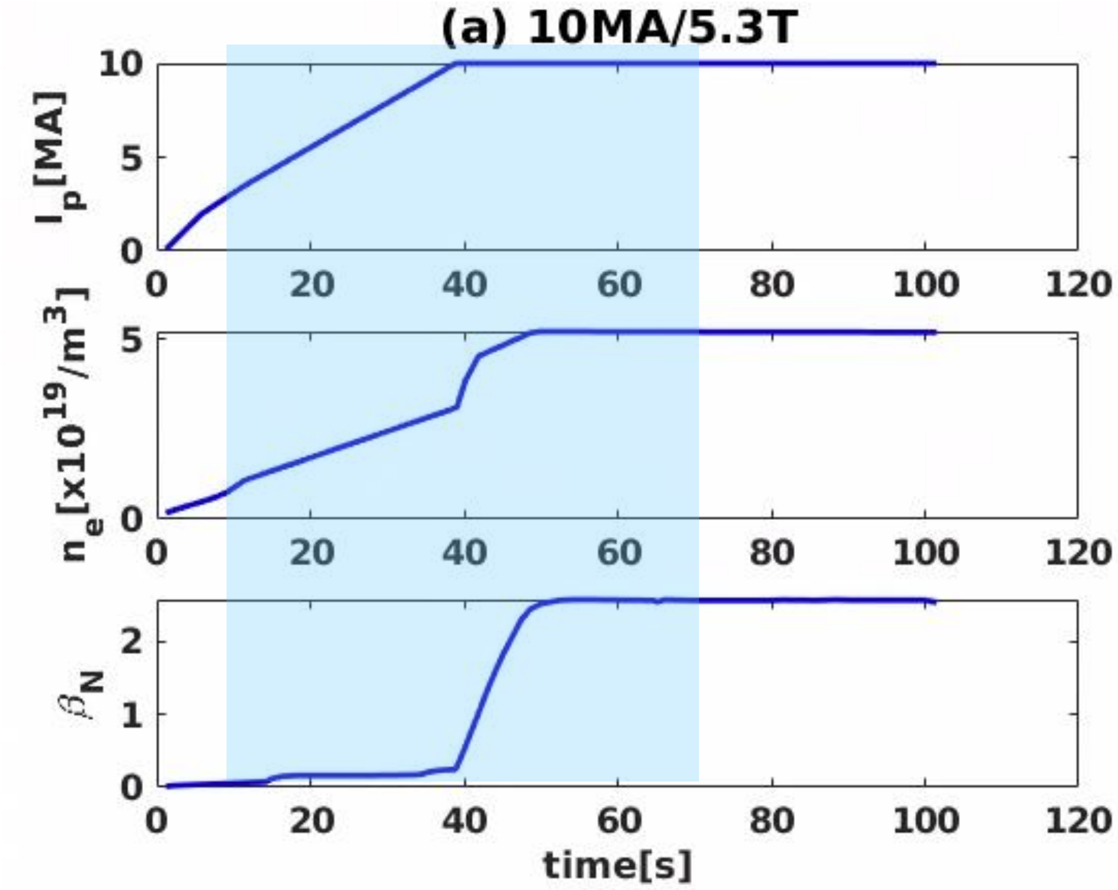
External Error Fields and the Plasma’s response vary over time.

Feedforward error field correction by 3-D fields in ITER – Xue Bai

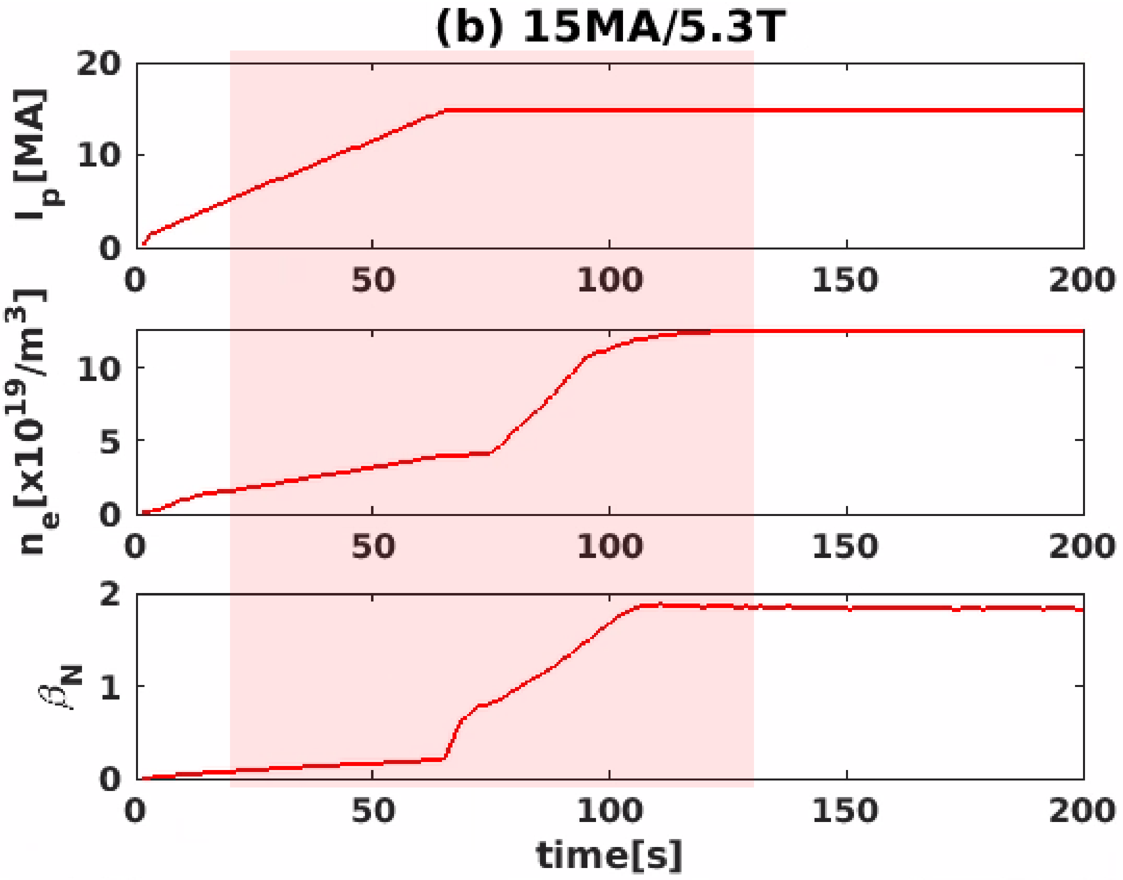




Two high β ITER scenarios selected for error field correction Study.

