Digital twin workflow development for SPARC

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IAEA Workshop on Digital Engineering for Fusion Energy Research
Dec 9, 2025

Commonwealth Fusion Systems

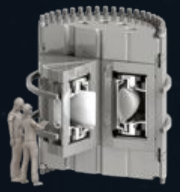
Outline of this presentation

- CFS Introduction
- Multi-fidelity Digital Engineering at CFS
- Grounding digital design with empirical data
- Preparing for SPARC Operations
- Looking ahead to ARC

Introduction to CFS and SPARC Progress

CFS: commercial fusion via concrete steps

R&D — Commercial demo — Commercial power plant



Physics
COMPLETED

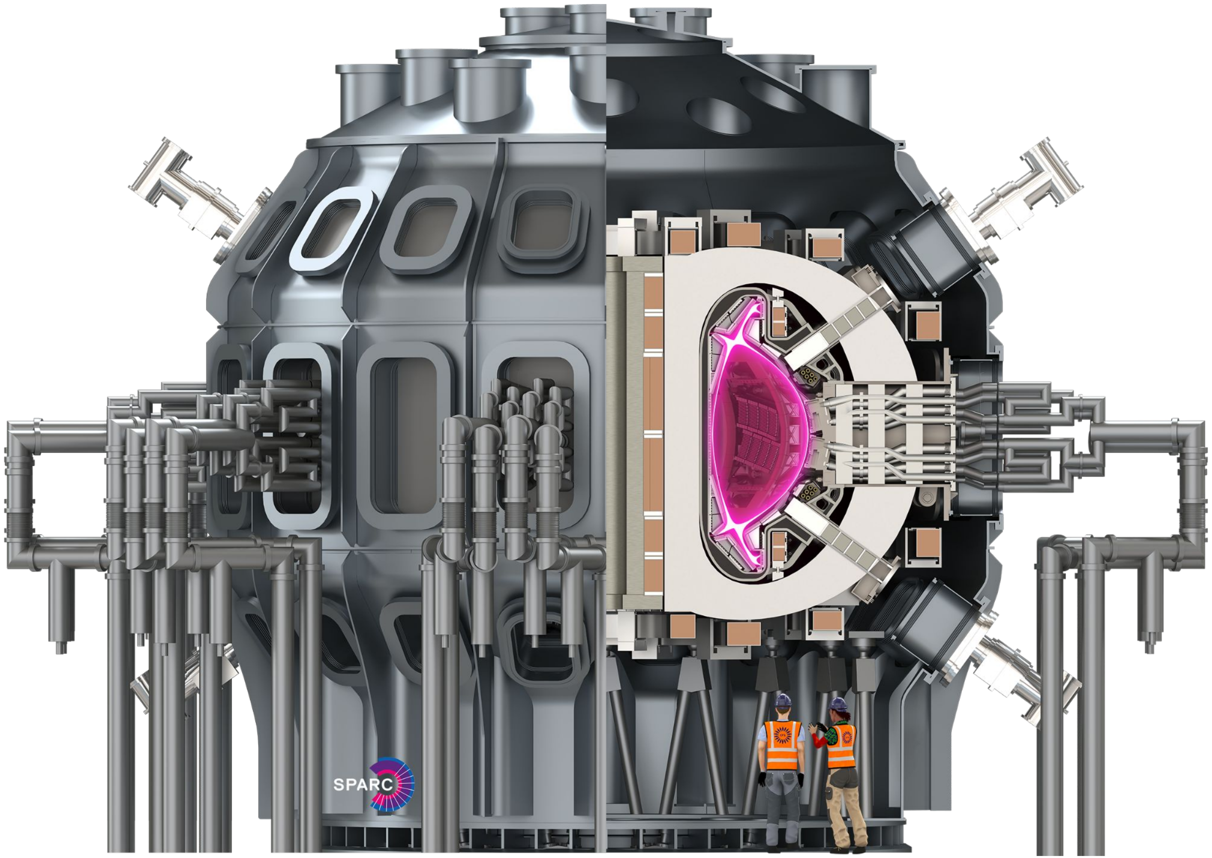
Magnet tech
COMPLETED

SPARC
UNDER CONSTRUCTION

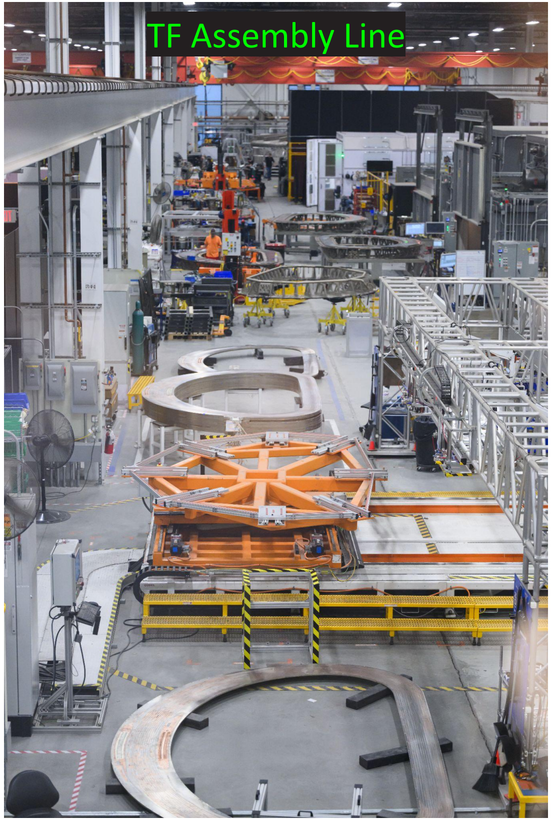
ARC
EARLY 2030s

SPARC is a high field (12T) energy gain tokamak being constructed in Devens, MA, USA

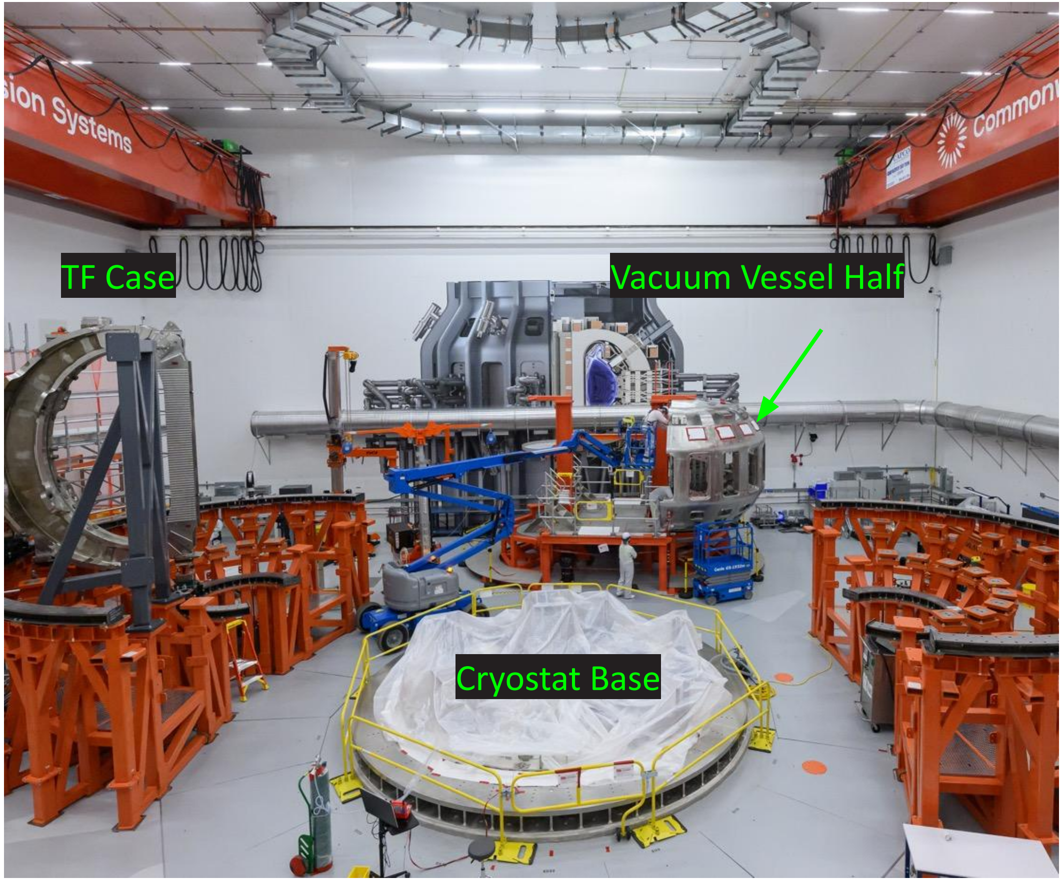
SPARC Primary Reference Discharge		
R	1.85	m
a	0.57	m
B_0	12.2	T
I_p	8.7	MA
q^*	3.05	(q_{95} = 3.4)
κ_{sep}	1.98	
$\langle T_e \rangle$	7.33	keV
$\langle n_e \rangle$	3.13	$10^{20} m^{-3}$
τ_E	0.77	s
f_g	0.37	
P_{ohmic}	1.7	MW
$P_{rf,coupled,operating}$	11.1	MW
P_{fus}	141	MW
Q	11.0	(h-mode)

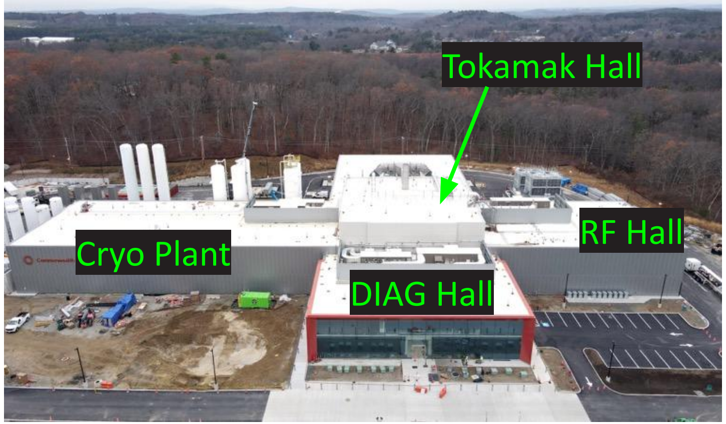


The CFS magnet factory continues to produce the magnets for SPARC across three assembly lines

