FREDA:
A Multi-Fidelity Plasma-Engineering Integrated Modeling Platform for Fusion Reactor Design & Assessment

Cami Collins
on behalf of The FREDA Team*

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ORNL IS MANAGED BY UT-BATTELLE LLC
FOR THE US DEPARTMENT OF ENERGY

*The FREDA Team

FES

ORNL Fusion Energy Division
Cami Collins, Rhea Barnett, Mark Cianciosa, Yashika Ghai, Ehab Hassan, Jeremy Lore, Jin Myung Park, Gary Staebler

ORNL Nuclear Energy and Fuel Cycle Division
Vittorio Badalassi, Jin Whan Bae, Katarzyna Borowiec, Robert Lefebvre, Arpan Sircar

Lawrence Livermore National Laboratory: Benjamin Dudson, Jerome Solberg, Jingyi Wang

General Atomics: Min-Gu Yoo

UC San Diego: Christopher Holland, Eric Bass

ASCR

ORNL Computer Science & Mathematics Division
Richard Archibald, Wael Elwasif, Ana Gainaru, Mark Coletti, Lance Drane, Kshitij Mehta

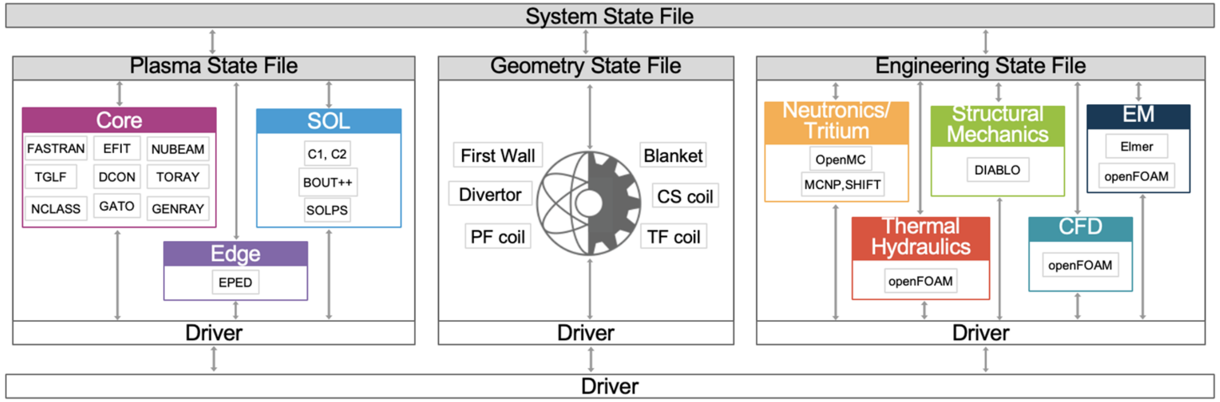
Sandia National Laboratories: Michael Eldred, Luis Damiano

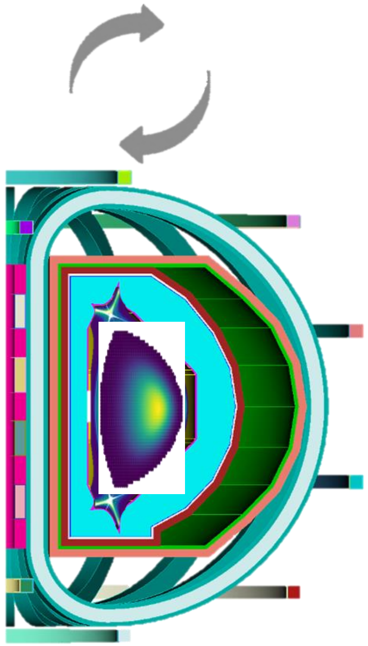
FREDA

Fusion REactor Design and Assessment
is a DOE SciDAC project (2023-27) developing integrated plasma+engineering workflows for whole-device modeling

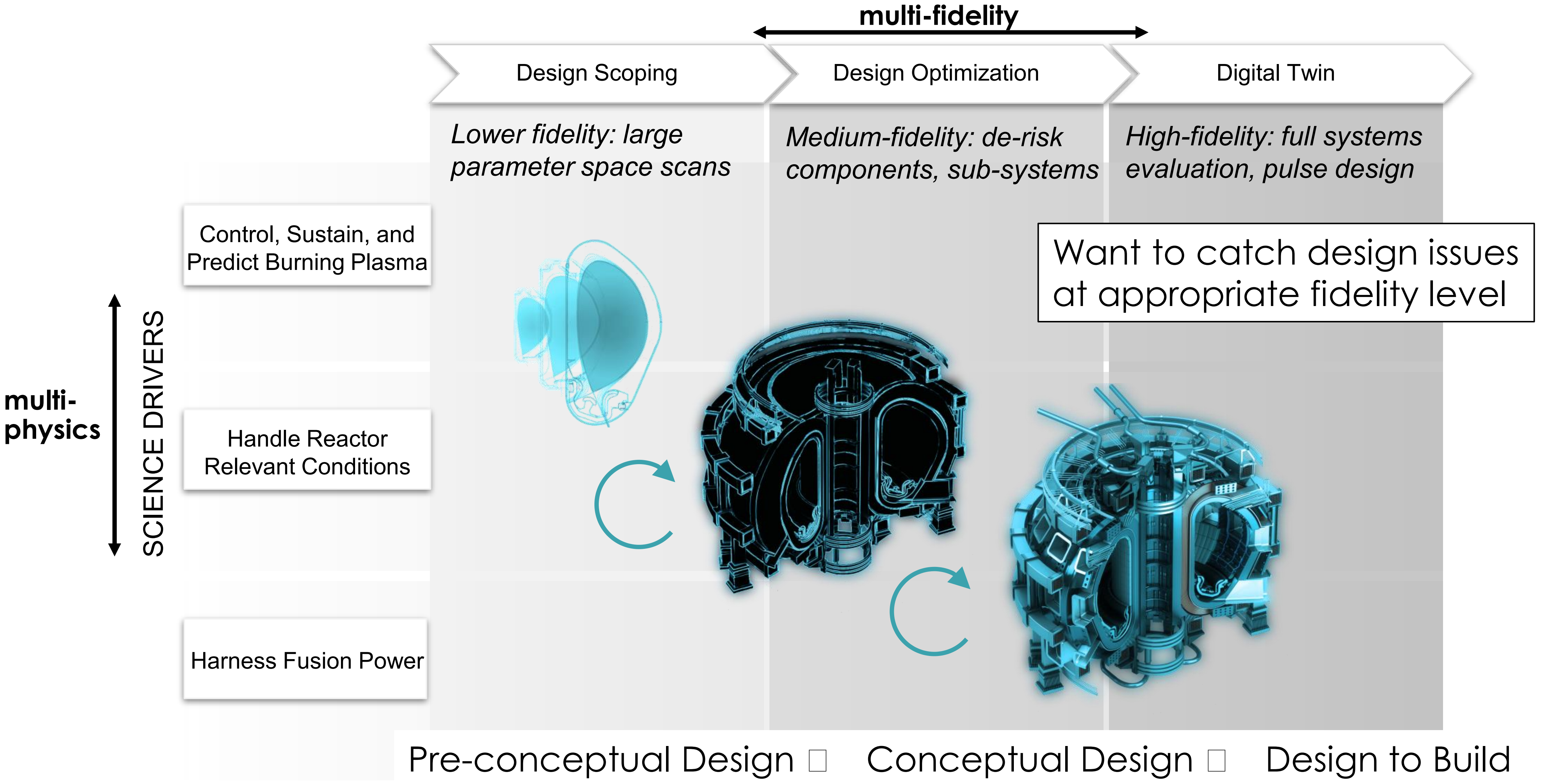
Outline

- Why integrated modeling?
- What is FREDA?
- How has FREDA been applied?
- Summary/Future