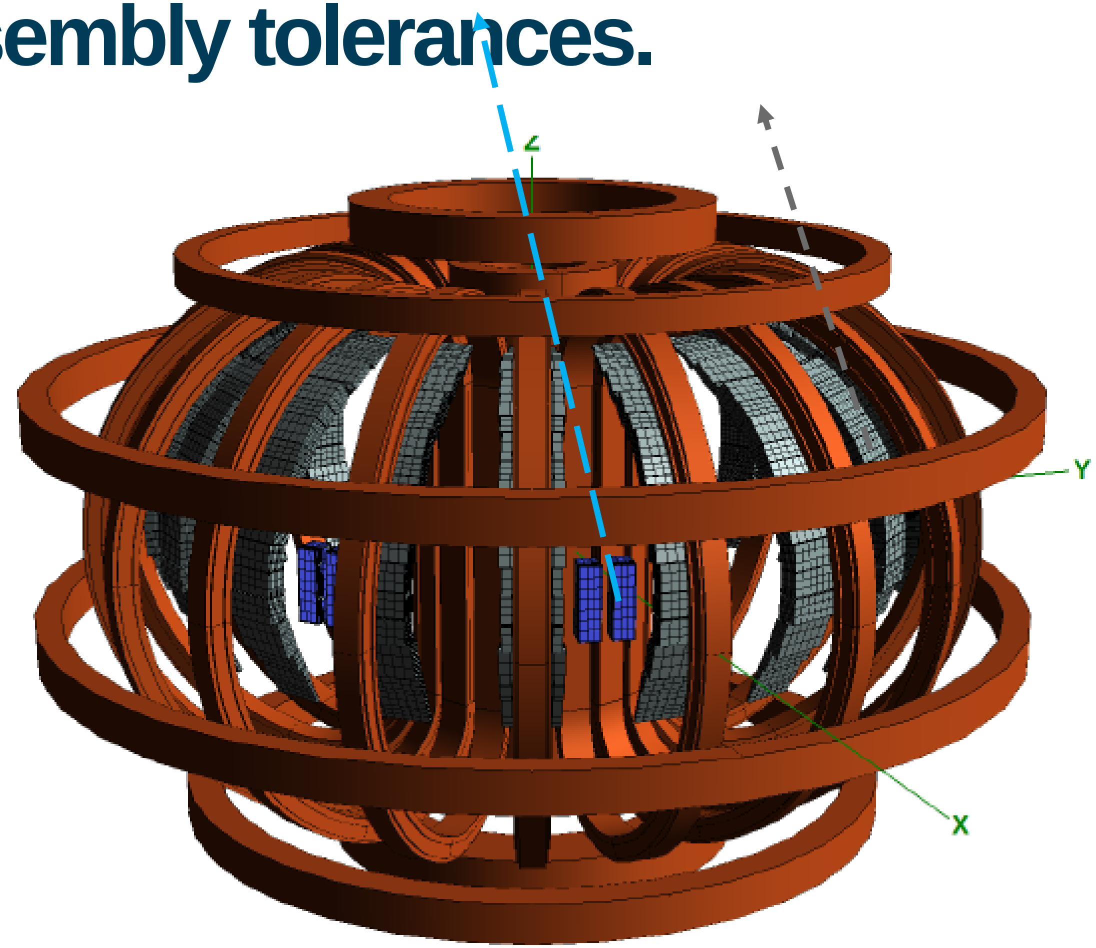


Long-pulse

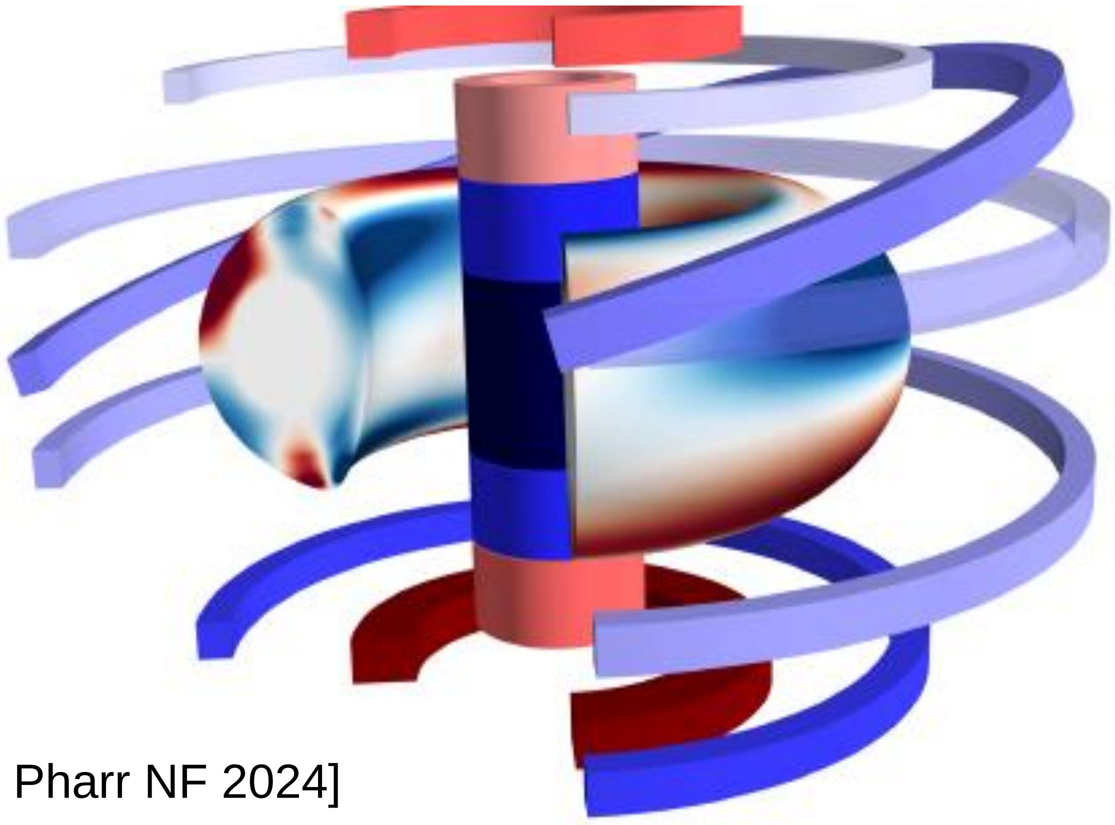


High performance

Poloidal error fields generated by non-asymmetric design and assembly tolerances.



Known asymmetries



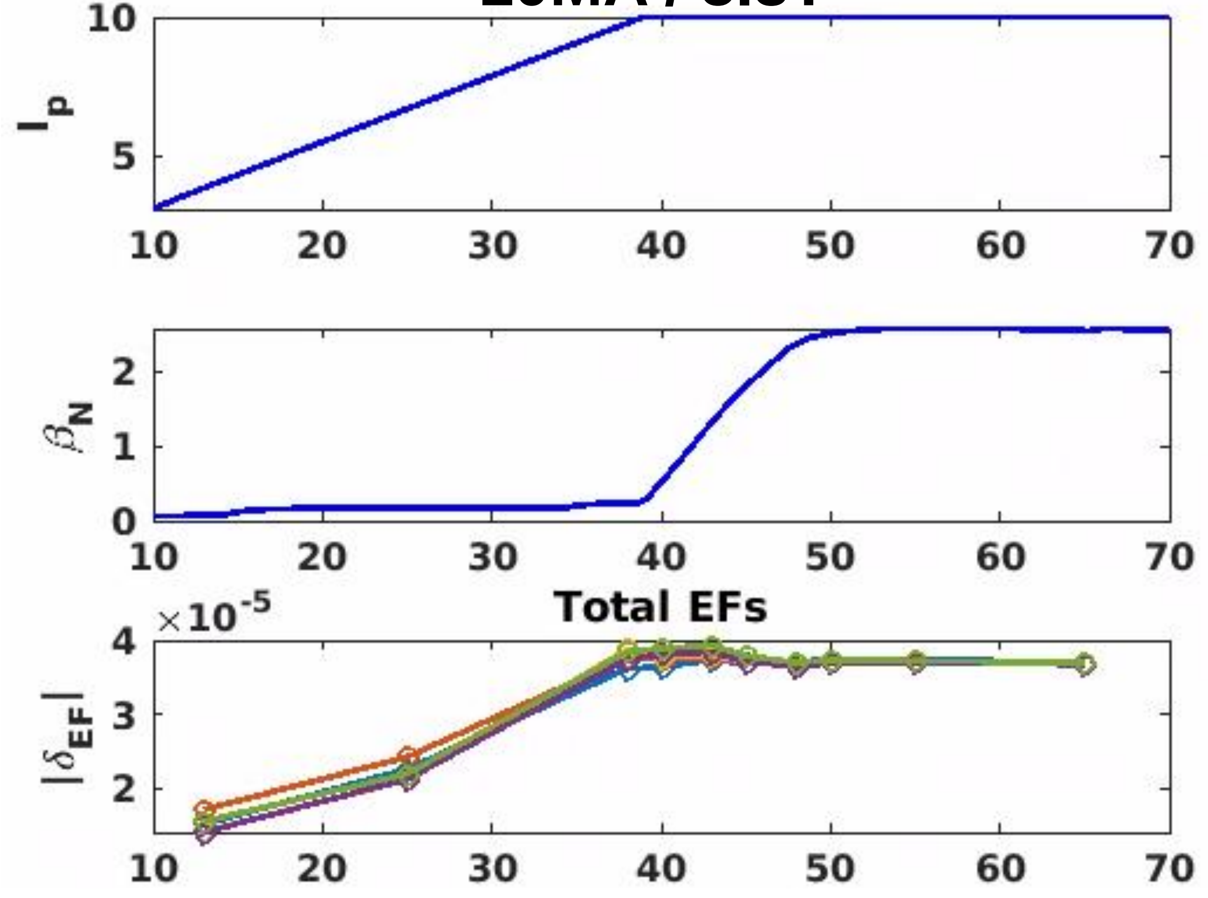
[M. Pharr NF 2024]

Unknown asymmetries

Unknown coil positioned sampled from a source distribution.

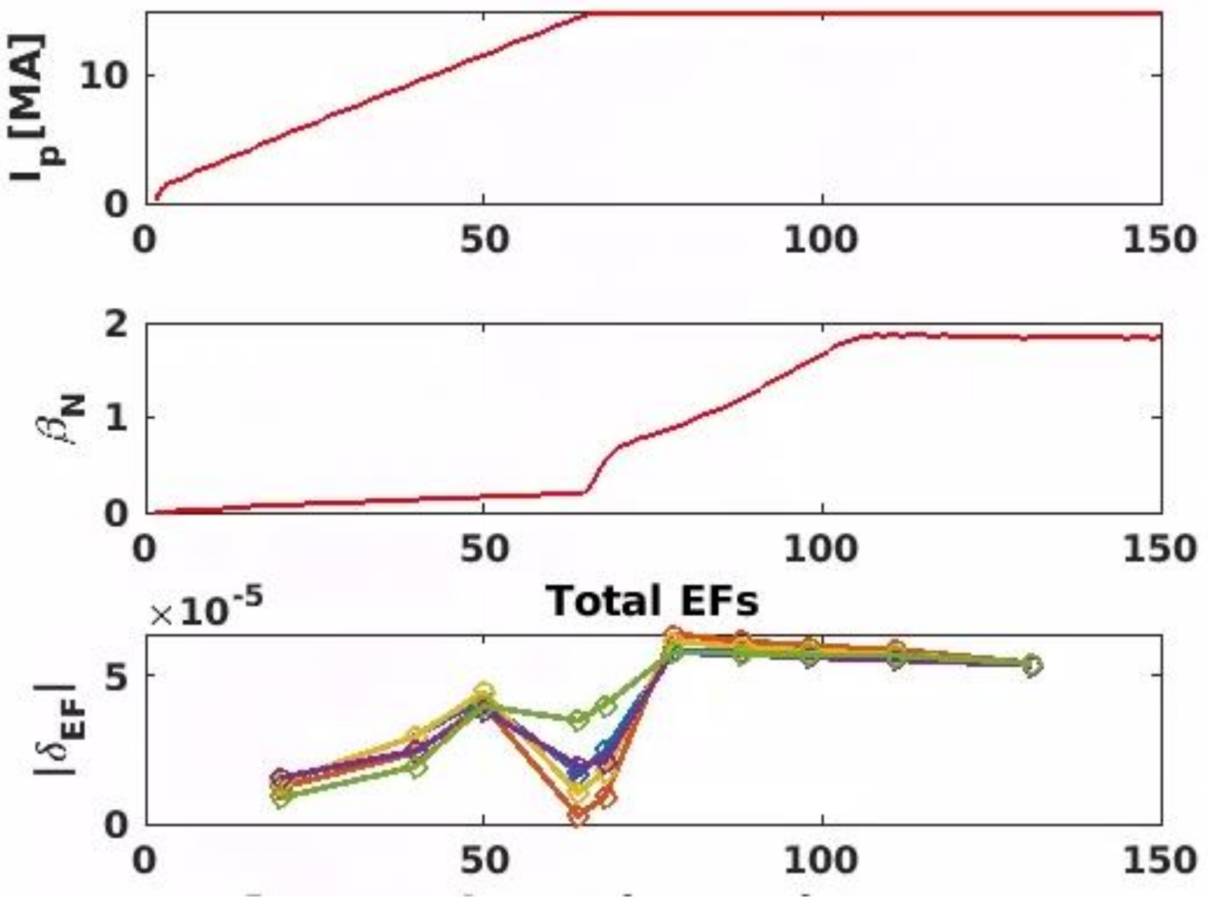
Different lines represent different combinations of coil miss-alignment (from 500,000 ensembles)