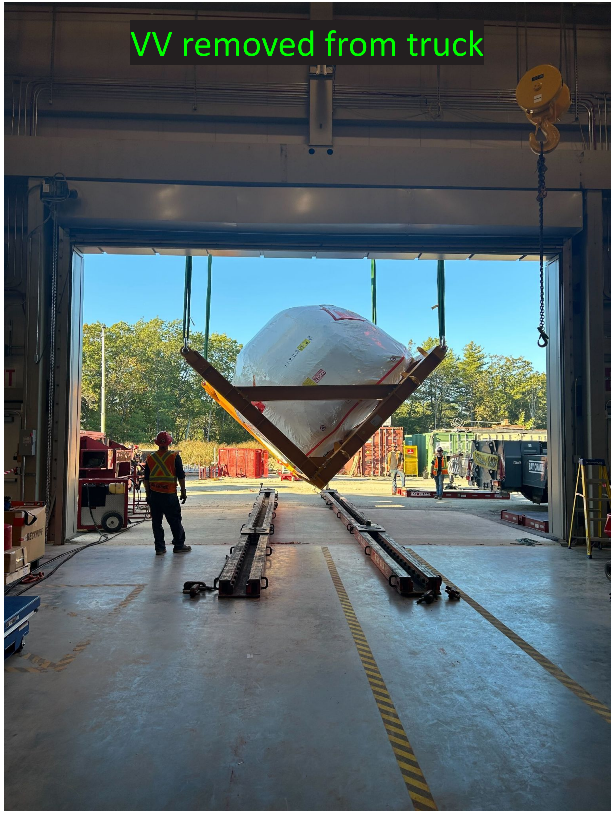


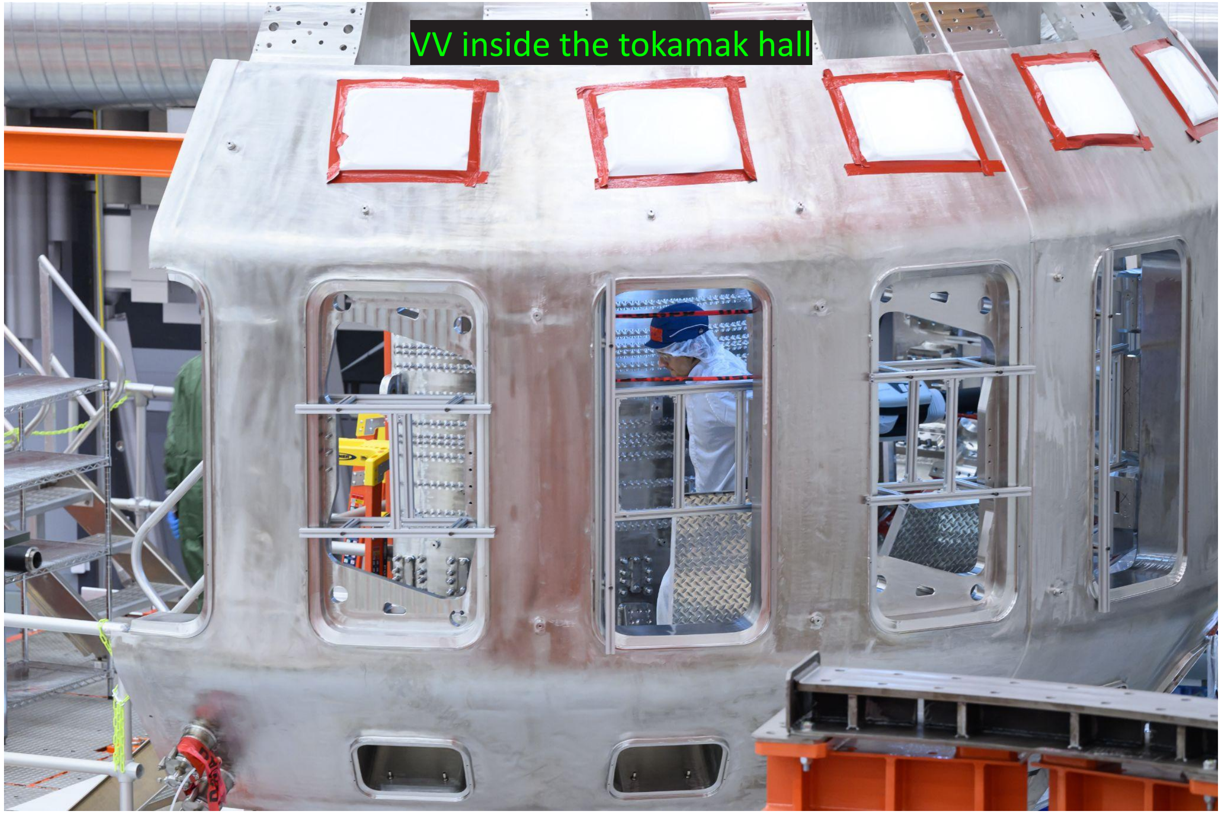
SPARC tokamak assembly is underway, plant systems are being commissioned, some systems are already complete





Metrology and component installation in the Vacuum Vessel has begun inside the tokamak hall





Multi-fidelity Digital Engineering at CFS

The CFS site contains many systems, with design and analysis happening across scales ranging from km to um

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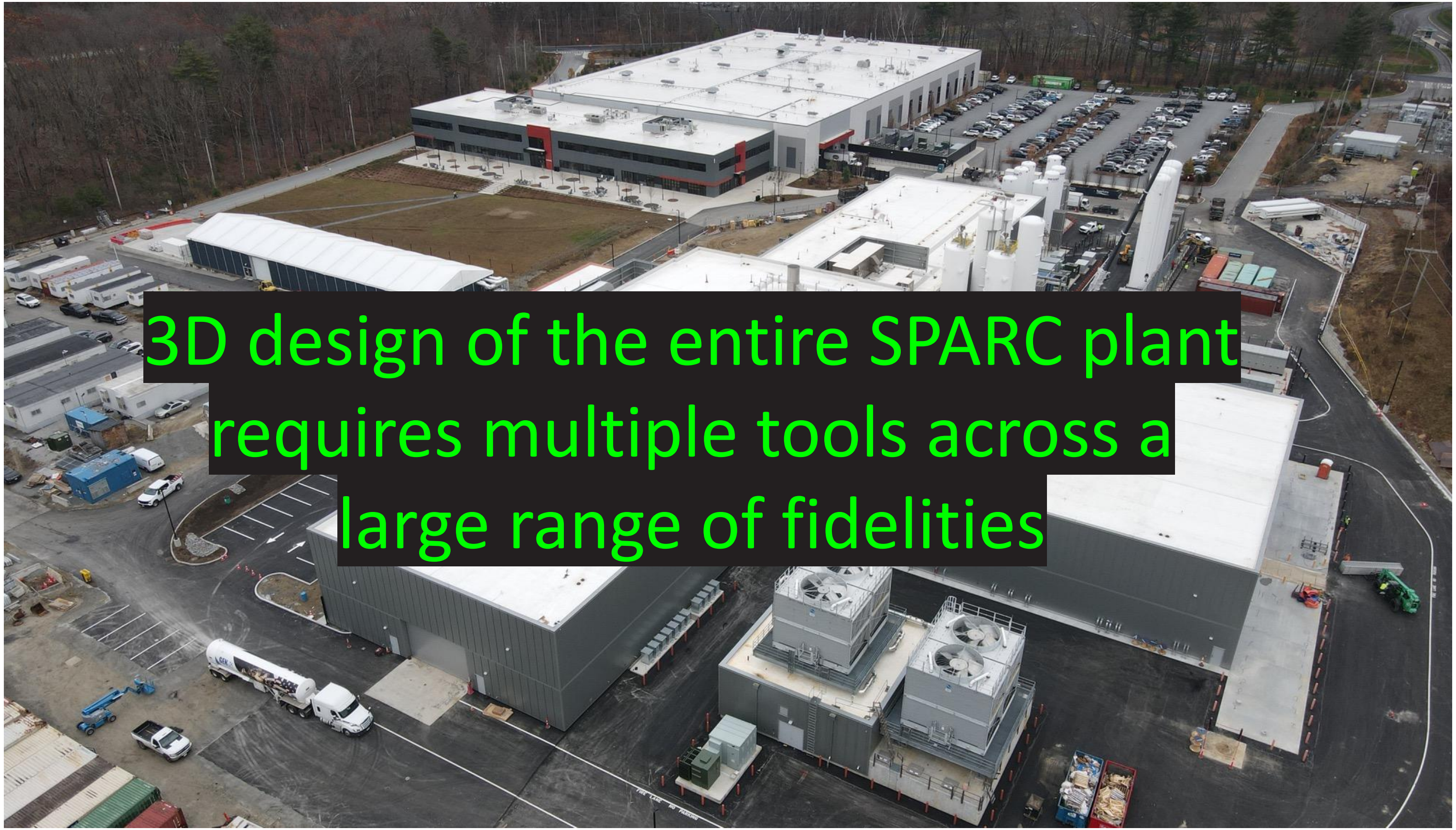
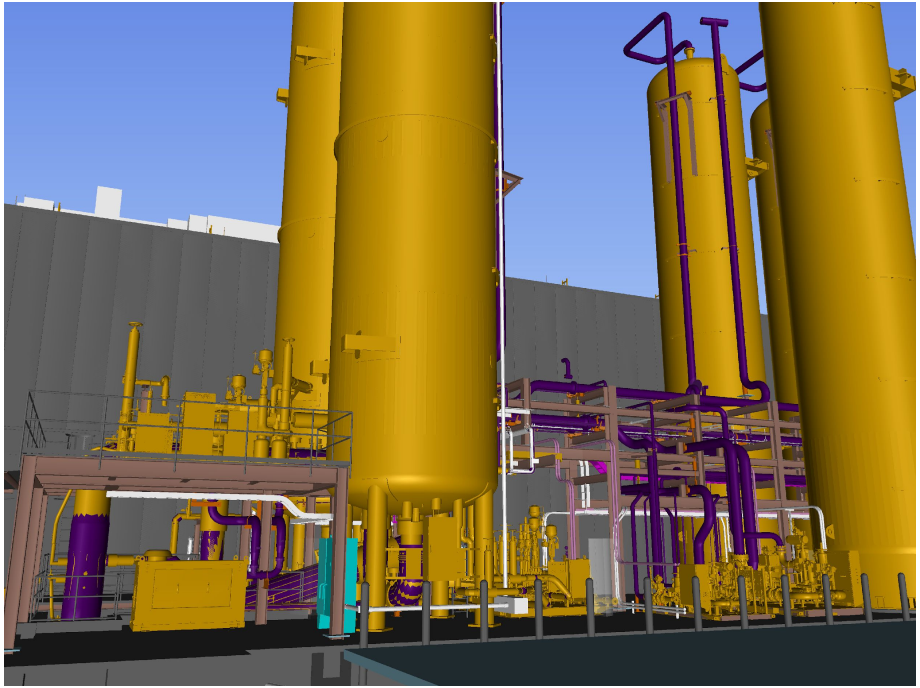


CFS employs a multi-fidelity approach to digital engineering: AVEVA and neutronics models cover entire SPARC site

SPARC plant design employs a data centric approach to design system interfaces, clearances, and space allocations

AVEVA Model

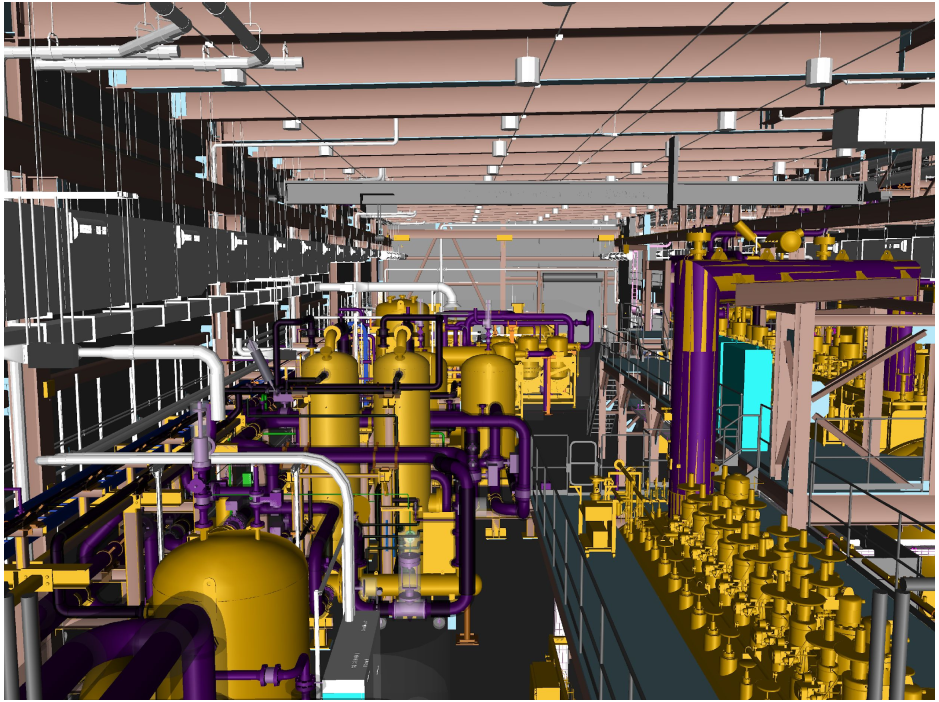


Real Life

From concept to construction, entire life cycle of components are tracked digitally