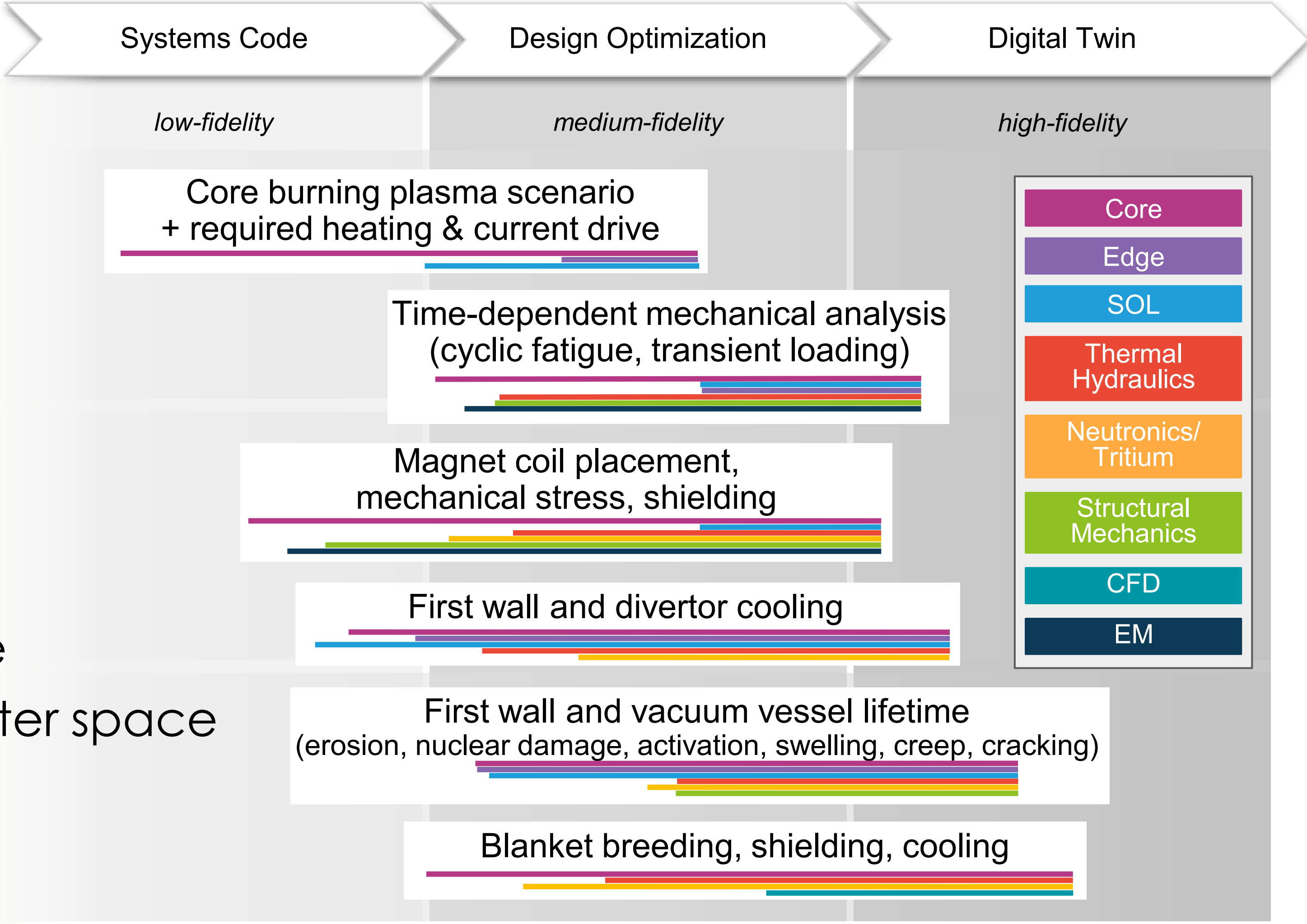
Overarching Goal: Enable **self-consistent, multi-fidelity, iterative optimization** workflows for the fusion reactor design process



The challenge of integration

- **Multi-physics**
  - CFD+neutronics+thermal…etc.
  - Multi-fidelity (high fid. vs. surrogate)
- **Multi-scale**
  - Micro- to macro-scales
    - Tungsten cracking□ component failure
    - Plasma turbulence□ fusion power
- **Across-regions, systems**
  - Linking core-edge-wall plasma
  - Single component to whole device
  - Validation across devices, parameter space
  - Remote maintenance strategy
- **Temporal**
  - Device evolution (ramp up/down, transients), lifetime

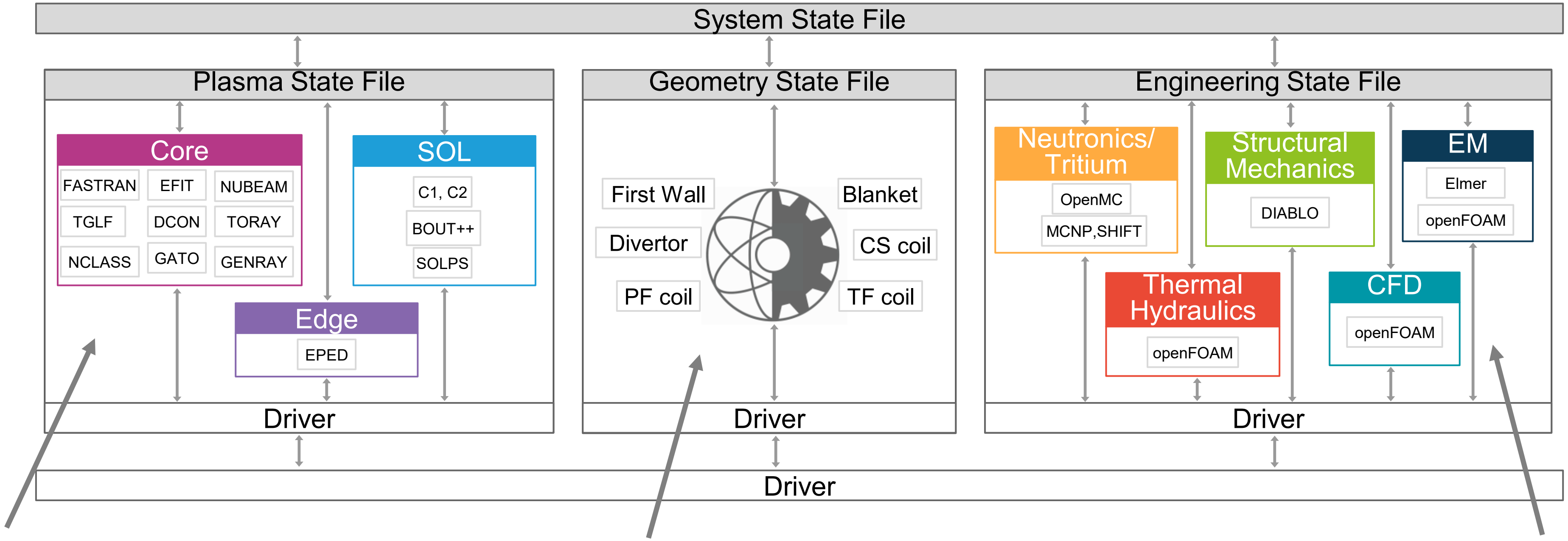
Examples of multi-physics integrated analysis