10MA / 5.3T



T [s]

15MA / 5.3T



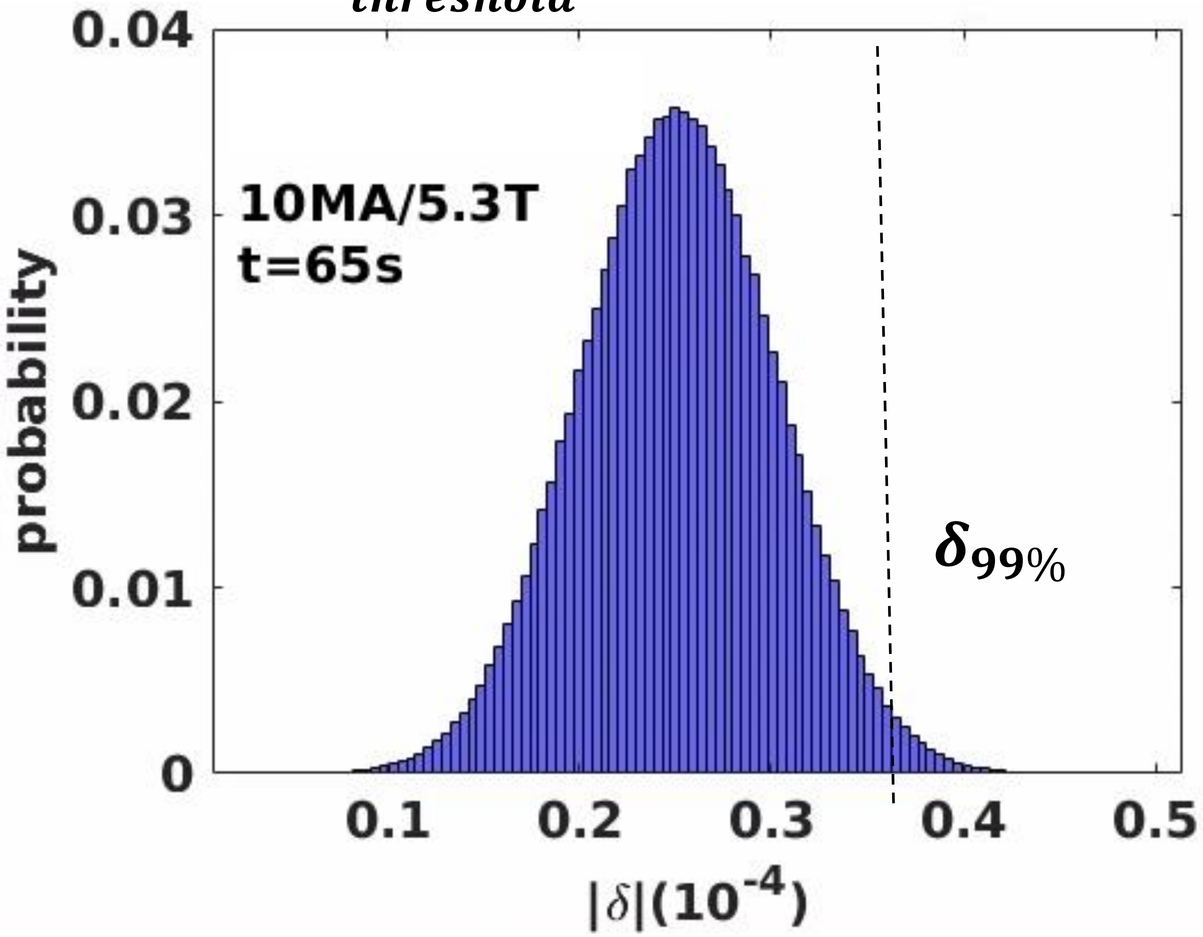
T [s]

iter

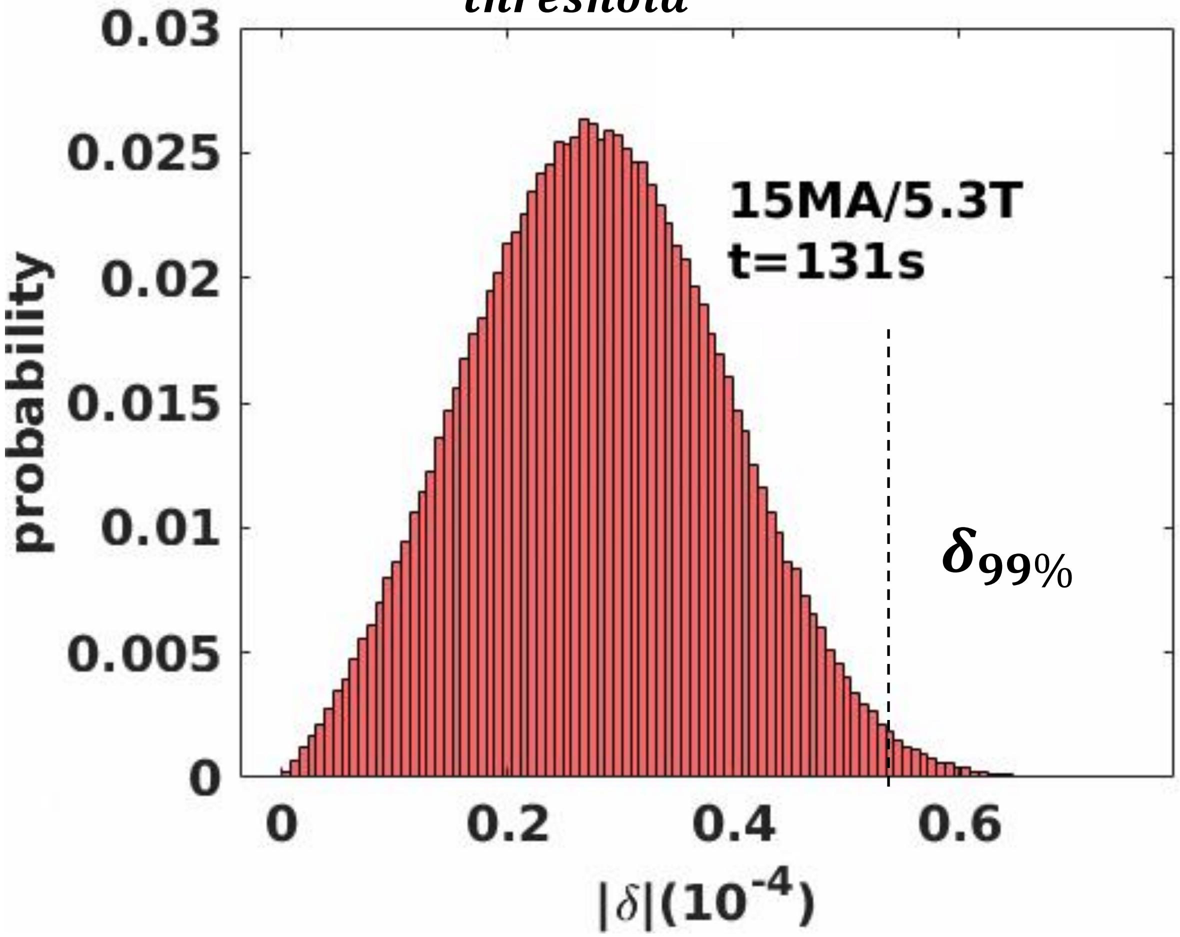
Total Overlap Error Field below lock-mode threshold (99% PI).

Error fields from coil miss-alignments are less that those from ferritic inserts and test blanket modules.