SPARC plant design employs a data centric approach to design system interfaces, clearances, and space allocations

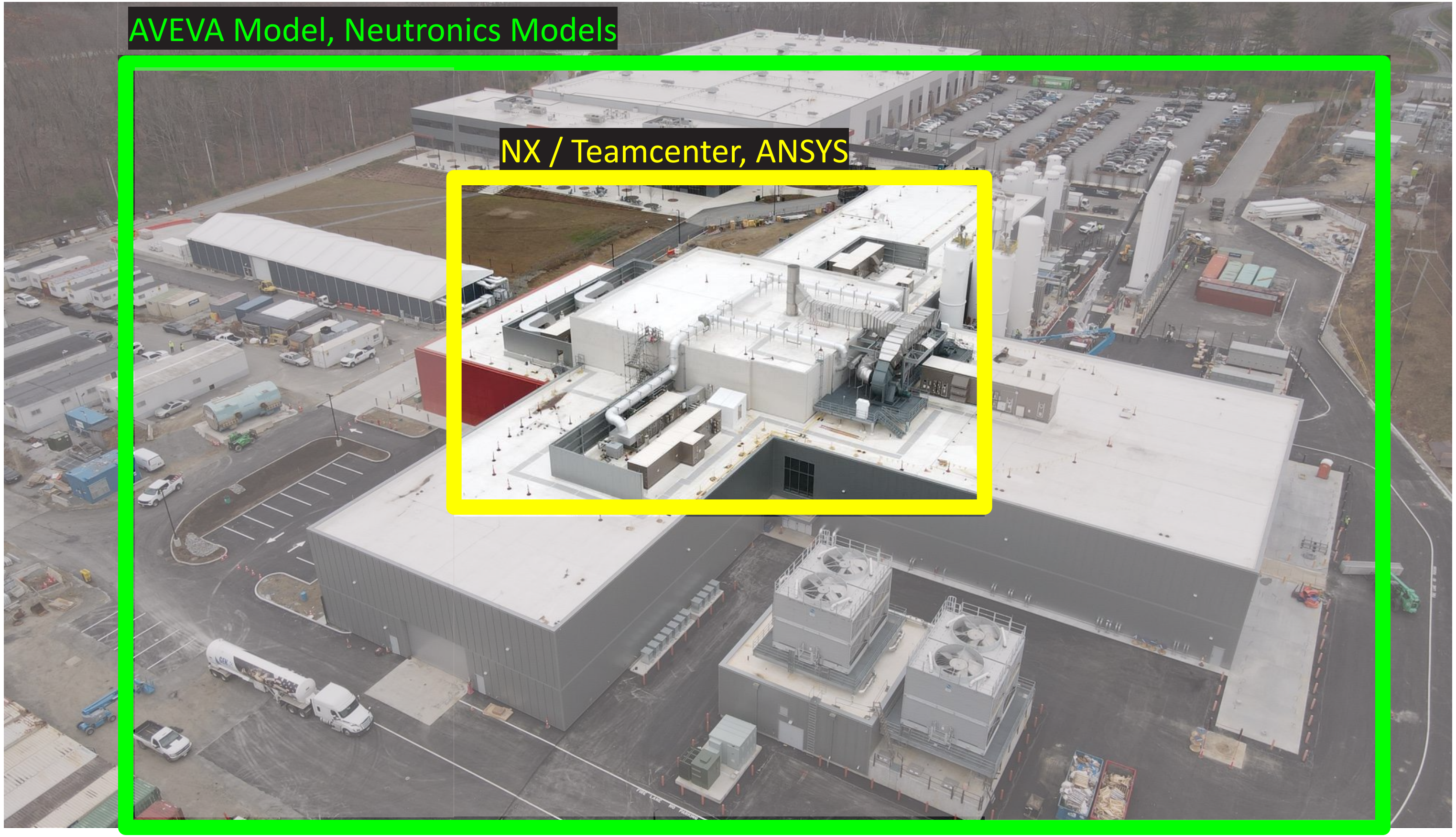
AVEVA Model



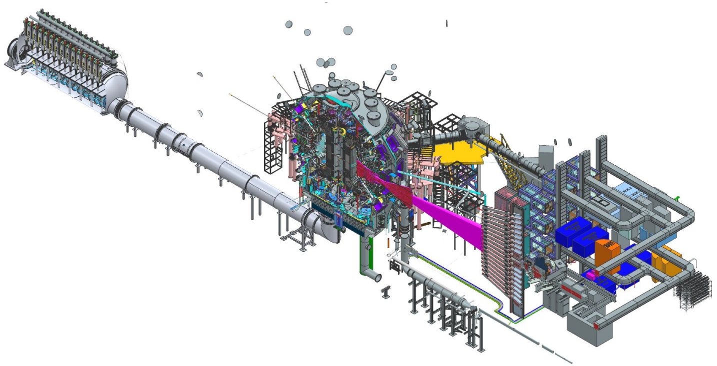
Real Life

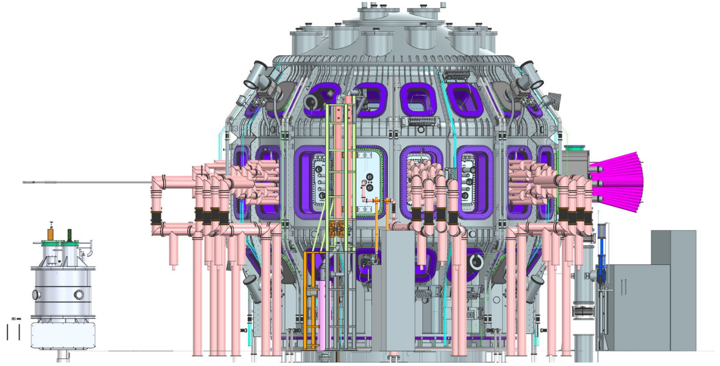
Construction drawings are produced directly from AVEVA

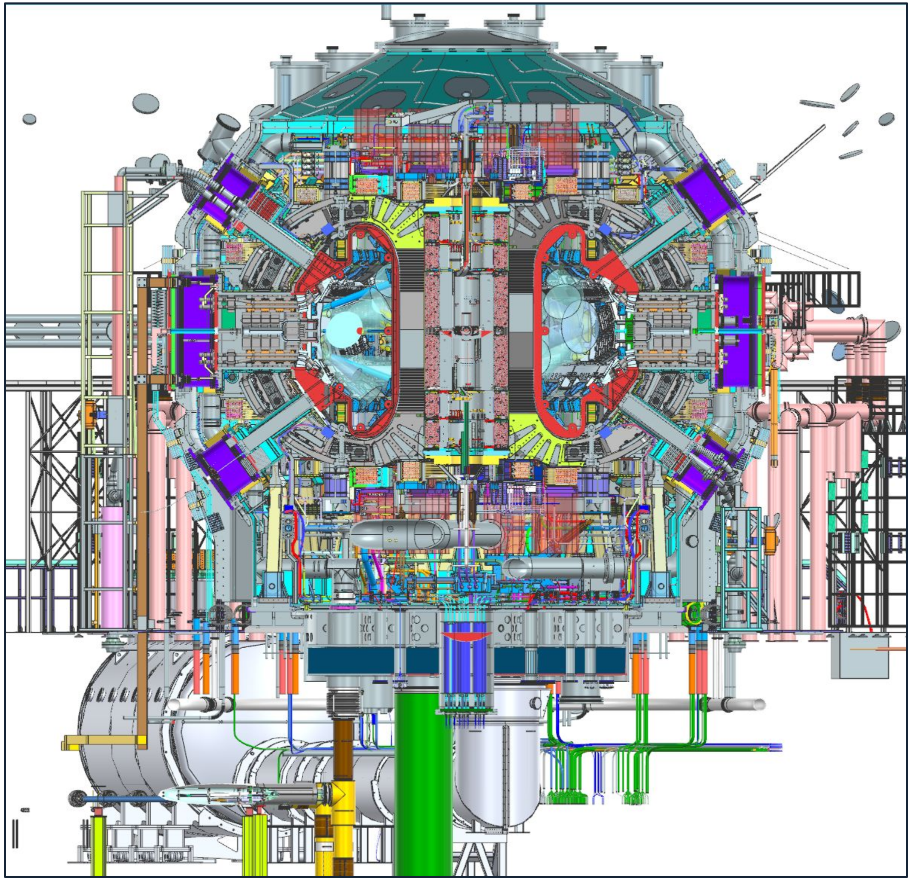
CFS employs a multi-fidelity approach to digital engineering: NX/Teamcenter used for systems inside the tokamak hall



Siemens NX + Teamcenter used to build 3D model of all systems inside the tokamak hall, 2D dwgs, etc.

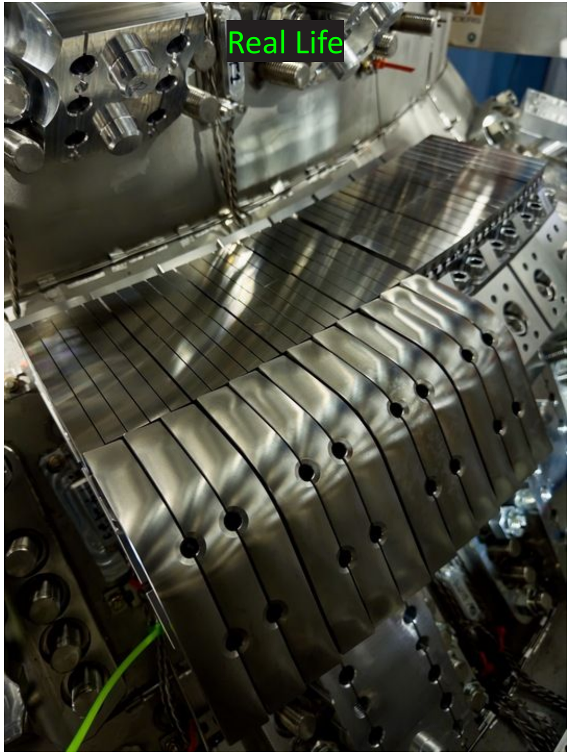


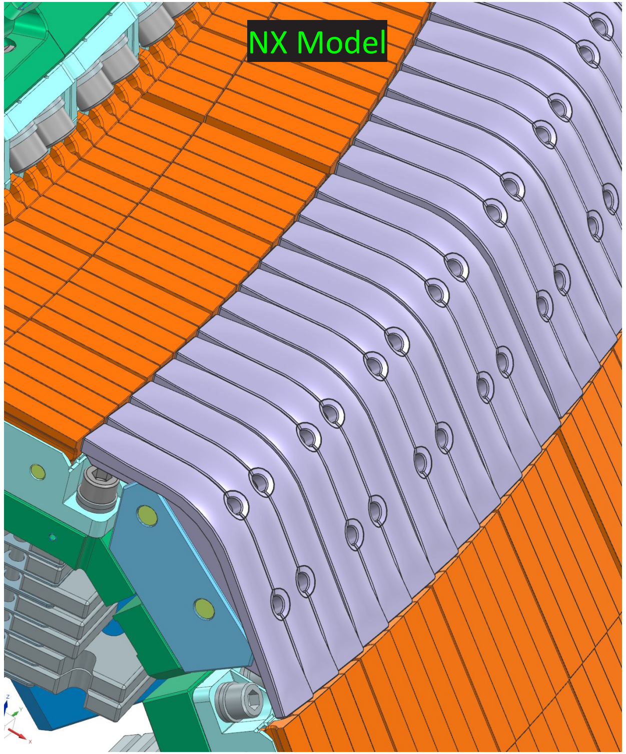


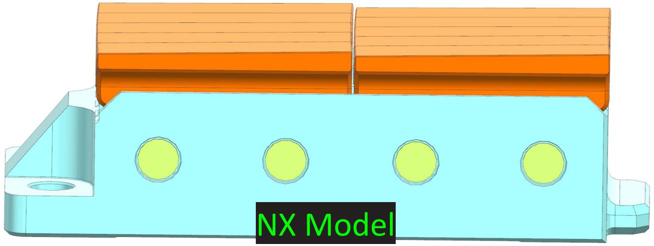


Images from T. Henderson, R. Ramirez Dominguez
For more info on SPARC CAD models see Johnson talk, this workshop

NX is the source of truth for all tokamak components. Example shown for plasma facing component (PFC) hardware.