FREDA's approach: flexible component-based framework & data structure

Framework & Workflow

Capable of integrating swappable modules with diverse CPU/GPU requirements



Fusion-Plasma

- Based on the open-source IPS (Integrated Plasma Simulator) developed over decade of SciDACs *(PI: JM Park)*

Parametric Geometry

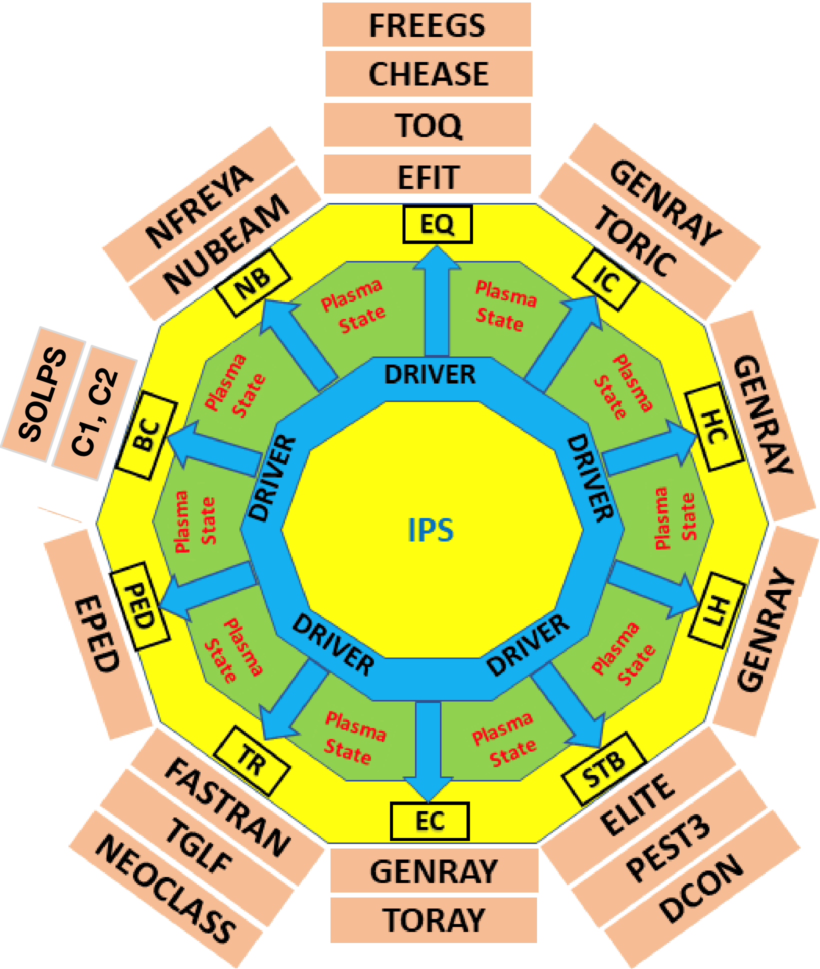
- Includes systems codes and parameterized geometry representation

Fusion-Engineering

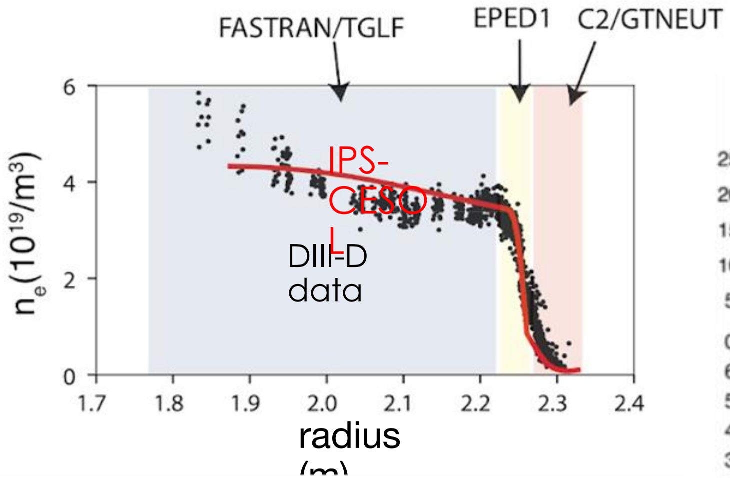
- Includes multiphysics tools from Fusion Energy Reactor Models Integrator (FERMI) developed through Arpa-E *(PI: Vittorio Badalassi)*

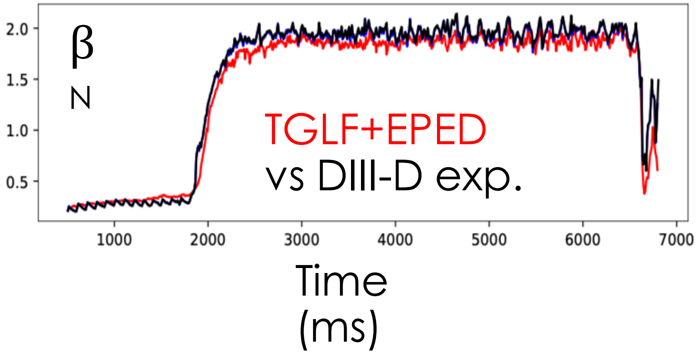
- aiming to use mainly open source tools
- will initially apply to tokamaks/STs, potential for expansion to stellarators

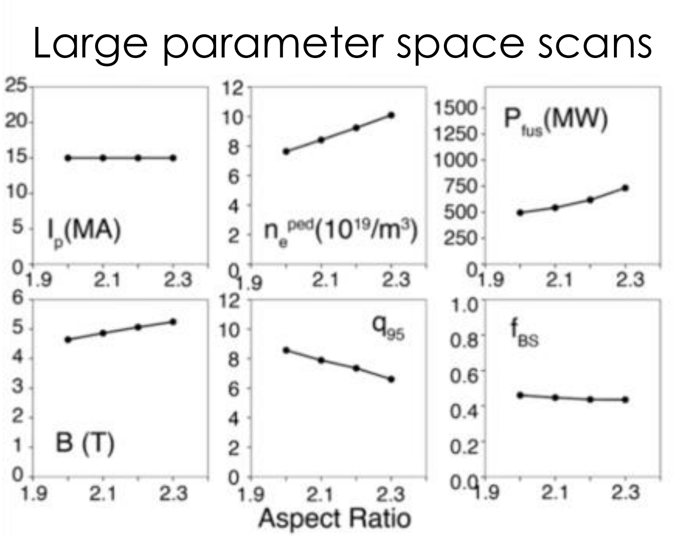
Plasma Approach: IPS



- IPS has been used in variety of studies
  - Steady-State Compact Advanced Tokamak reactor
    Buttery Nucl. Fusion 61 046028 (2021)
  - Projection and validation on DIII-D, KSTAR
    Park PoP 25 012506 (2018)