$\delta_{threshold} = 0.45 \times 10^{-4}$

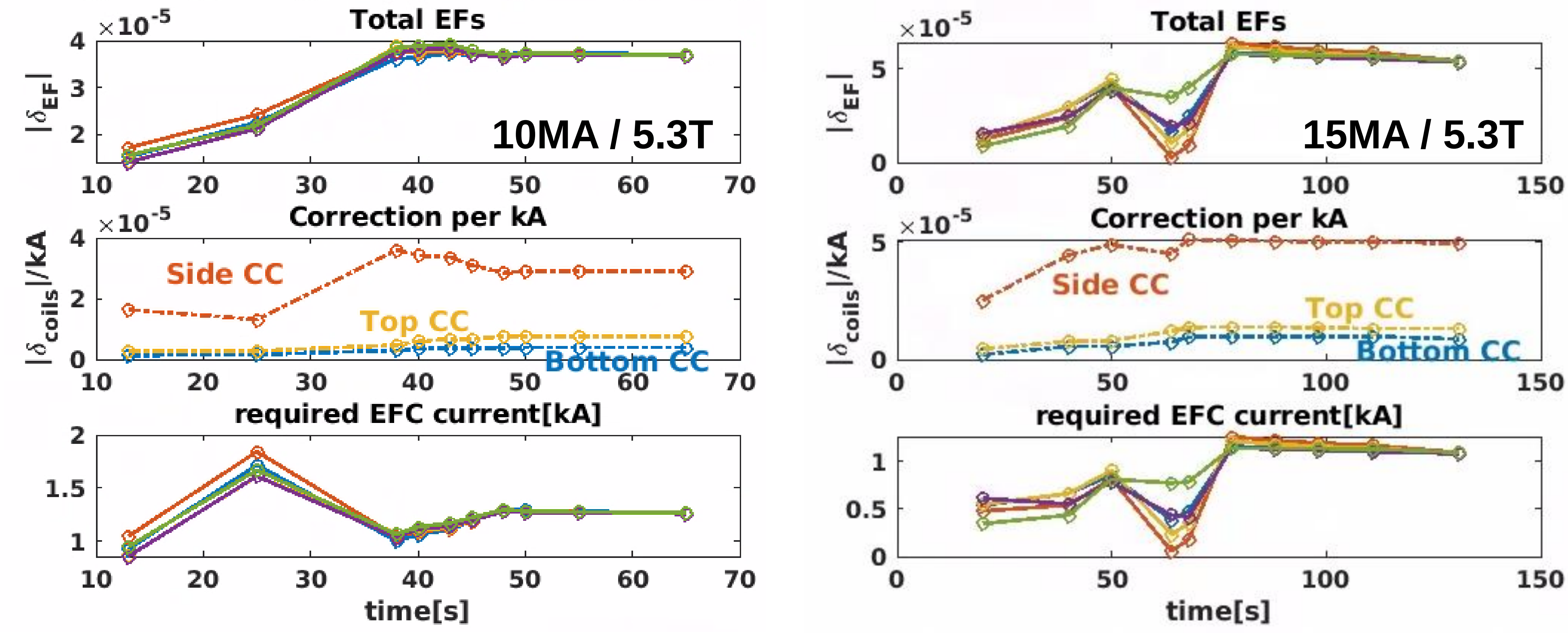


$\delta_{threshold} = 2 \times 10^{-4}$



Required Error Field Correction Current is less than 2kA (limit 10kA)

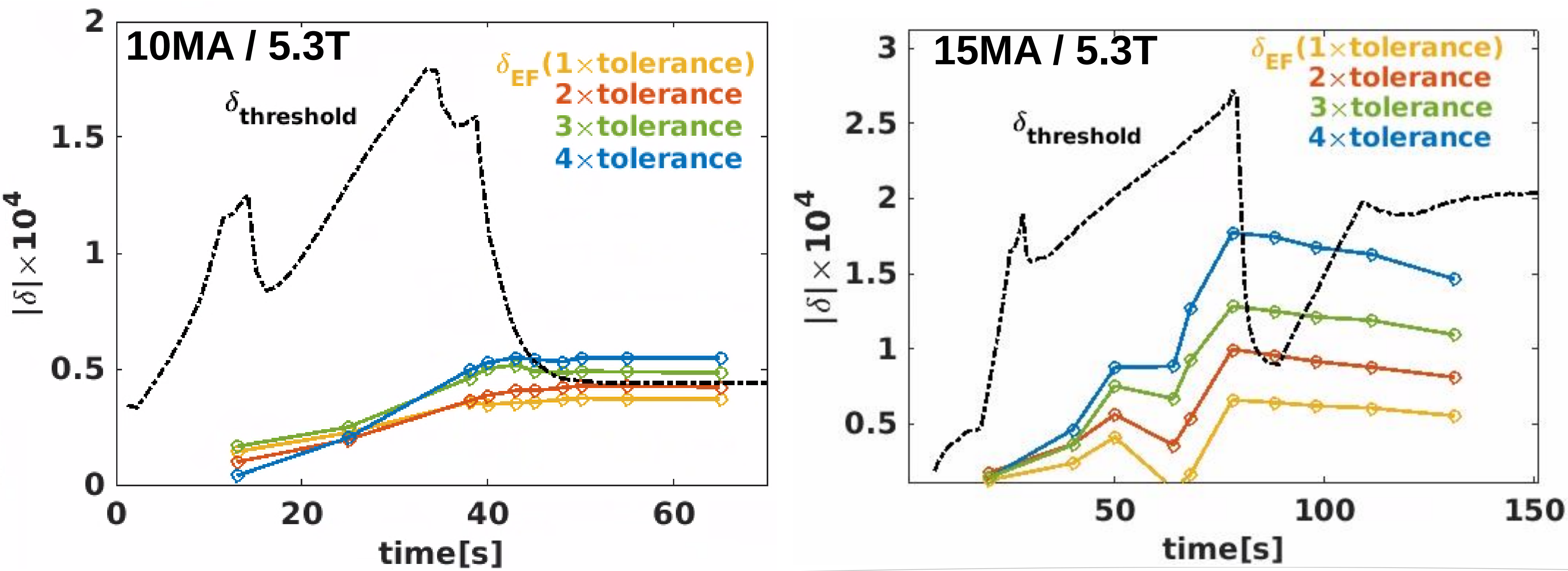
Model results provide confidence that ITER's CC are capable of correcting intrinsic error fields.



Empirical overlap error field threshold is time dependent.

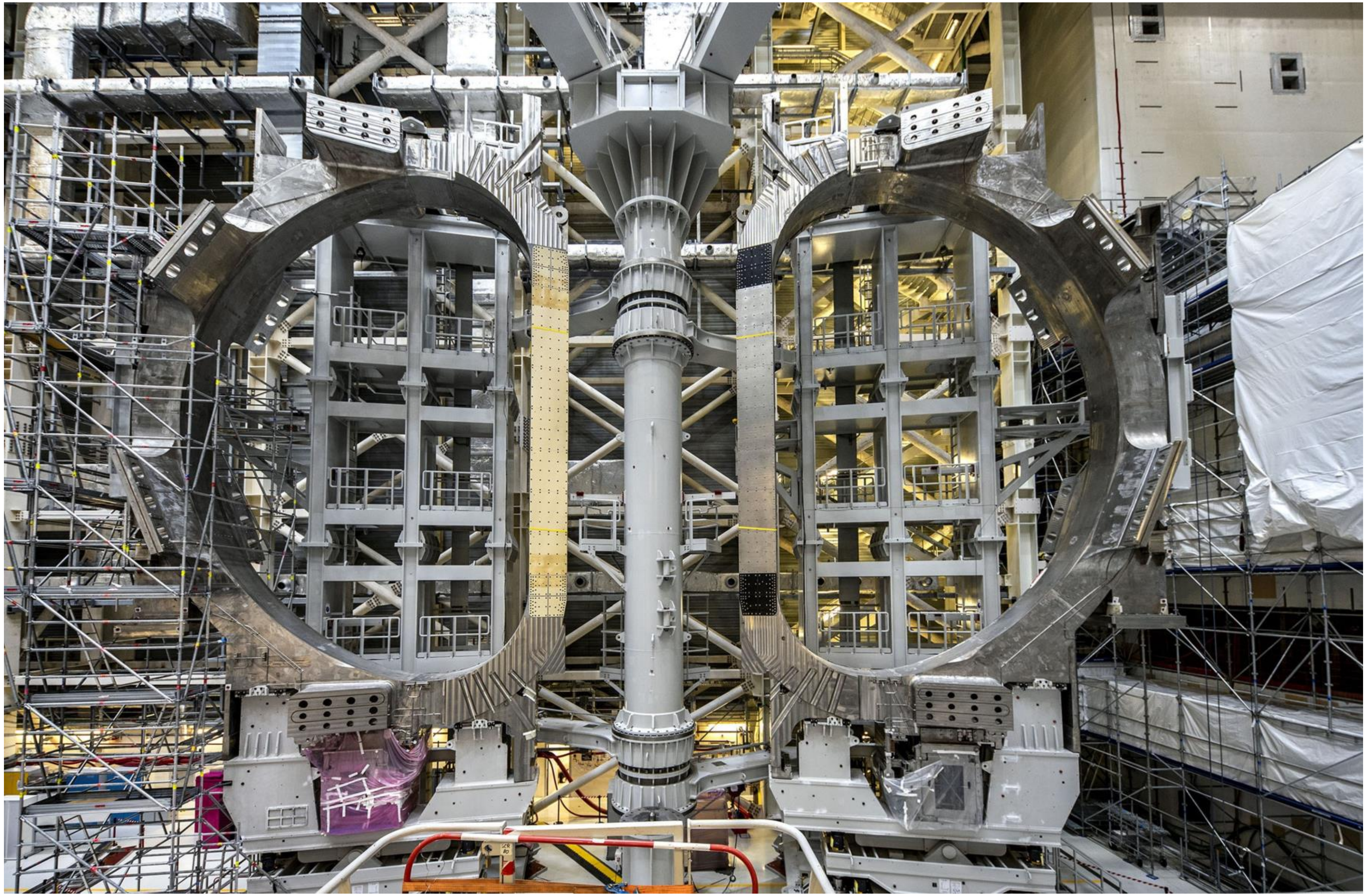
Lock-mode threshold met when assembly tolerance estimates are scaled by a factor of two.

$$\delta_{threshold} = 0.45 \times 10^{-4} n_e^{1.4\pm0.13} B_T^{-1.8\pm0.16} R_0^{+0.81\pm0.24} \beta_N^{-0.86\pm0.14}$$