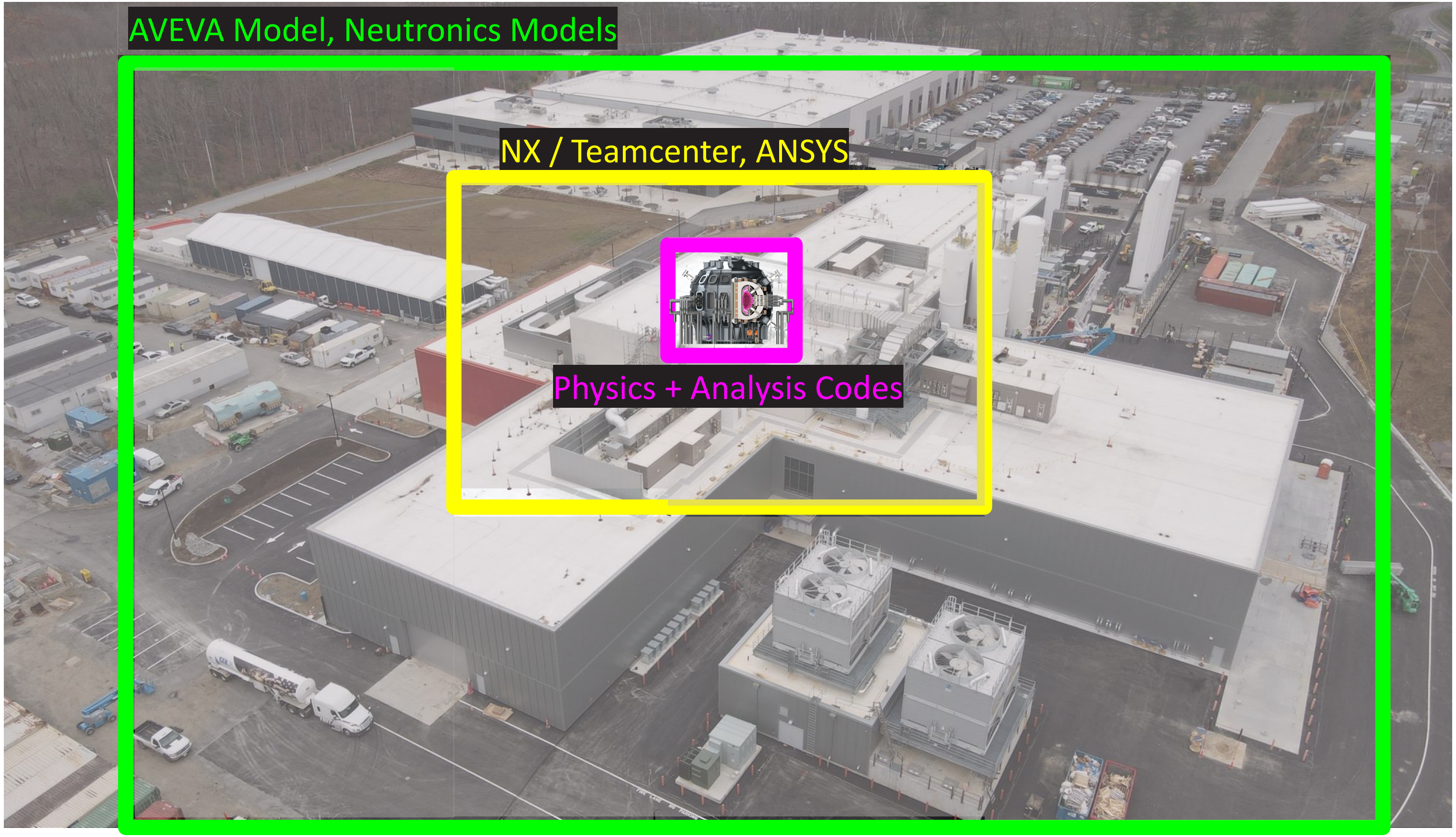




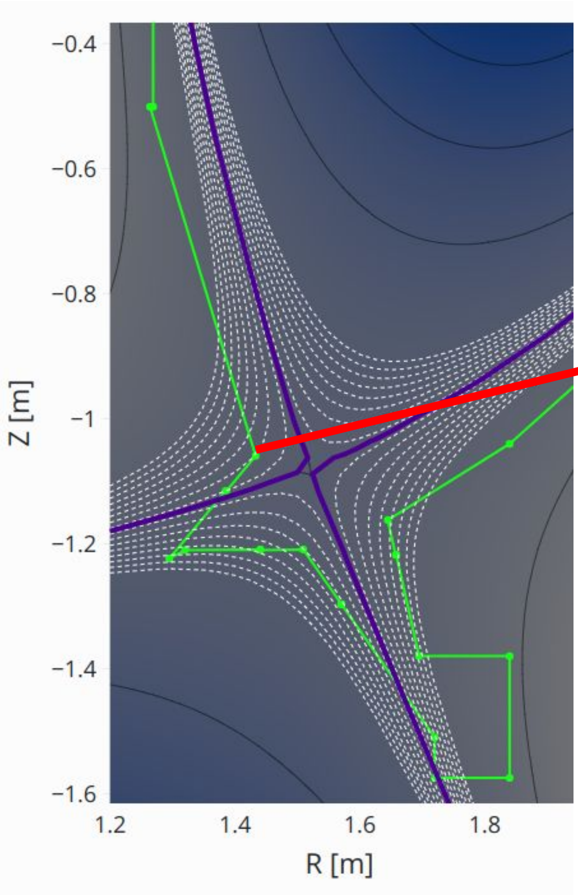


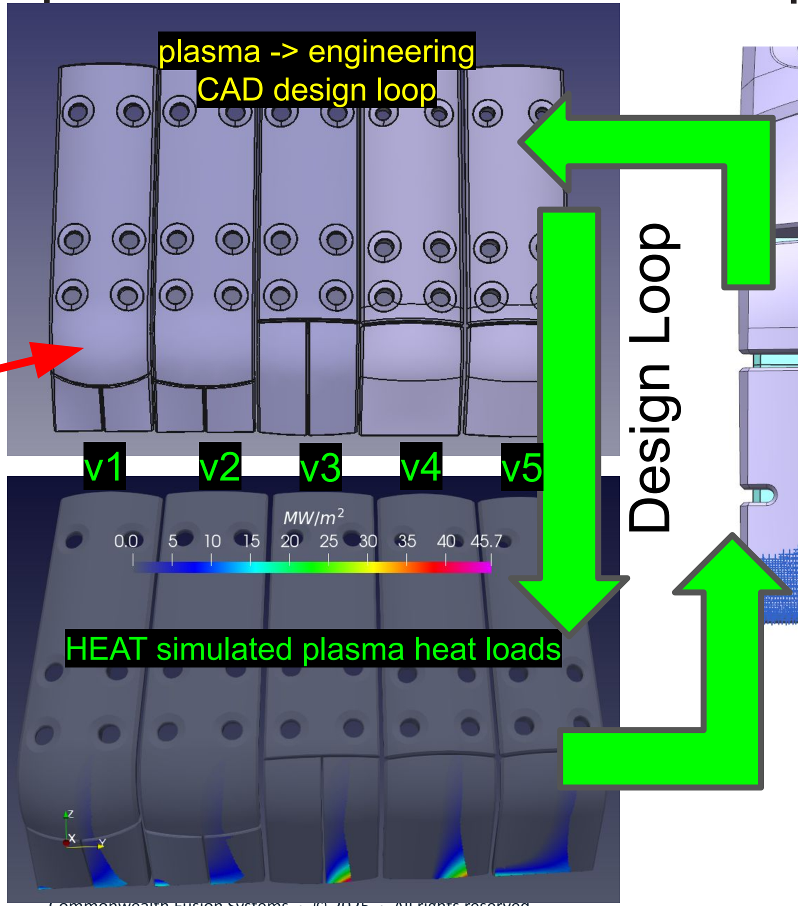
Roughly 1800/4000 PFC subassemblies completed

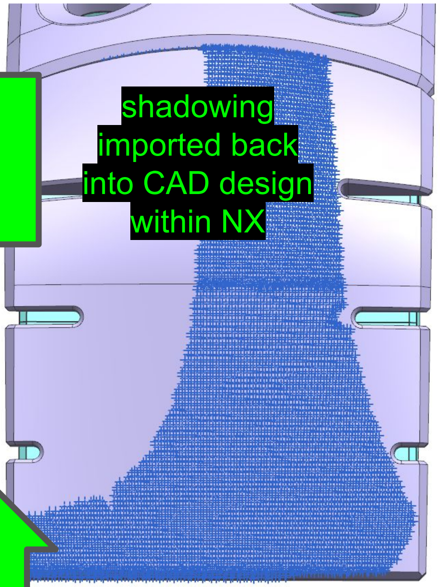
CFS employs a multi-fidelity approach to digital engineering: physics and analysis codes simulate machine state



Physics codes are coupled to engineering design/analysis codes for design and operational scenario development



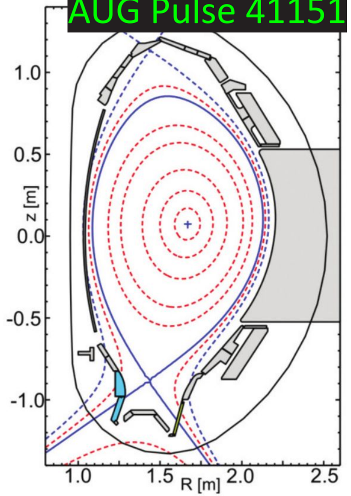




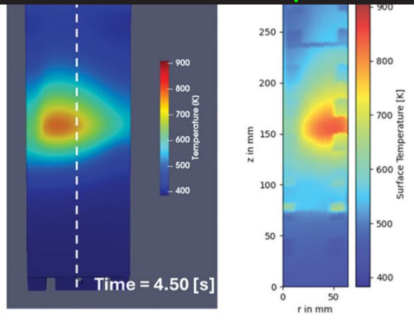
HEAT: T. Looby et al Fusion Science and Technology, 2022