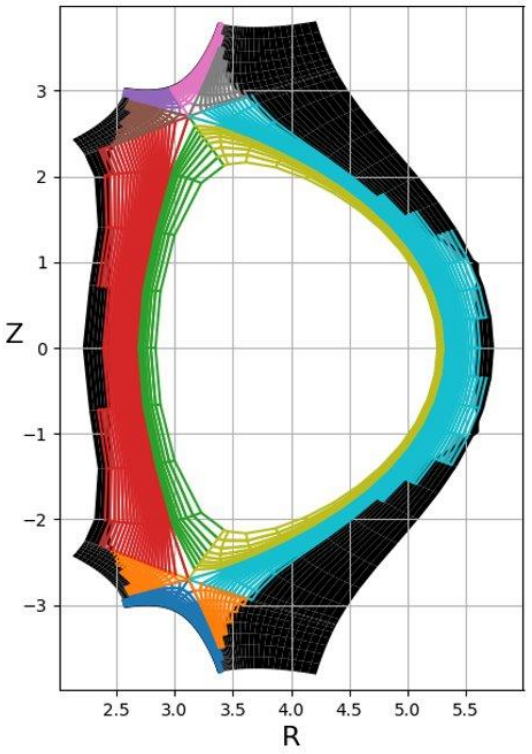






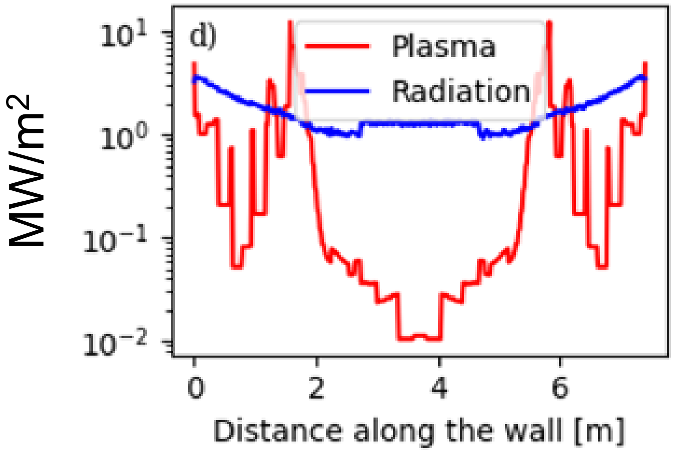
FY25 plasma development highlights

- Key focus: connecting the plasma to PFCs

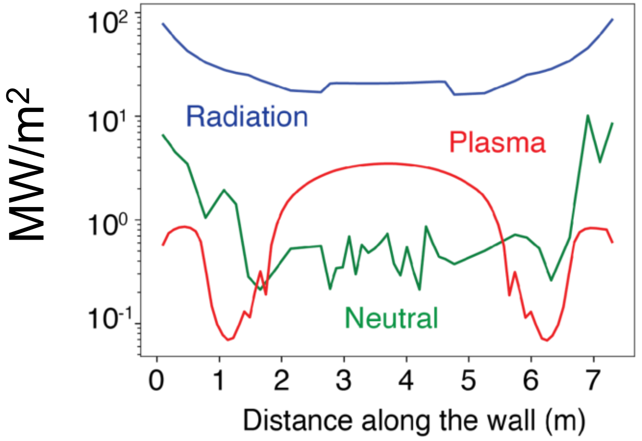


BOUT++ with boundary masking, IPS-HEAT (SOLPS) components added

BOUT++/Hermes-3



SOLPS-ITER + HEAT



First wall heat flux

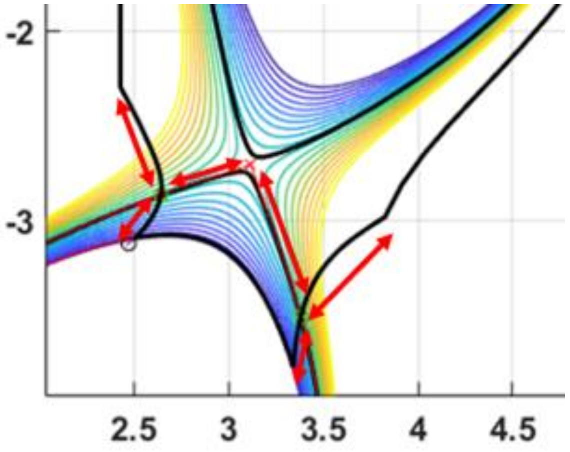
Routinely map the predicted heat flux to PFCs.

FY25 plasma development highlights

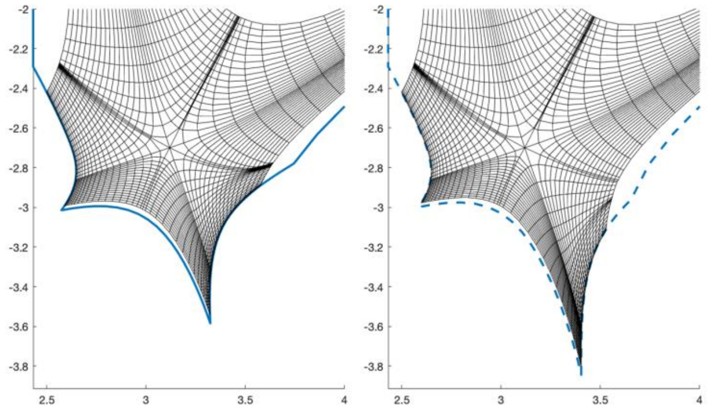
- Another key focus: developing faster divertor, PFC design workflows

A new **parametric divertor tool** is being used to generate SOLPS-ITER grids and specify the PFC boundary

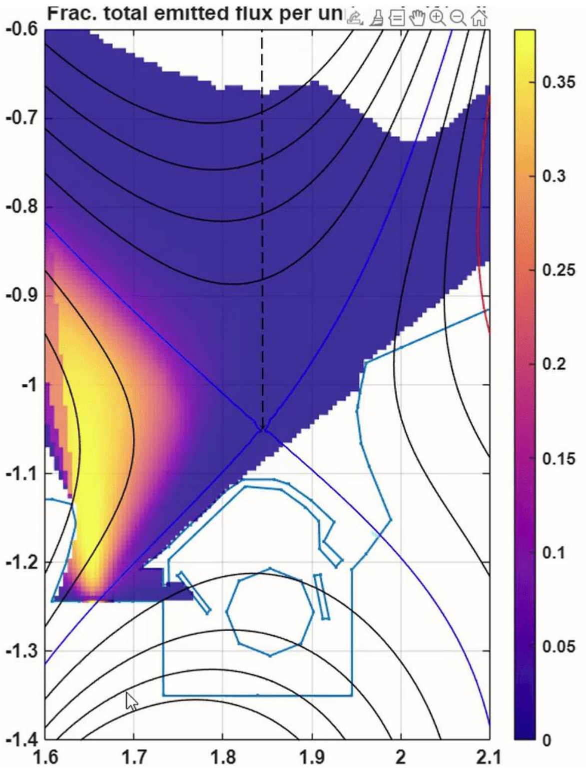
automated scans



AI/ML generated grid



interactive option



Still To-Do-: automated checks and input parameter tuning of SOLPS or BOUT++ runs

Uses semi-analytic neutral particle model to see response to geometry change

Plans for **Fusion-Plasma** Improvements

Year 1 | Year 2 | Year 3 | Year 4

Couple SOLPS-ITER, UEDGE, BOUT++

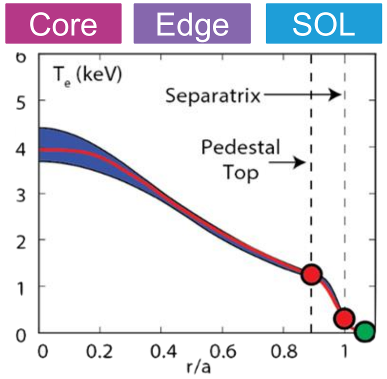
auto-grid generation

Connect plasma to PFCs

Add missing plasma models → fast-ion transport; core pellet fueling; plasma breakdown; RF models (Bonoli SciDAC); high fidelity core transport (Holland SciDAC)