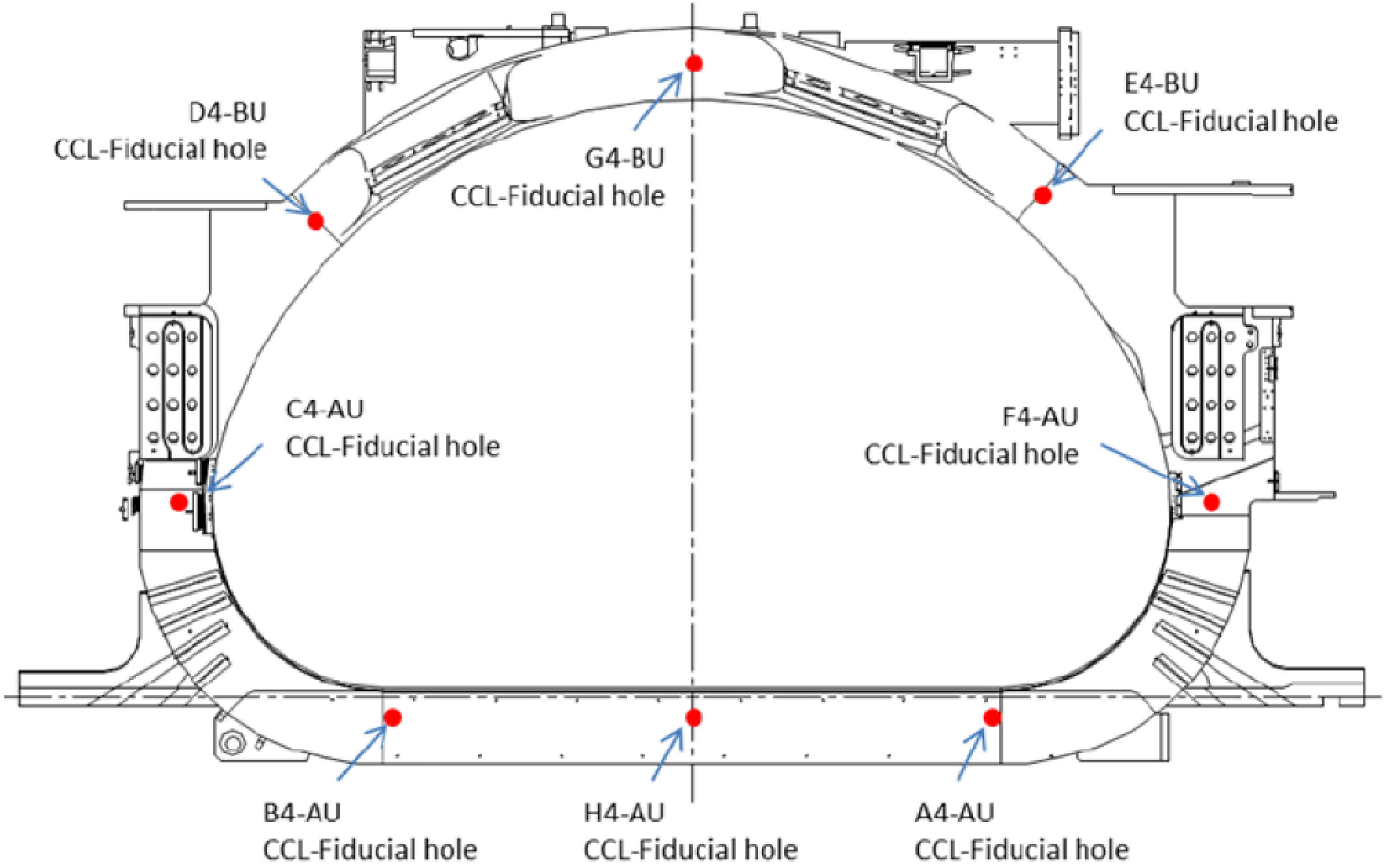


The alignment of ITER's 17 meter high, 360 tonne D-shaped Toroidal Field magnets is a feat of precision engineering.

Exceptionally low tolerances that are repeatable and stable over time.

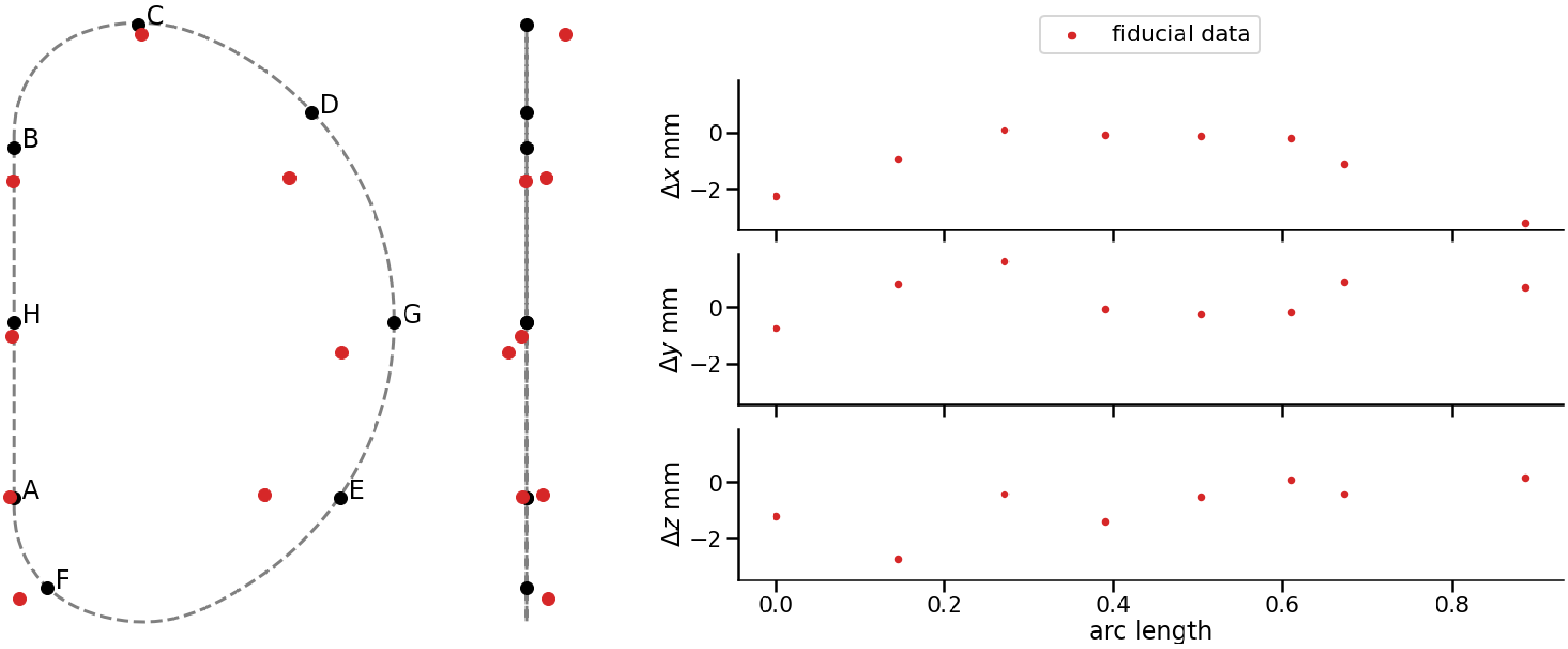


Fiducial targets are used to track the location of the coil's effective current centerline from manufacture to machine assembly.



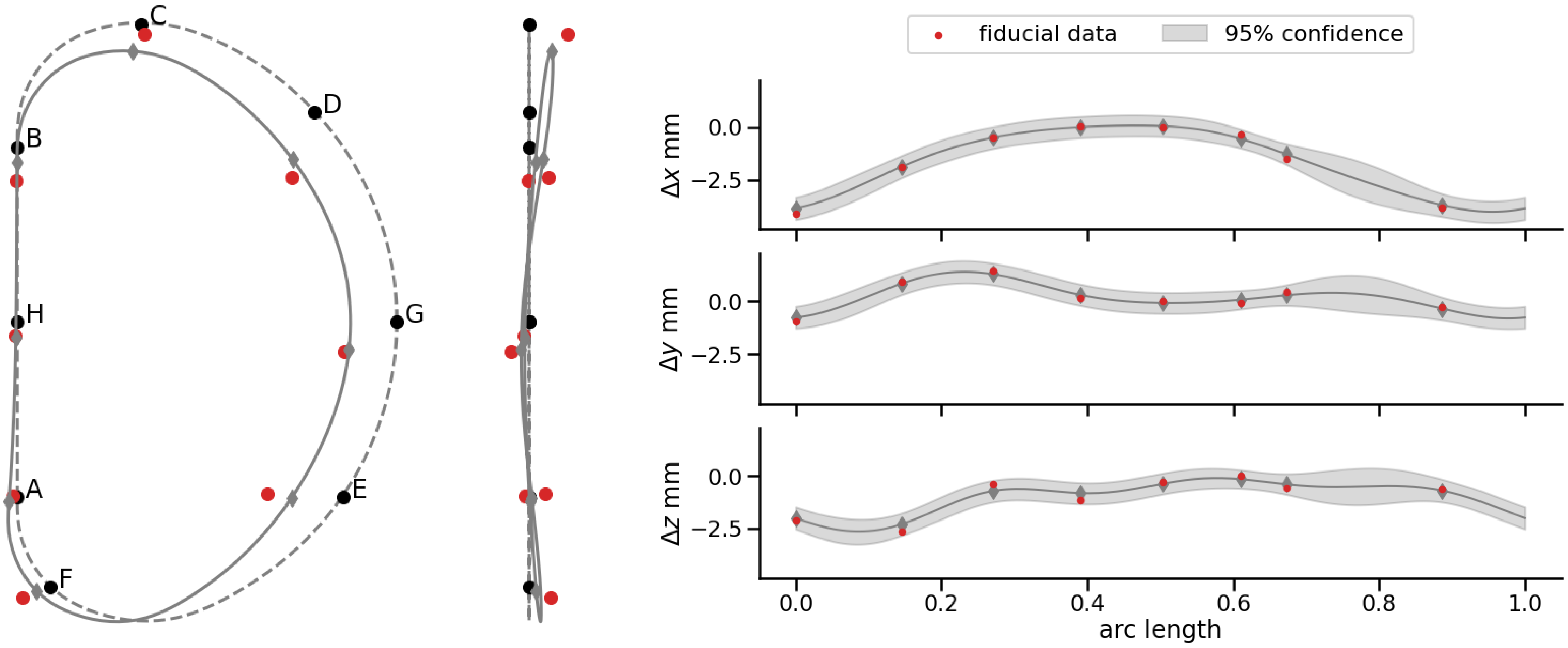
The closure of TF coil case welds generates large deformations.