Physics codes are validated experimentally at other tokamaks, example shown for HEAT at AUG

AUG Pulse 41151



IR camera sim vs experiment



Simulated profiles vs experiment

Physics code (HEAT) in red

Experimental data in blue

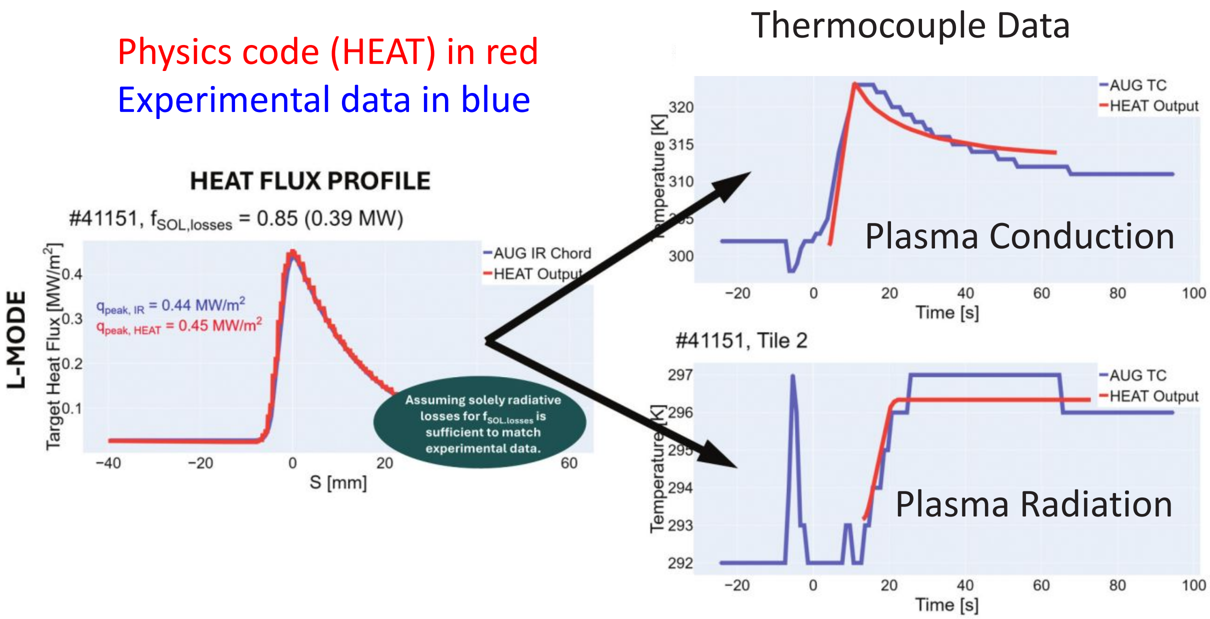


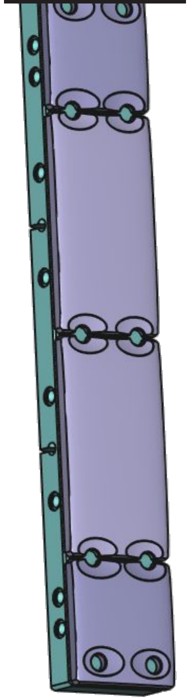
Fig. 13. Illustration of the agreement between the heat flux data extracted from the divertor target (red: HEAT, blue: IR) and the temperature (red: HEAT, blue: TCs) for two TC positions of AUG pulse #41151. For this simple case, reasonable agreement between experiment and simulation for both measurements can be achieved. Note that for the Tile 1 FEM simulation, a constant, negative outflux is applied to the tile rear side in order to mimic the AUG cooling water system.

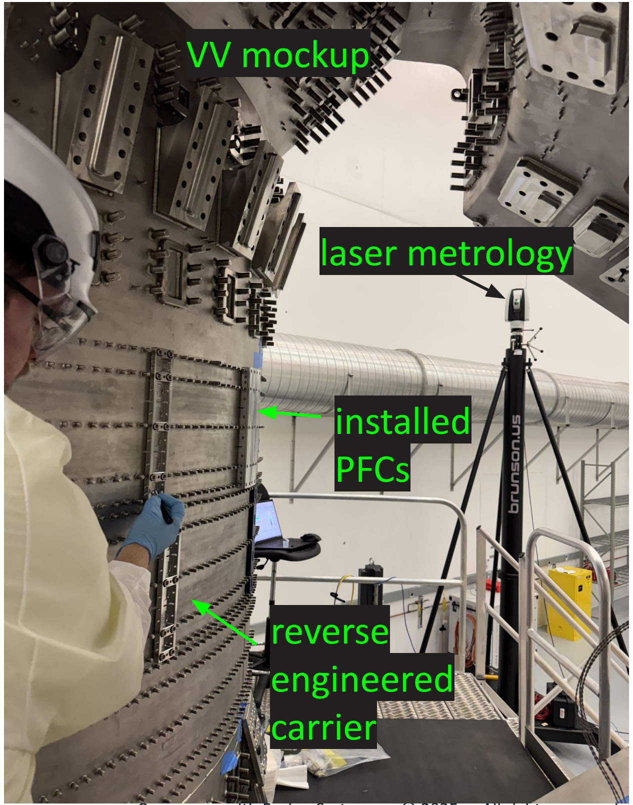
Redl, A., Faitsch, M., Looby, T., & Eich, T. (2025). The Experimental Validation of HEAT on the ASDEX Upgrade Tokamak. Fusion Science and Technology, 81(7), 623–641. https://doi.org/10.1080/15361055.2025.2478720

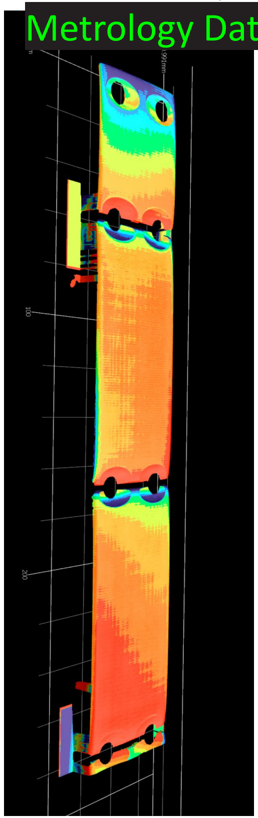
Grounding 3D models with empirical data

As hardware is manufactured and installed at CFS HQ, models evolve into "as built" Digital Twin Instances (DTIs)

Digital Twin Prototype → Digital Twin Instance

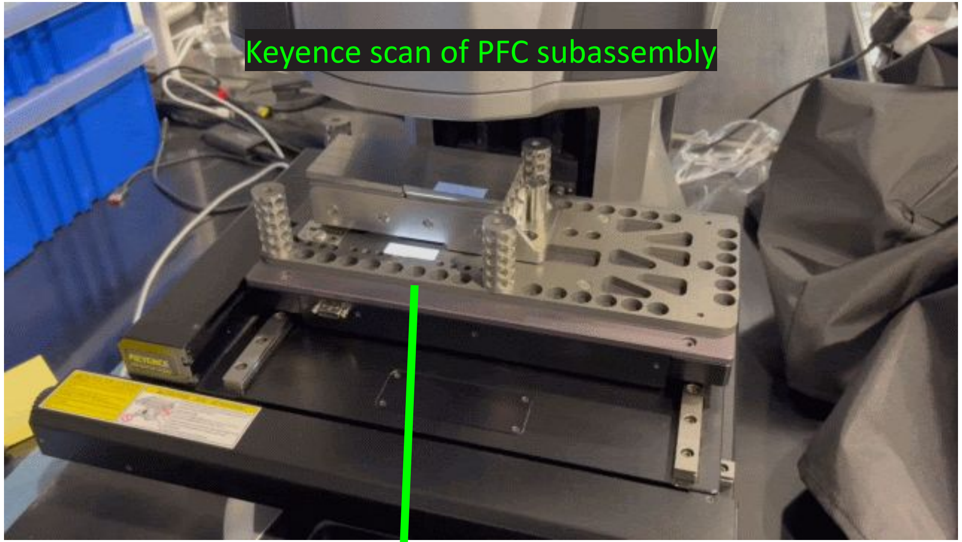


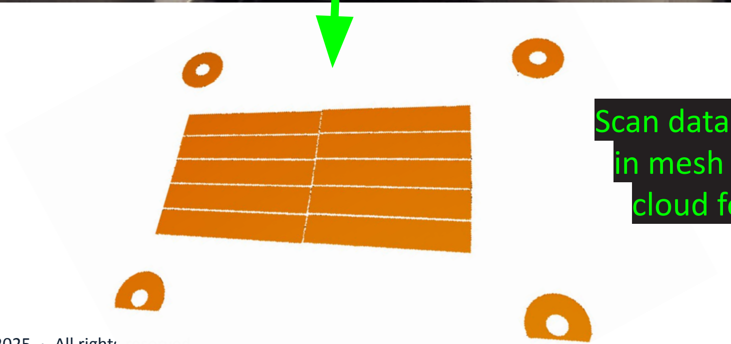




Each PFC subassembly is scanned independently to validate the as-built assembly is within tolerances

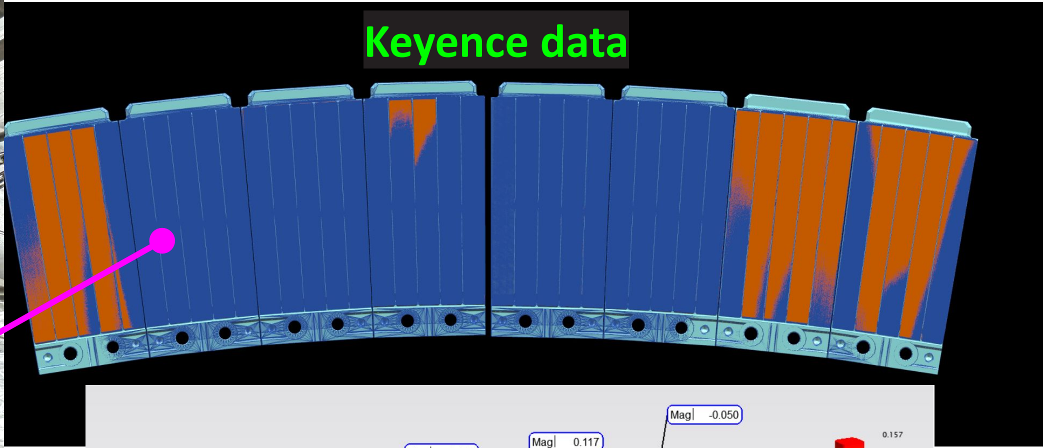
Slide from M. Lagieski, B. Okray

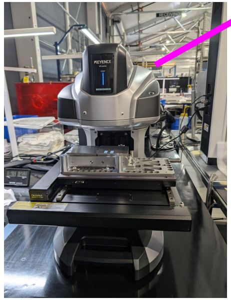




Scan data is output in mesh or point cloud formats

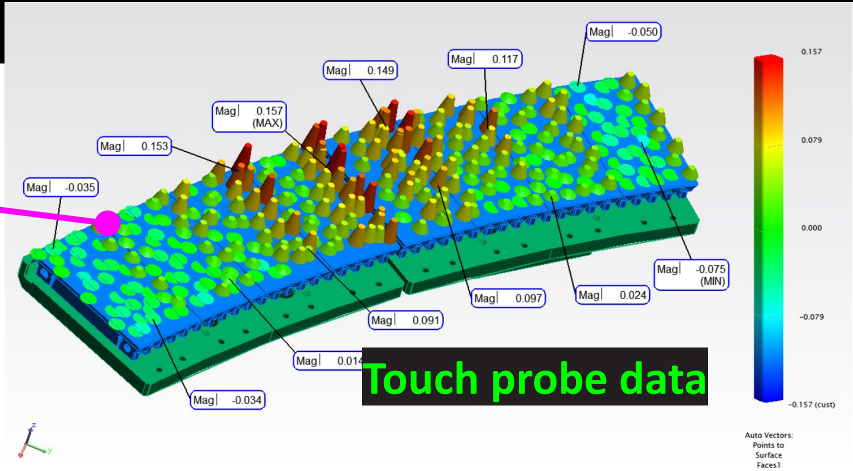
Data from multiple metrology sources is compared and synthesized to generate as-built models of the PFC geometry