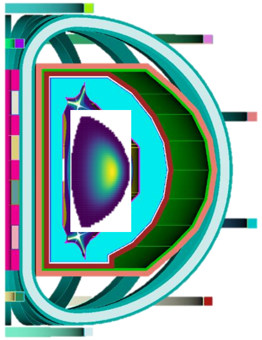
Enable whole pulse simulation → free boundary equilibrium; GPU TGLF/EPED

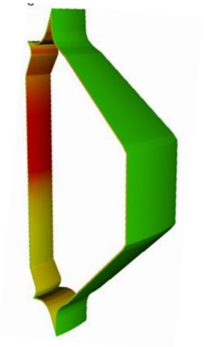
The frontier: integrating materials prediction into reactor design

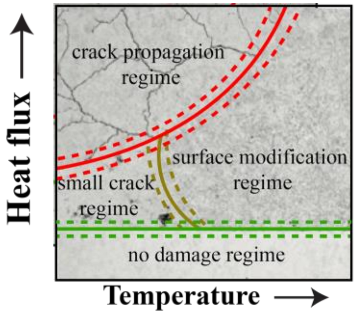


plasma scenario

map heat & particle flux to components



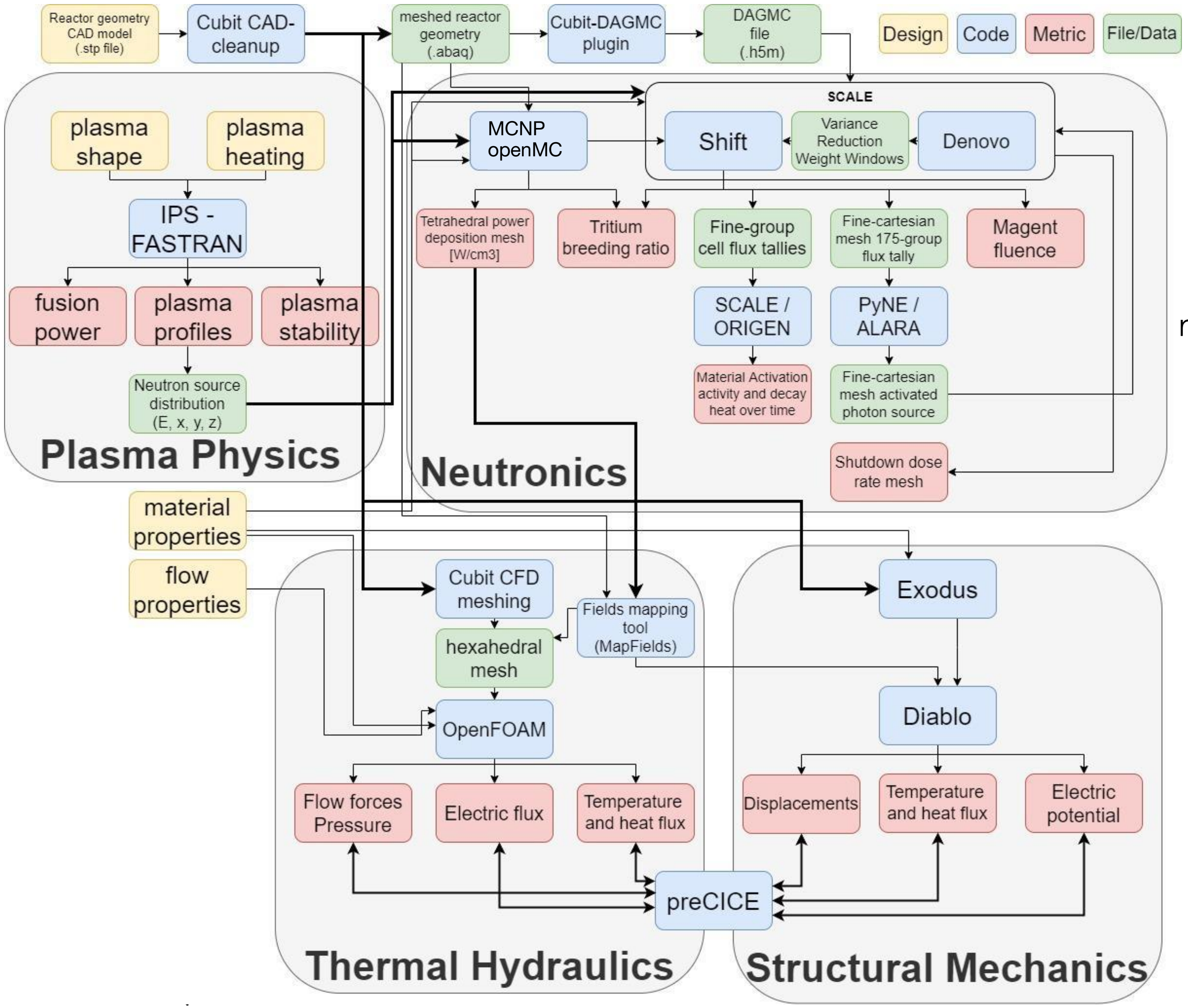




- When will degraded FW/divertor affect plasma performance?
- When will SLAG become a problem (tritium retention, UFOs)

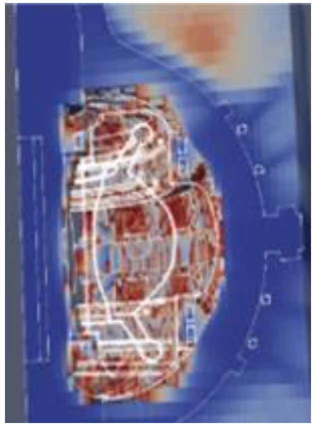
define operating limits ← impurity influx ← thermo-solid mechanics + materials models