Maximum deformation of ~3mm compared to a tolerance of ±1.5mm (shown magnified by 500x).



A periodic Gaussian Process Regressor filters measurement noise.

A periodic kernel is applied to deformations in each coordinate direction.



Successful demonstration of in-pit sector alignment.

cylindrical fiducial	r	rphi	z
A	-0.58	-0.44	
B	-2.06	0.13	
C		2.18	3.12
D		0.67	0.70
E		0.47	3.10
F		0.92	2.31
G		-1.19	
H	-1.18	0.23	
A	0.37	2.16	
B	-1.70	1.36	
C		3.21	3.17
D		2.69	0.10
E		0.63	0.31
F		1.57	0.80
G		2.34	
H	-0.62	-0.09	

Close Collaboration between Metrology, Integration and Science.

Integrated modeling activity spans multiple divisions at ITER, crossing computational boundaries.

Metrology

Integration

Science

TF coil case fiducial metrology.

Update CCL fiducial locations and uncertainties.

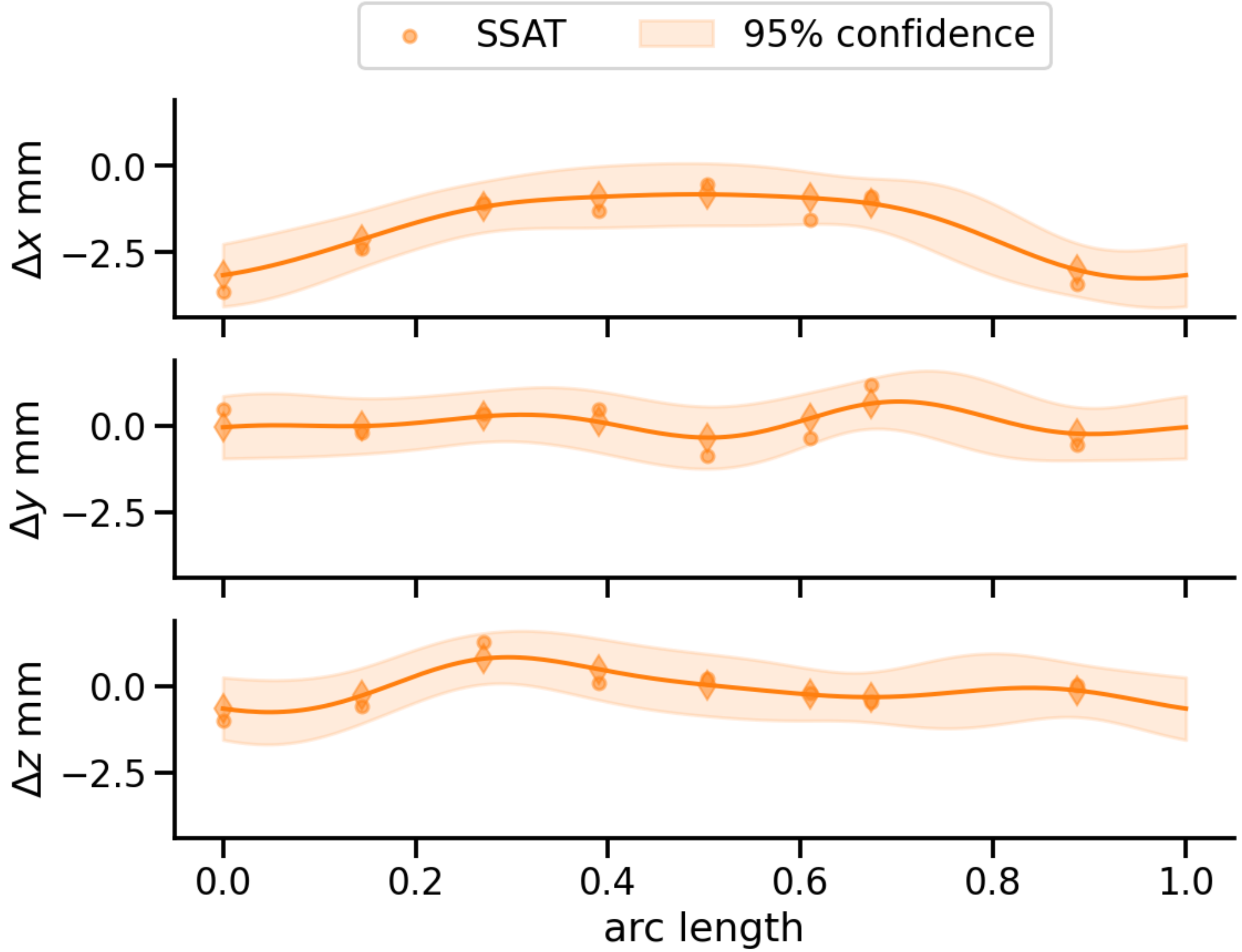
Fit Gaussian Process regressor to new CCL points.

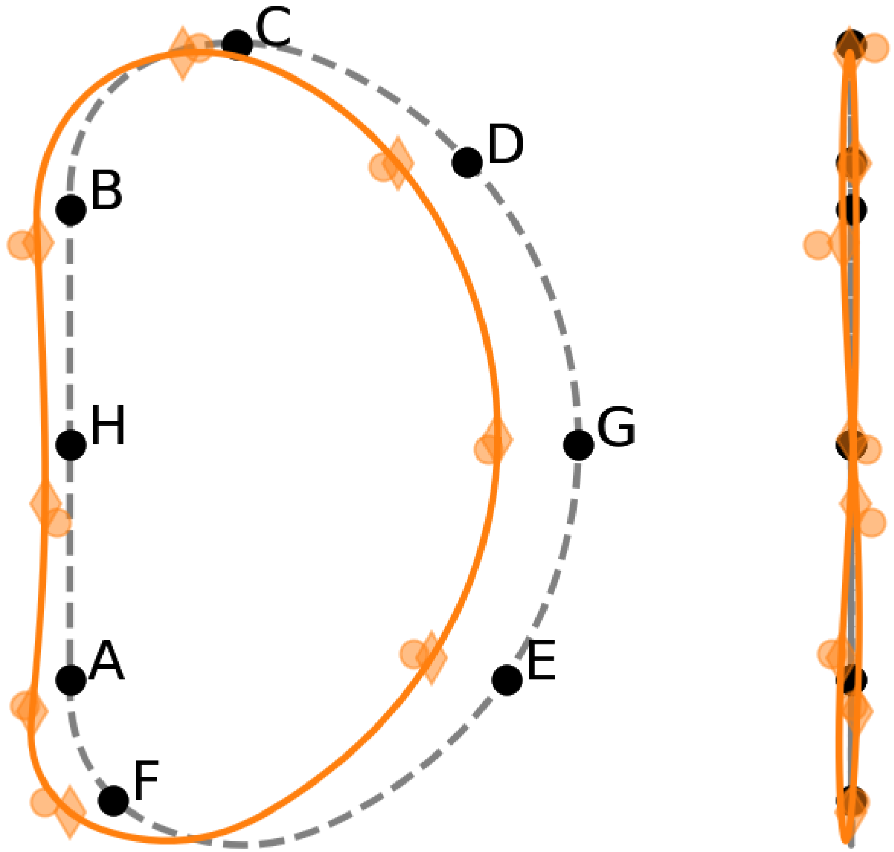
Update CCL fiducial locations and uncertainties.

Optimize position of TF coil and generate alignment targets.

Check interfaces – update targets if and only if necessary.

Metrology of Sector #7 on SSAT defines coil shape (with given prior).

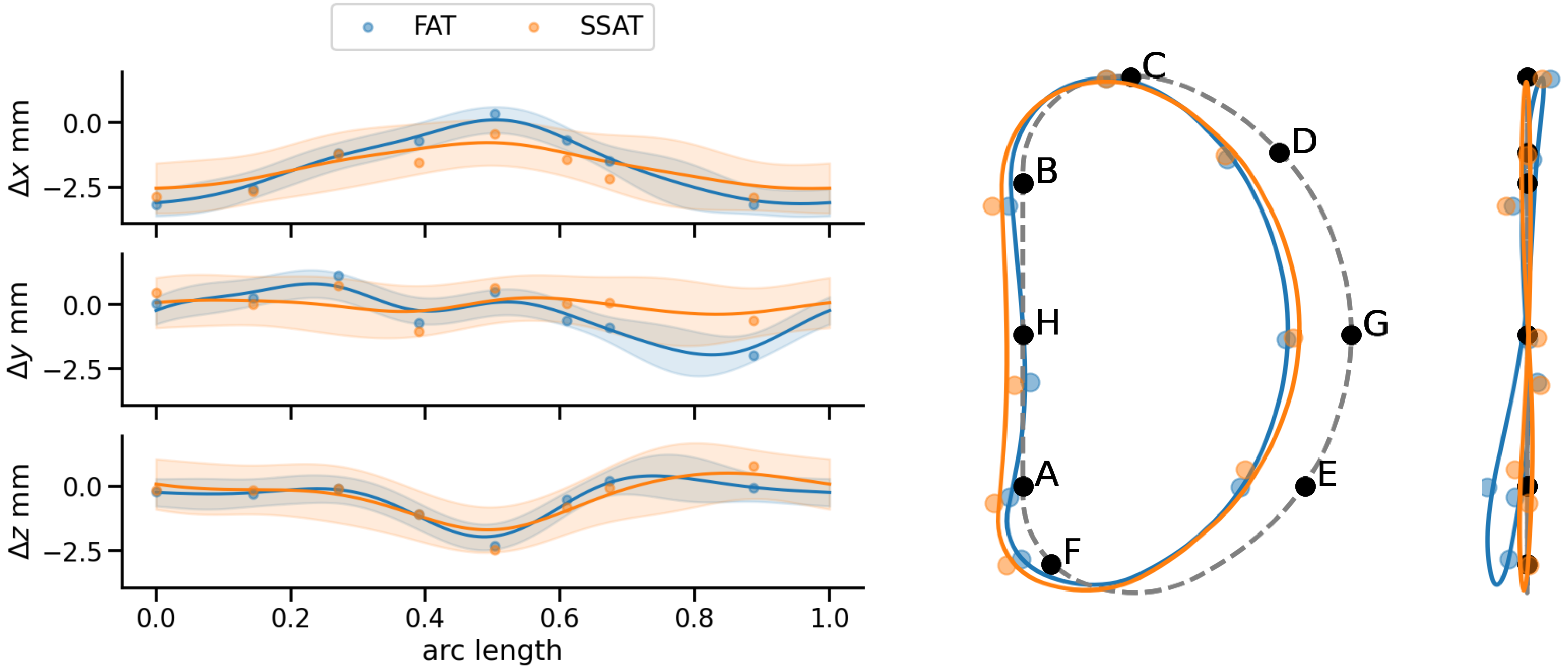




Coil alignment is based on inferred CCL positions (diamonds)