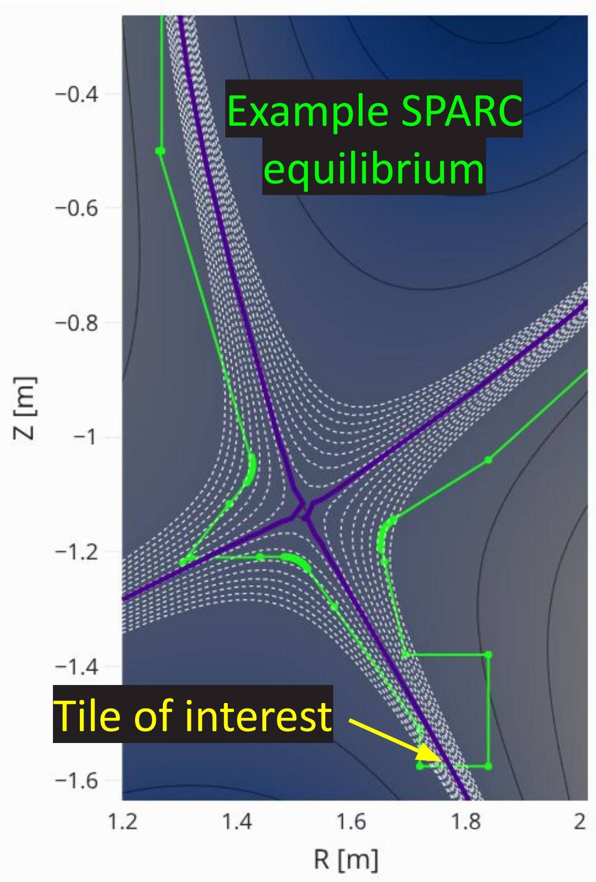
Keyence VR-6000 scans PFCs

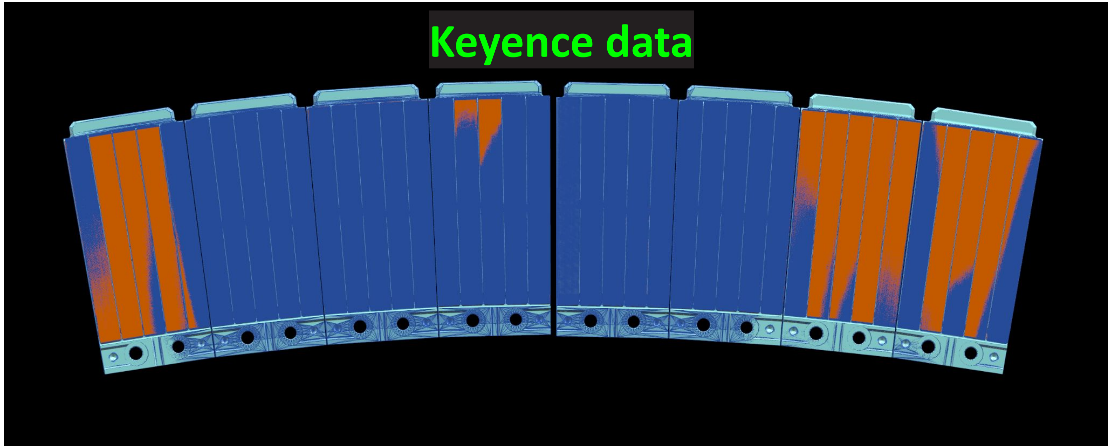
Leica T-Probe provides touch test across machine

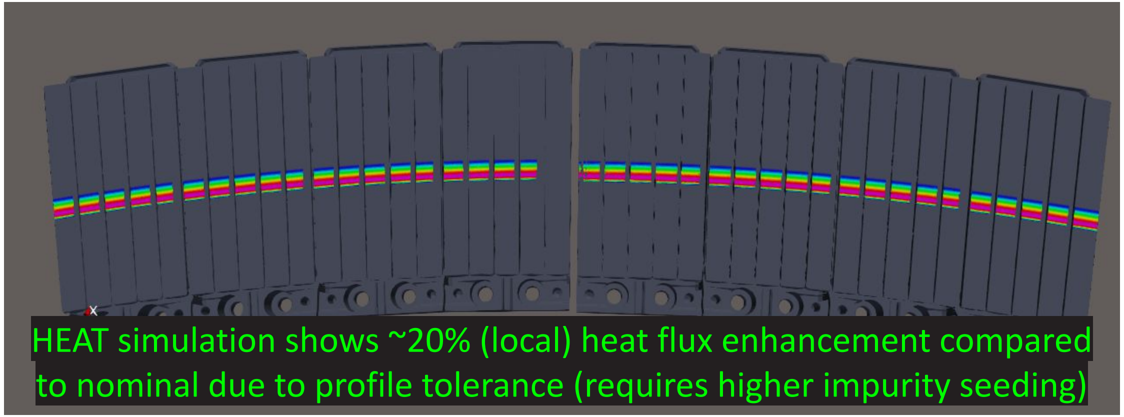


Images courtesy of E. Neill, A. Wick

As-built models can then be fed back to the physics codes to quantify physics performance cost of misalignments





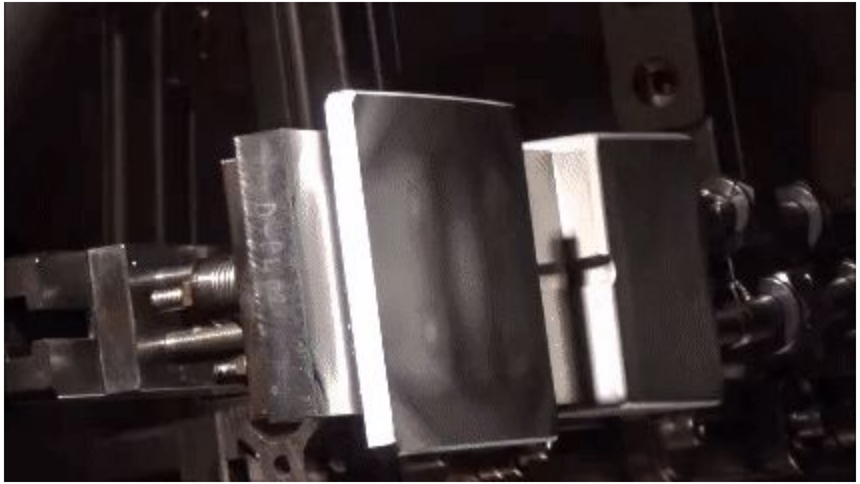


High heat flux testing is performed to define the operational limits of plasma facing materials and assemblies, and to benchmark ANSYS models

Tungsten slices

Surprisingly, W slices did not crack, but plastically deformed

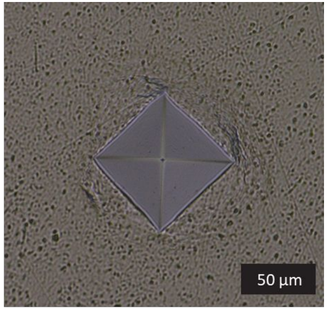
Tungsten Heavy Alloy

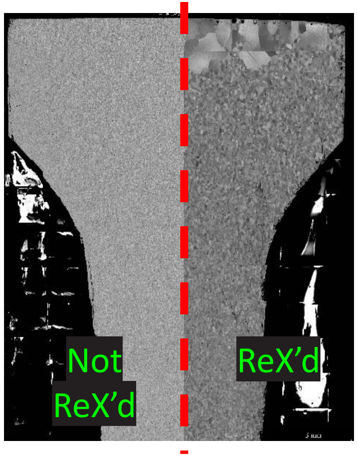


WHA undergoes “pomegranate effect”

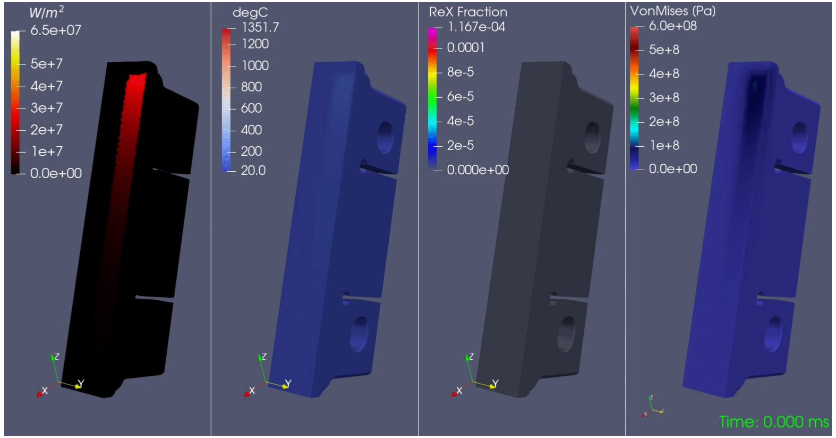
Material test data is connected to physics/engineering models to quantify material evolution for each SPARC scenario

We bake SPARC W for varying time and temperatures and measure hardness, a recrystallization (ReX) proxy