Engineering Approach: FERMI

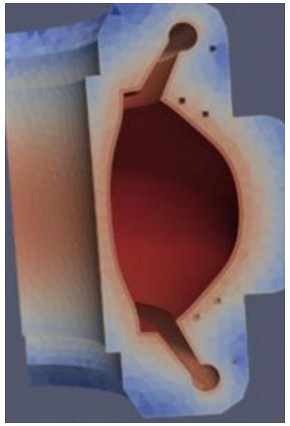


- Mostly open source
- All able to run on supercomputers

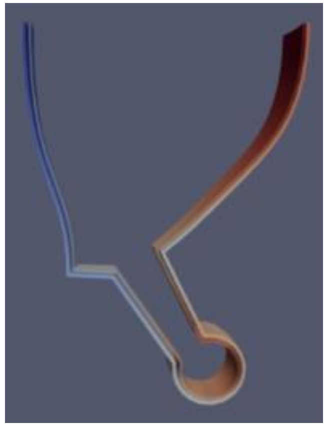
material activation



energy deposition



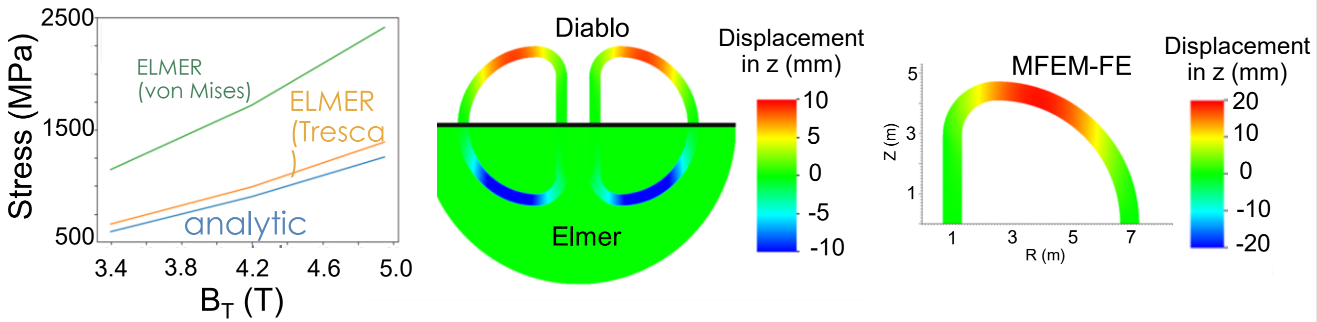
displacement



[Badalassi Fusion Sci. Tech., 79 (2023)]

FY25 engineering development highlights

Multi-fidelity benchmark of **magnet coil casing stress**
(analytic model, Elmer, Diablo, MFEM-FE)



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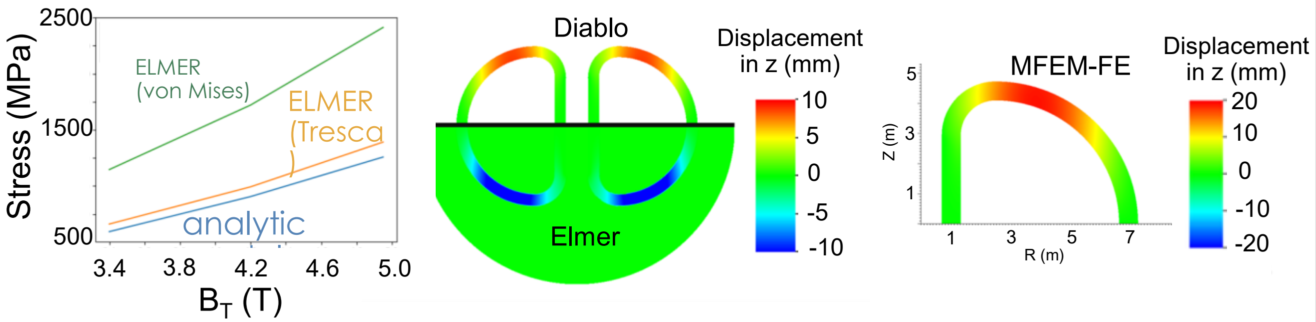
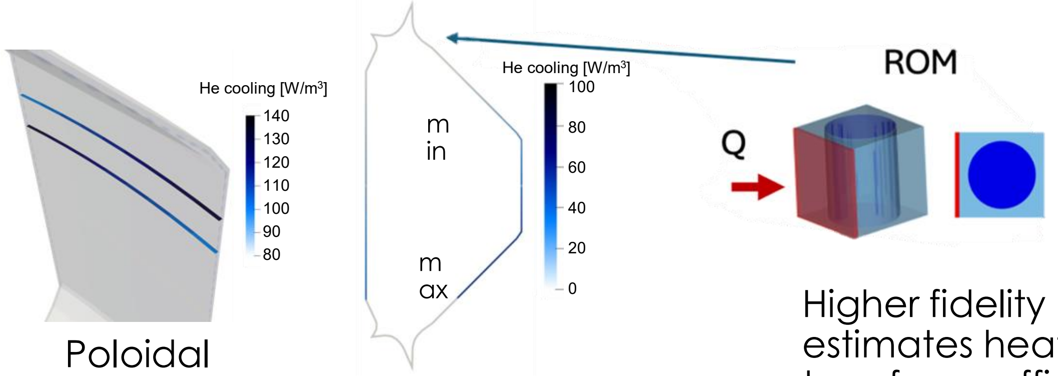


Developed first-wall **helium cooling representations,** reduced-order models for divertor



Poloidal Orientation

Toroidal Orientation

Higher fidelity model estimates heat transfer coefficient

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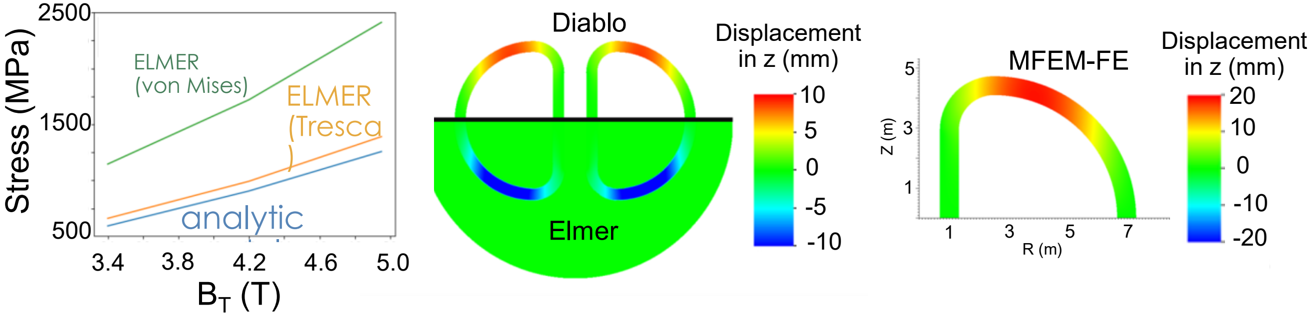

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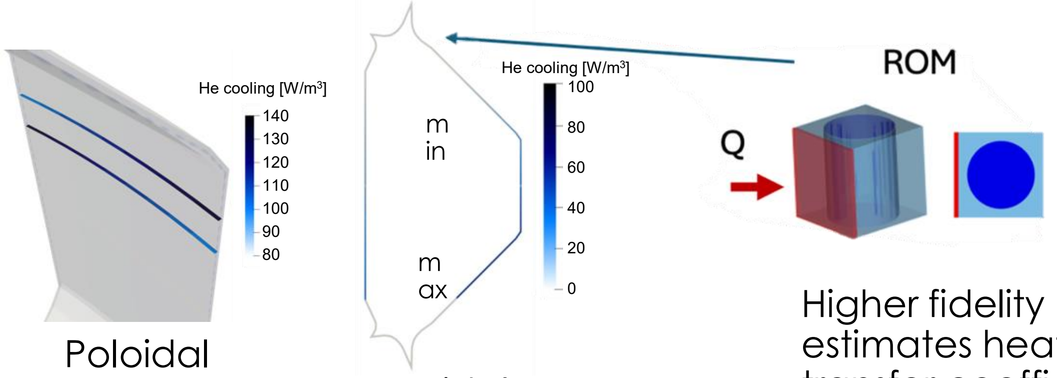