Deformation x500

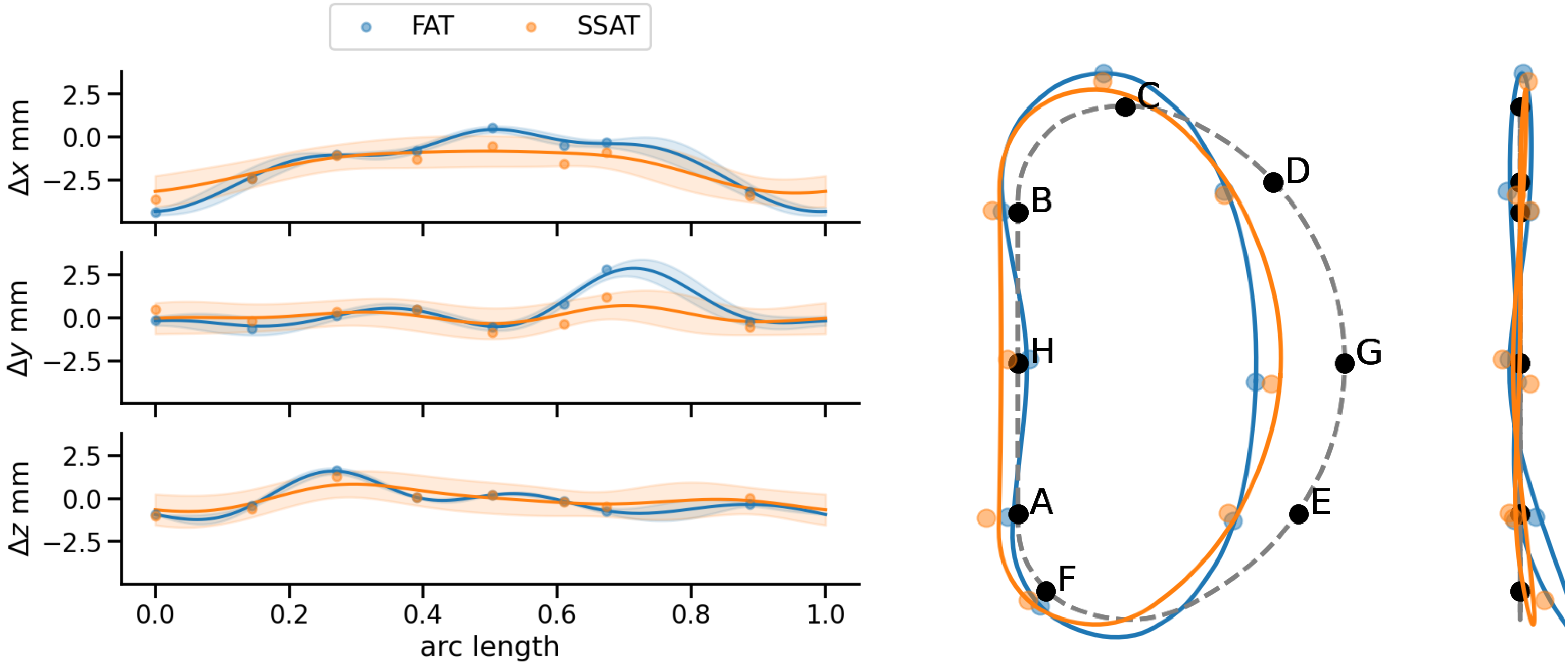
The orientation of each TF Coil affects its shape (Coil #8 Japan)



Deformation x500

iter

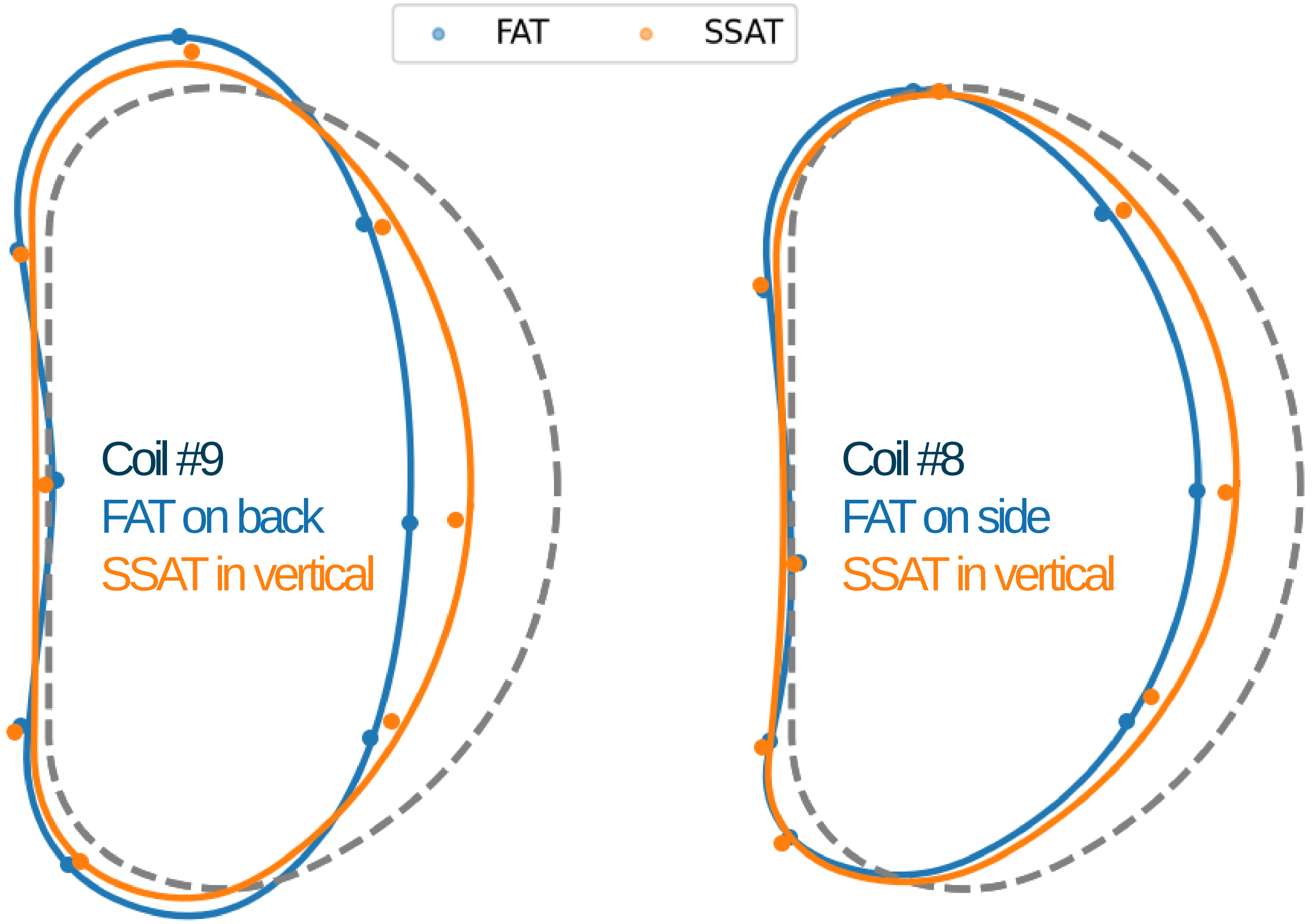
The orientation of each TF Coil affects its shape (Coil #9 EU)