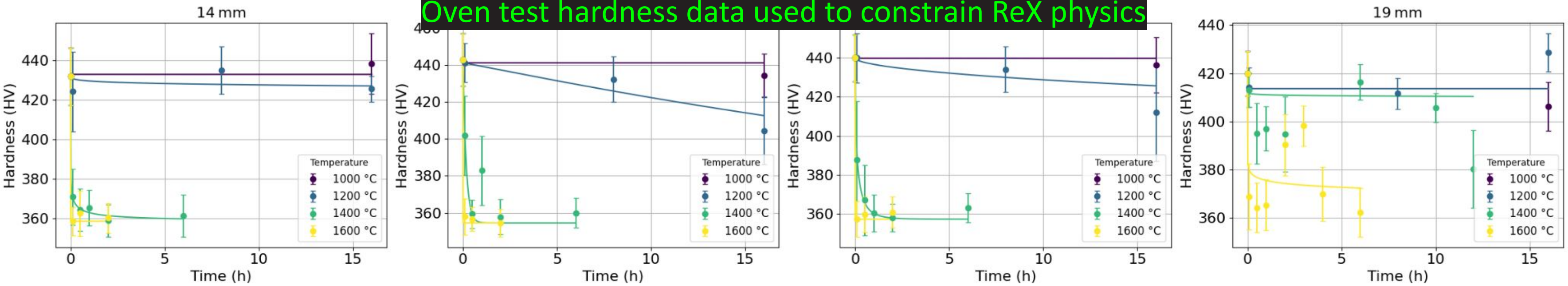




Empirical ReX data pushed into physics codes



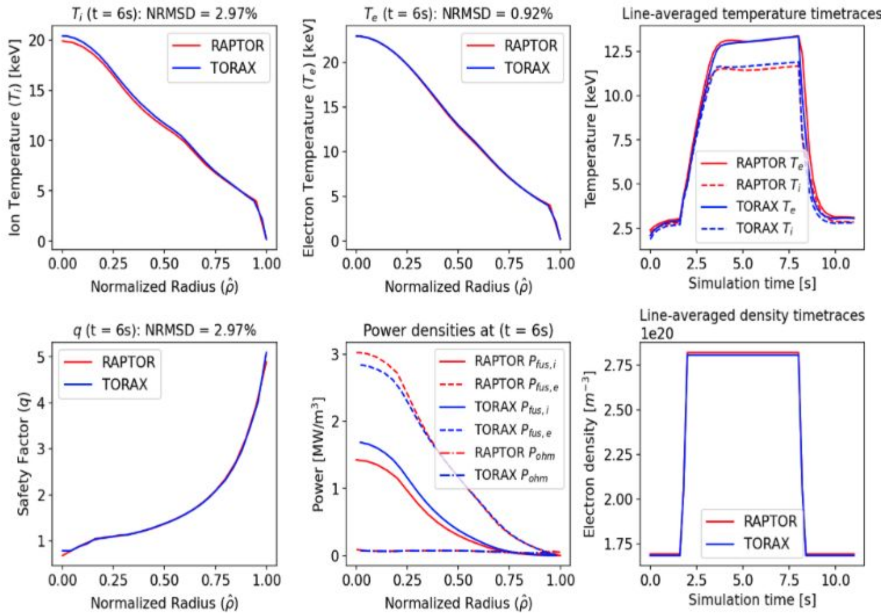
Oven test hardness data used to constrain ReX physics



Preparing for SPARC operations

TORAX: foundational framework for rapid pulse predictions

- Python-JAX auto-differentiable framework for tokamak transport
  - Enables gradient-based non-linear PDE solvers
- TORAX is open-source with professional software management Google DeepMind
- Coupled core and SOL models[1] to enforce core-edge solutions
- JAX enables efficient coupling of ML-surrogate models



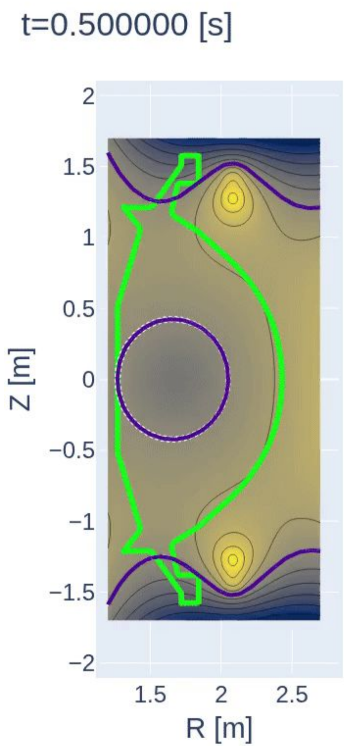
Δt=0.2s: RAPTOR walltime: **~70s** , TORAX walltime: **~7s**

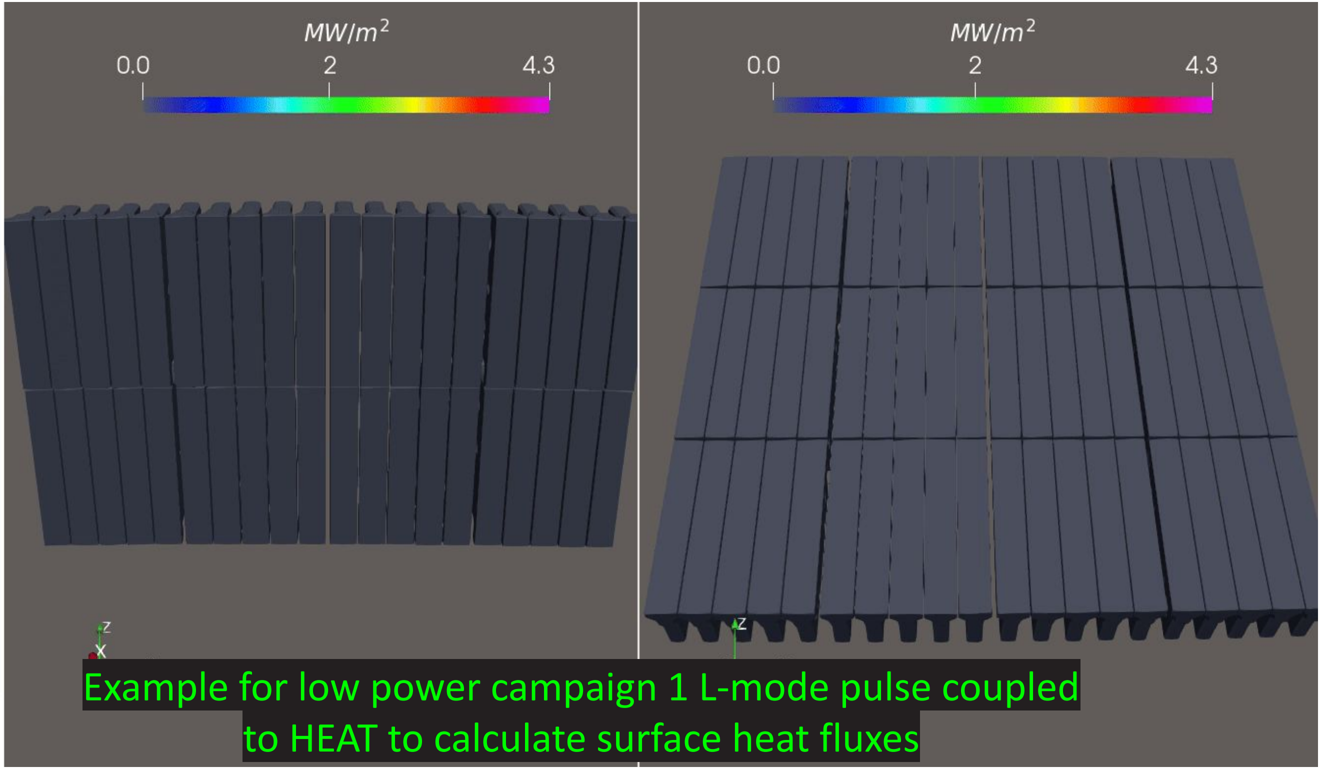
TORAX: A Fast and Differentiable Tokamak Transport Simulator in JAX
https://doi.org/10.48550/arXiv.2406.06718

[1] Tom Body et al. Nuclear Fusion (2025)

TORAX

Integrated physics / engineering toolchains are used for pulse design and operational scenario planning





Example for low power campaign 1 L-mode pulse coupled to HEAT to calculate surface heat fluxes

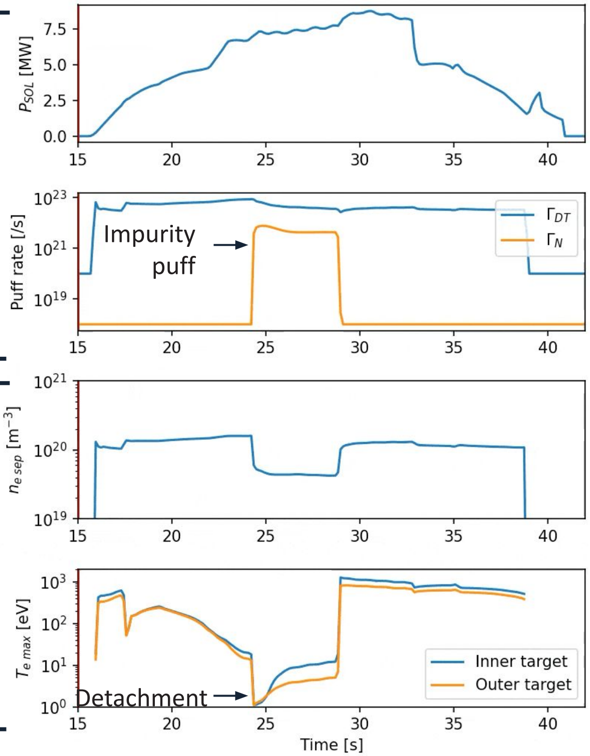
Neural networks are trained on high fidelity plasma codes to enable rapid (sub-ms) predictions for ops and control

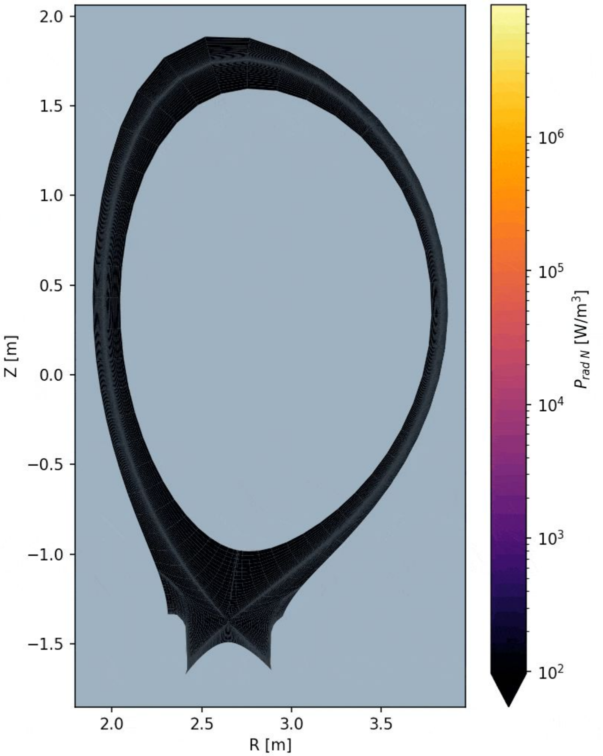
Inputs

P_{SOL}
puff rates

Outputs

$n_{e\ sep}$
$T_{e\ targets}$
P_{rad}

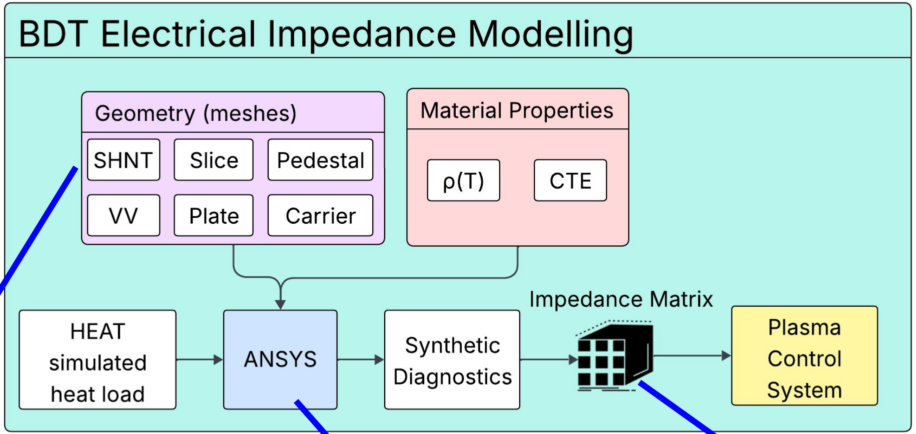


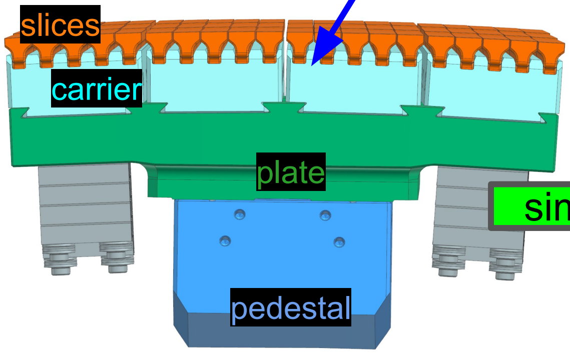


SOLPS-NN example provided by S. Ballinger

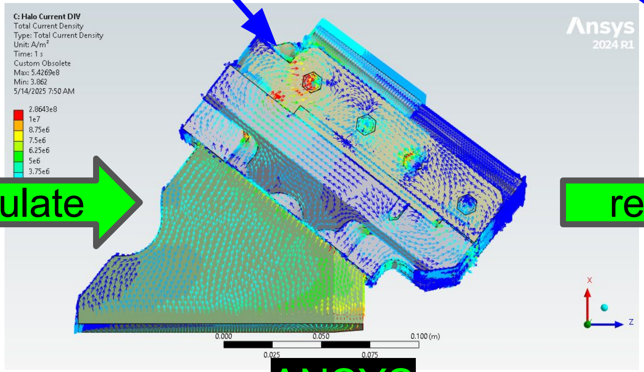
Surrogates of high fidelity FEM calculations for use by the plasma control system are under development