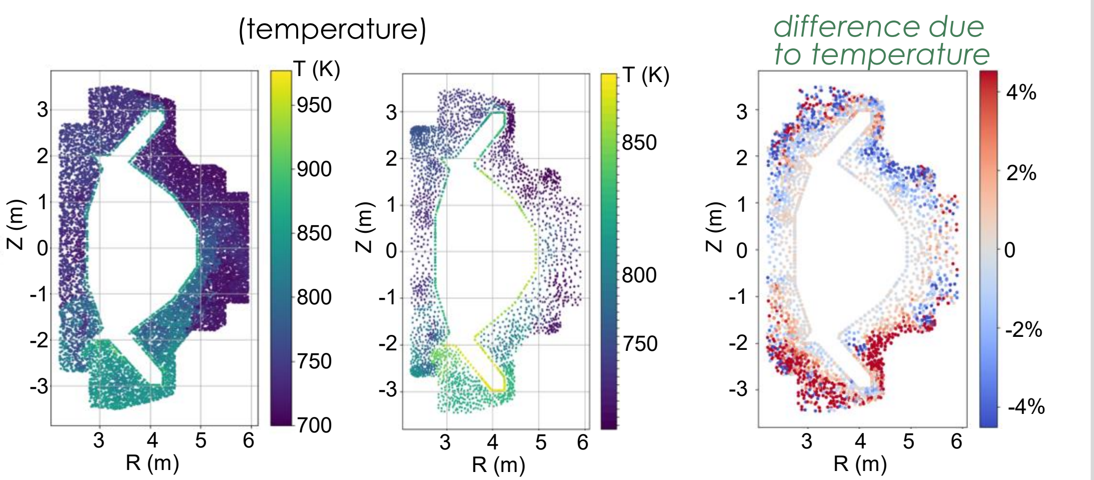
Poloidal Orientation

Toroidal Orientation

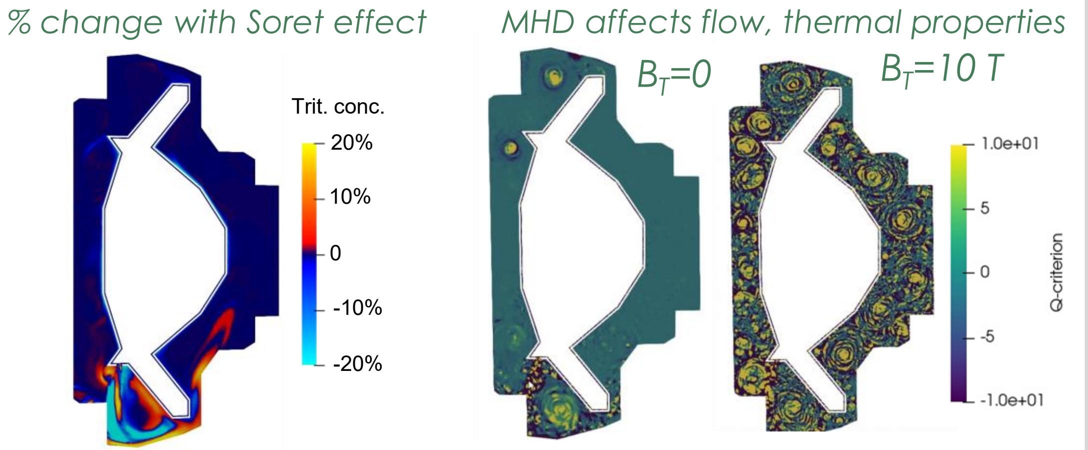
Higher fidelity model estimates heat transfer coefficient

Coupled CFD, neutronics for more accurate **tritium tracking,** impact of materials properties

CFD ⟷ neutronics ⟶ tritium breeding



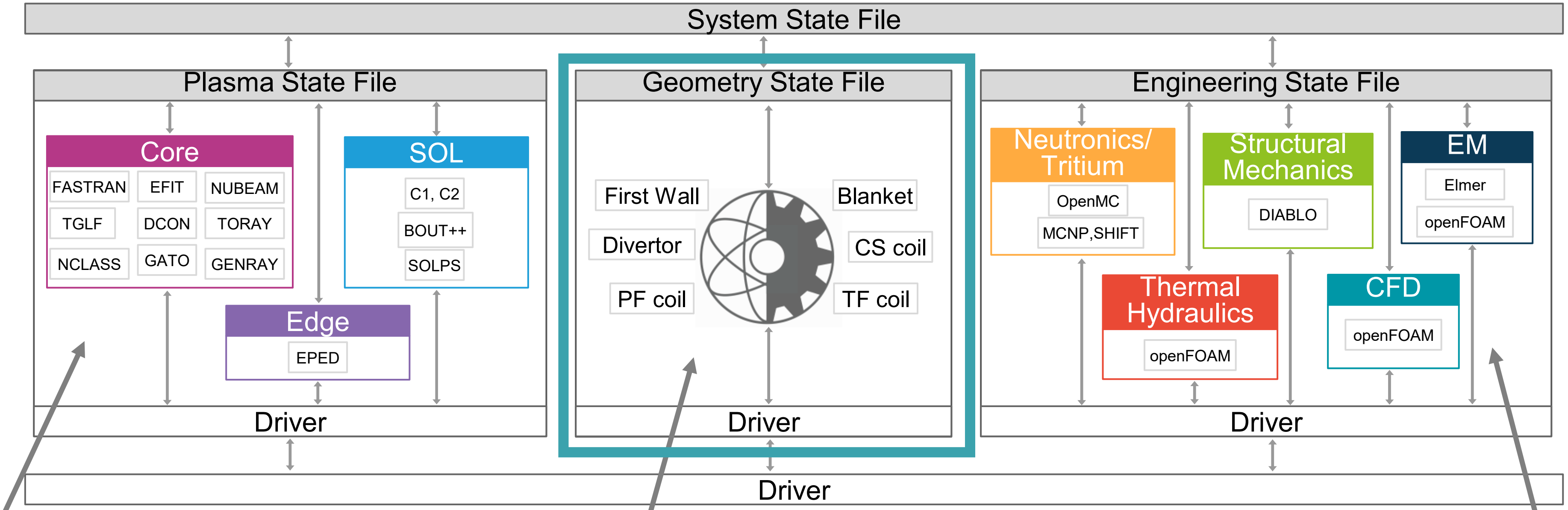
tritium concentration



FREDA's approach: flexible component-based framework & data structure

Framework & Workflow

Capable of integrating swappable modules with diverse CPU/GPU requirements



Fusion-Plasma

Parametric Geometry

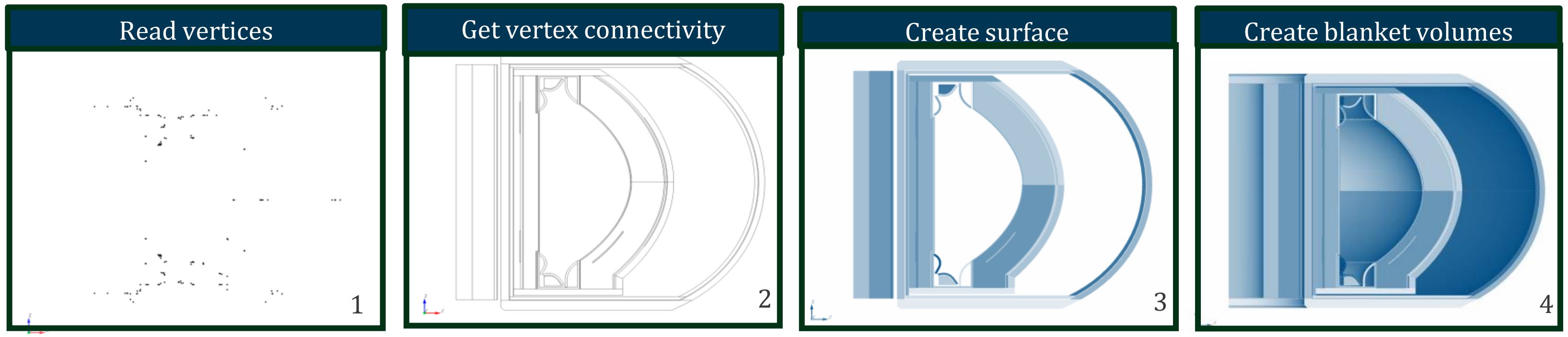
- Includes systems codes and parameterized geometry representation