Deformation x500

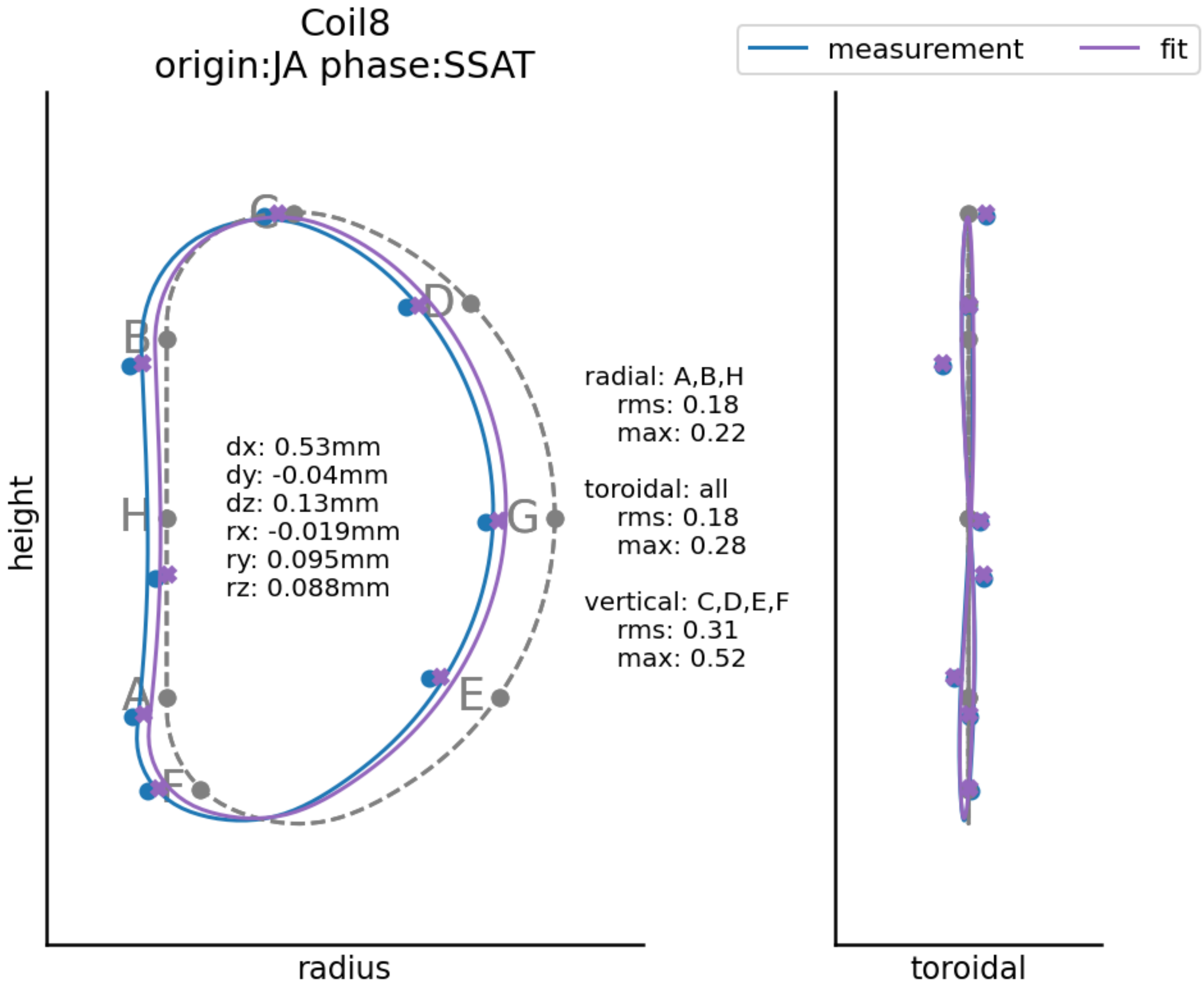
Metrology of TF Coils in the vertical improves EU-JA agreement

Coil metrology carried out with a common orientation reduces the magnitude of the 'vendor' error field



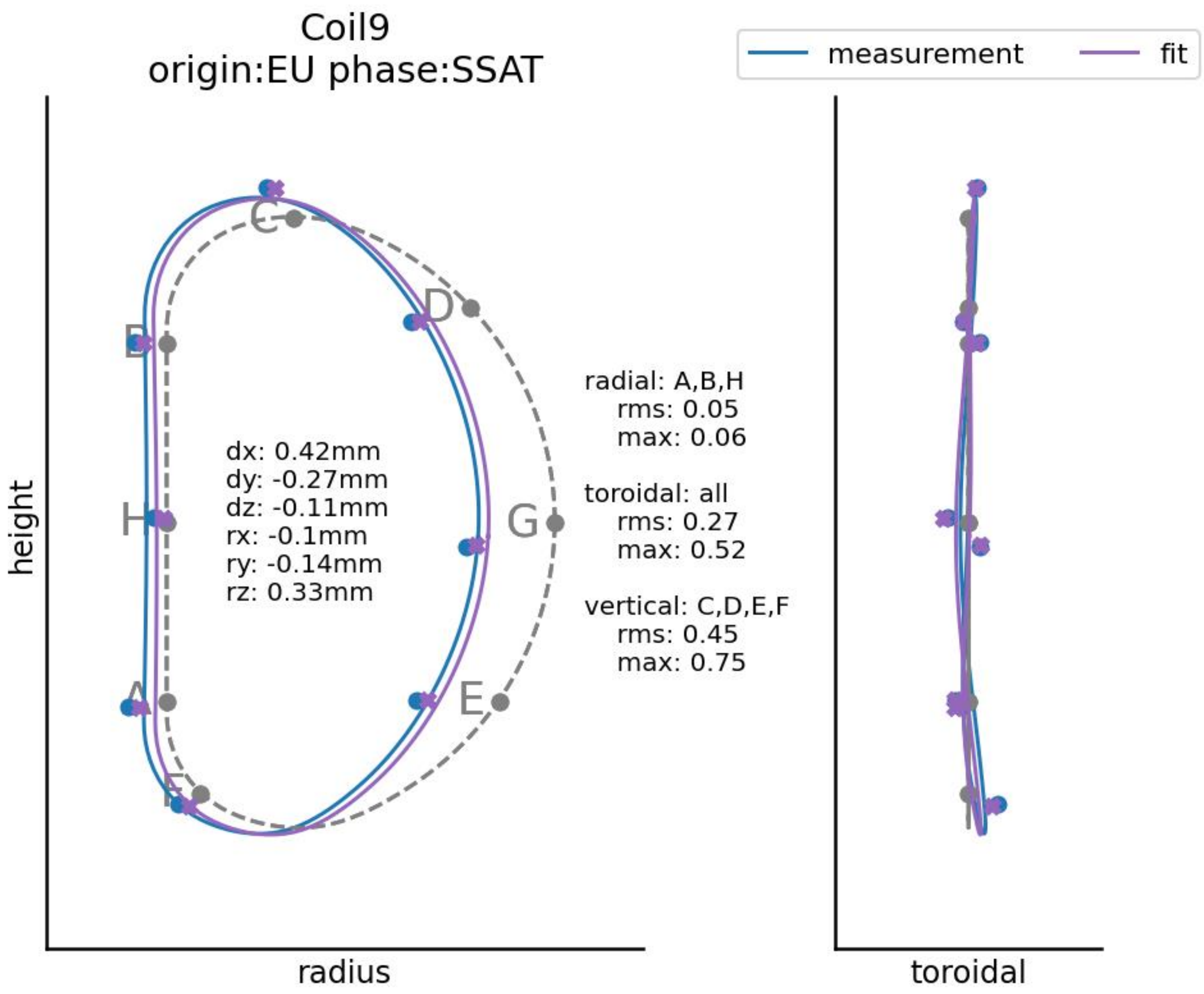
Deformation x500

Optimized SSAT targets generated by Science Division for Coil #8



Deformation x500

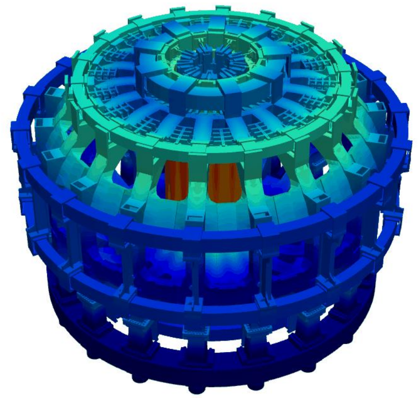
Optimized SSAT targets generated by Science Division for Coil #9

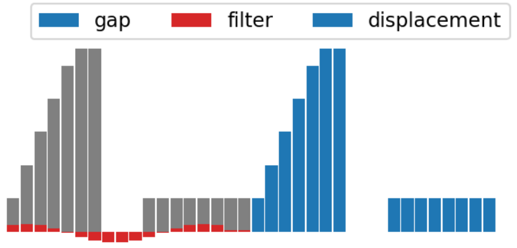


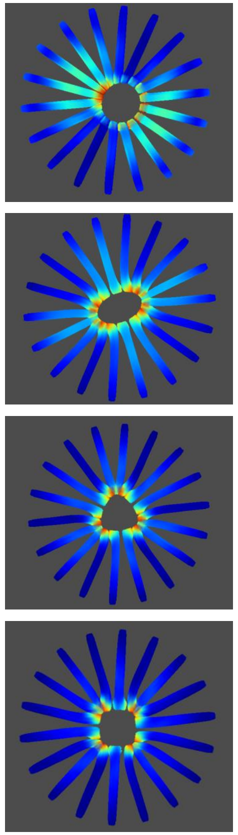
Deformation x500

In summary we have shown how ITER's assembly targets and tolerances are defined to comply with key operational physics limits.

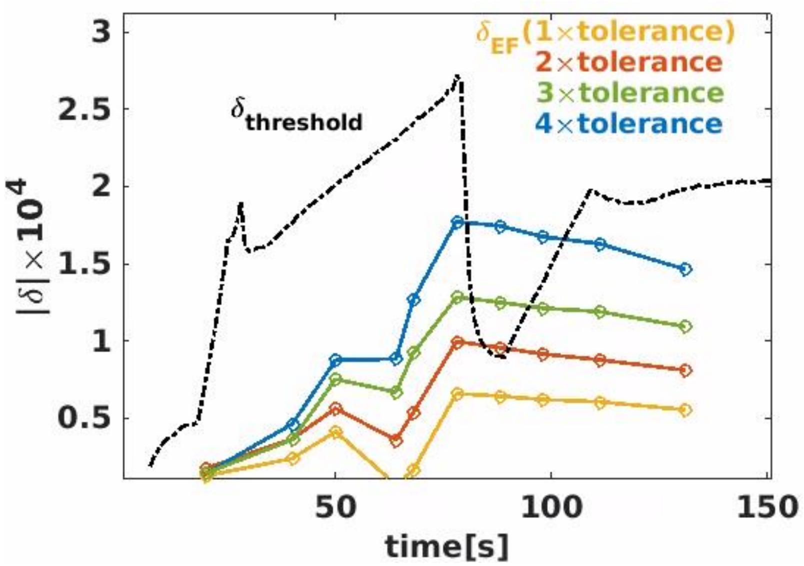
Translating Physics limits to mm







All models are wrong, *some* are useful



In-pit sector alignment