BDT = Boundary Digital Twin

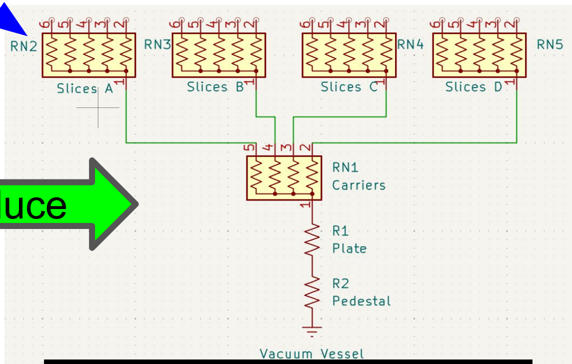




simulate



reduce

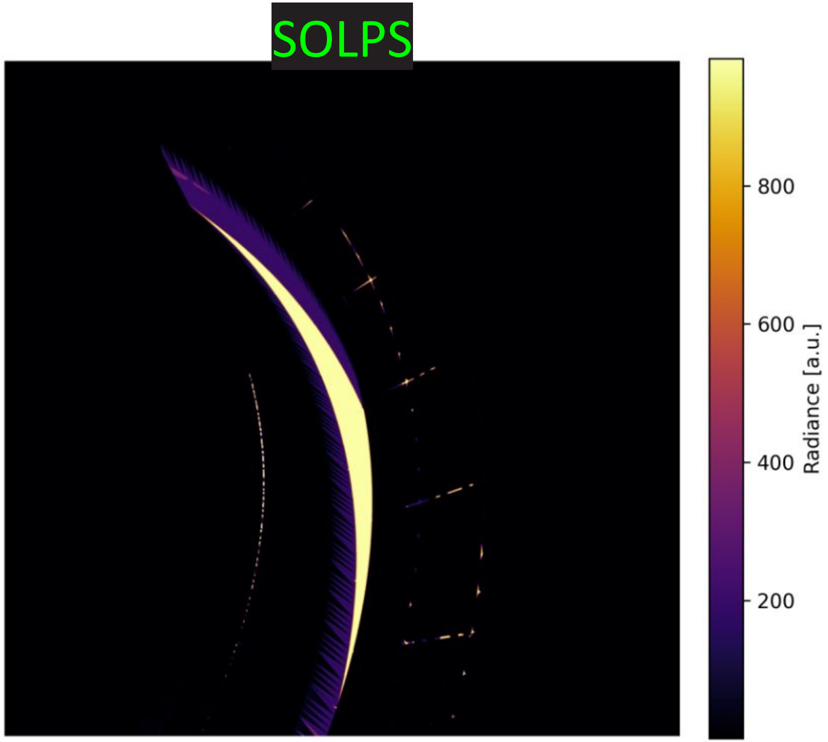


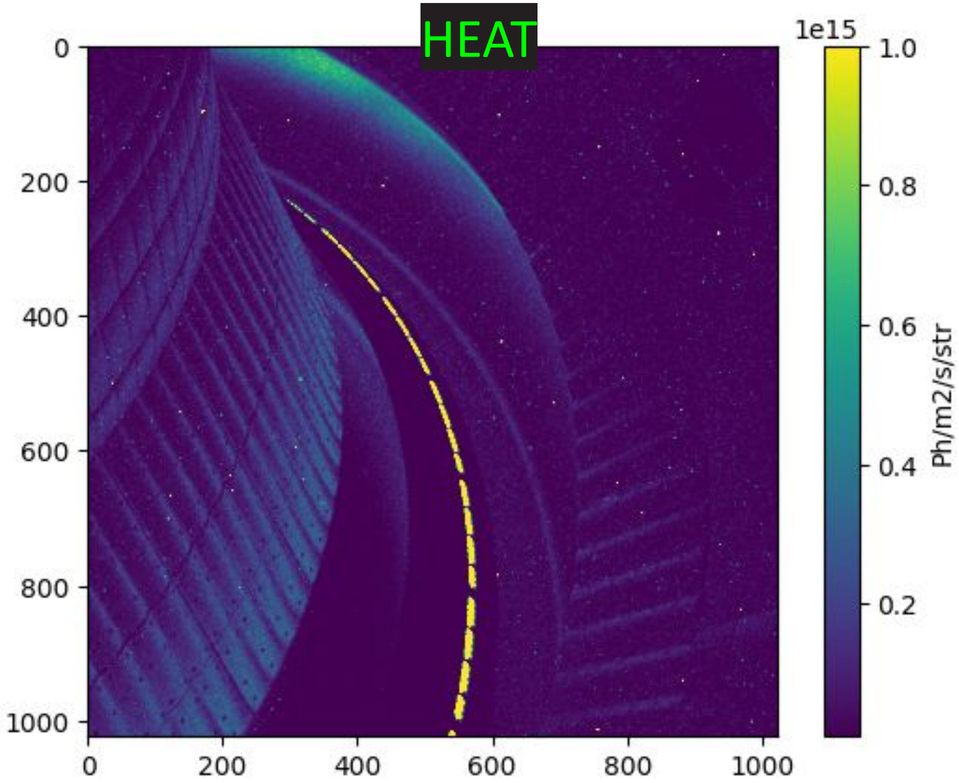
Assembly CAD model

ANSYS

Equivalent circuit diagram

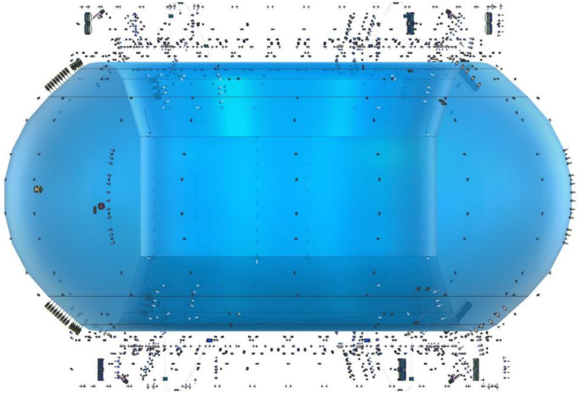
Synthetic diagnostics are developed to design operational scenarios and reconstruction workflows

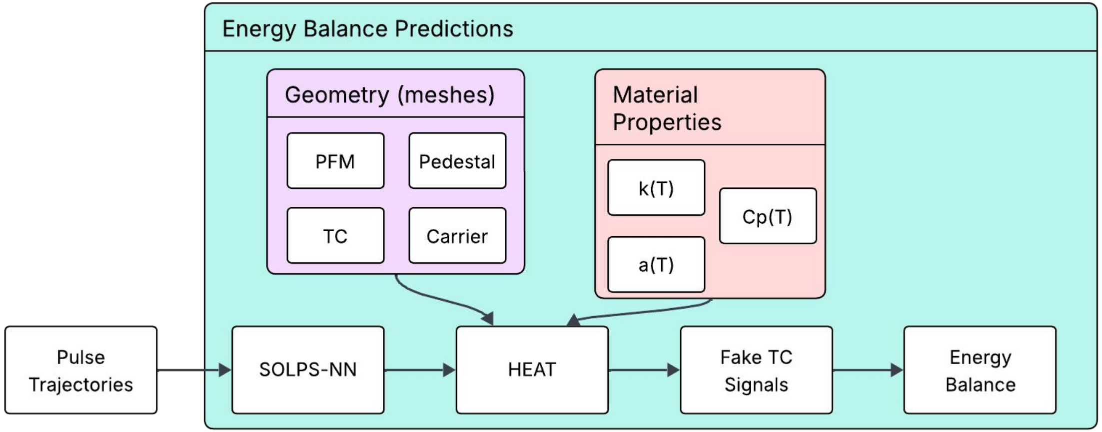


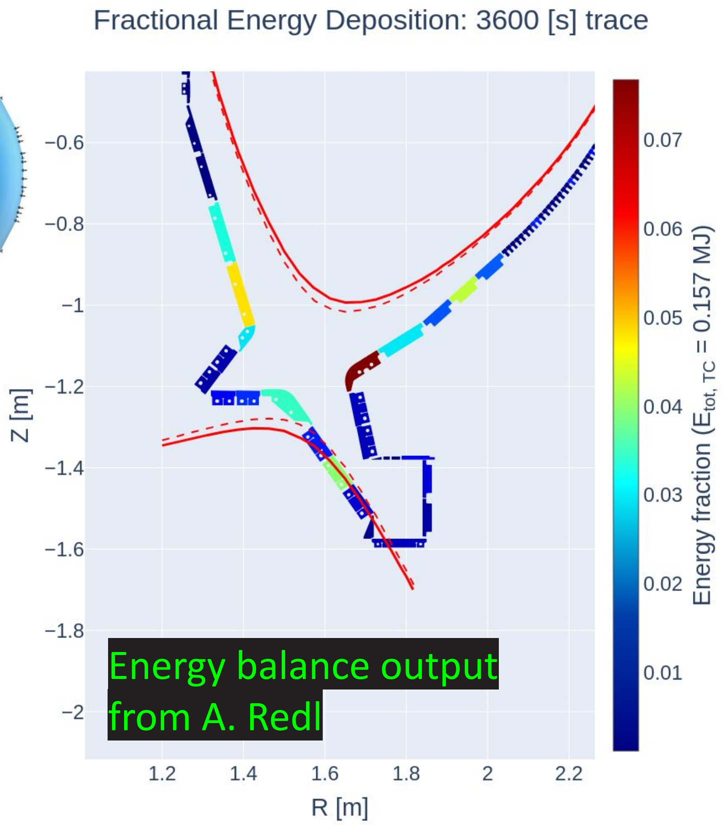


Post-processing and data analysis workflows are being developed to reconstruct physics parameters

~1500 thermal sensors in SPARC will be used to generate high fidelity energy balance







Looking ahead to ARC

Operating an ARC^{TM}-class power plant will require us to depend upon our digital models

- Neutron irradiation in ARC will be extreme. Camera, bolometers, windows, will all get destroyed within a short period of time
- Diagnostics are expensive, and reducing the number of diagnostics in a power plant will make commercial fusion more economical
- **We will need to lean on physics and engineering models more heavily when running ARC than SPARC (or any other tokamak)**

Thank you for your attention