Fusion-Engineering

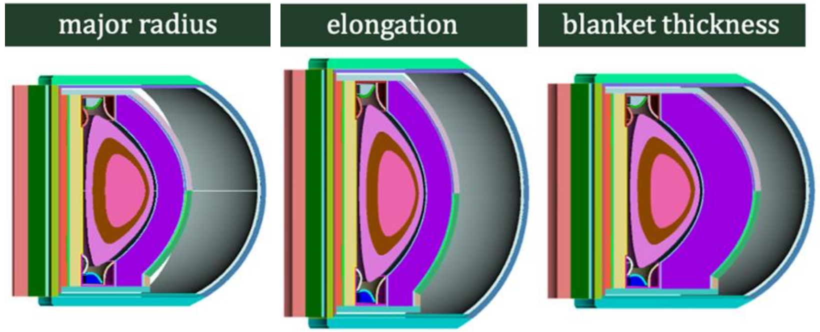
Parametrized Geometry Handling with TRACER tool

Borowiec Fusion Eng. and Design, 200 114159 (2024)

TRACER – READ: Generate parametrization from existing CAD



 Example transformations



- TRACER uses Cubit python API automated meshing for multiphysics
- Enables geometry defeaturing, material homogenization, single component/slice

Parametrized Geometry Handling with TRACER tool

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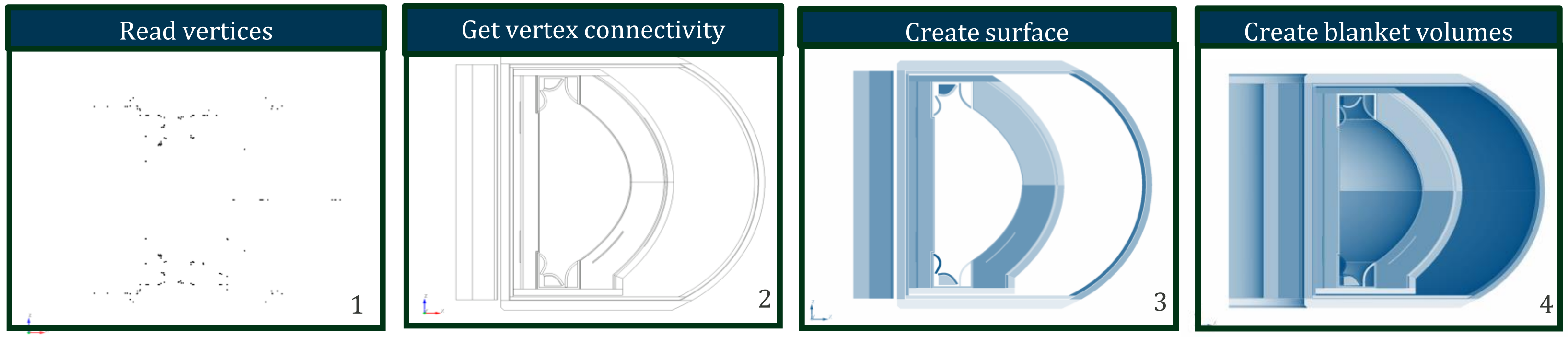
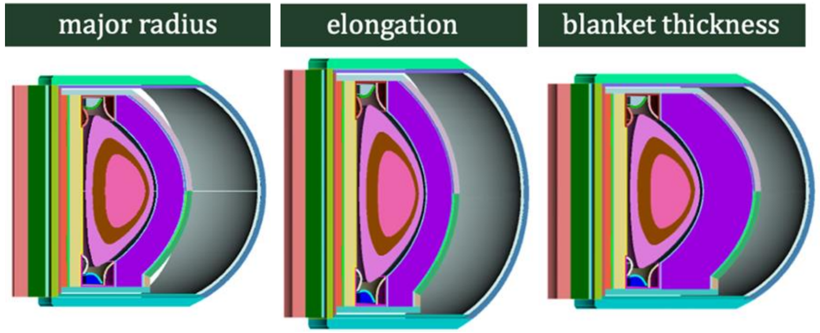


□ *Example transformations*



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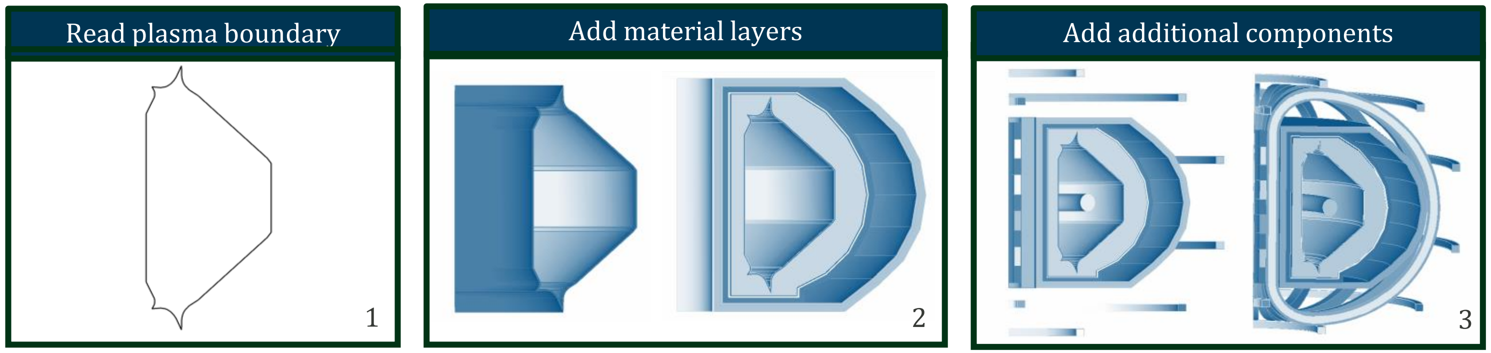
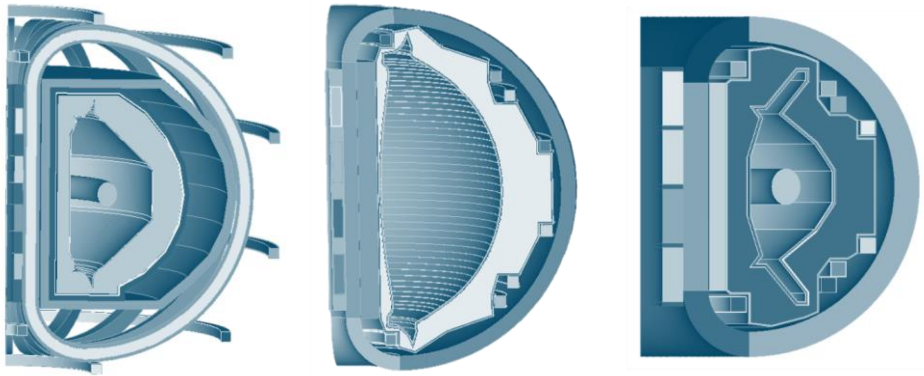
TRACER – BUILD: Create parametrized CAD from code

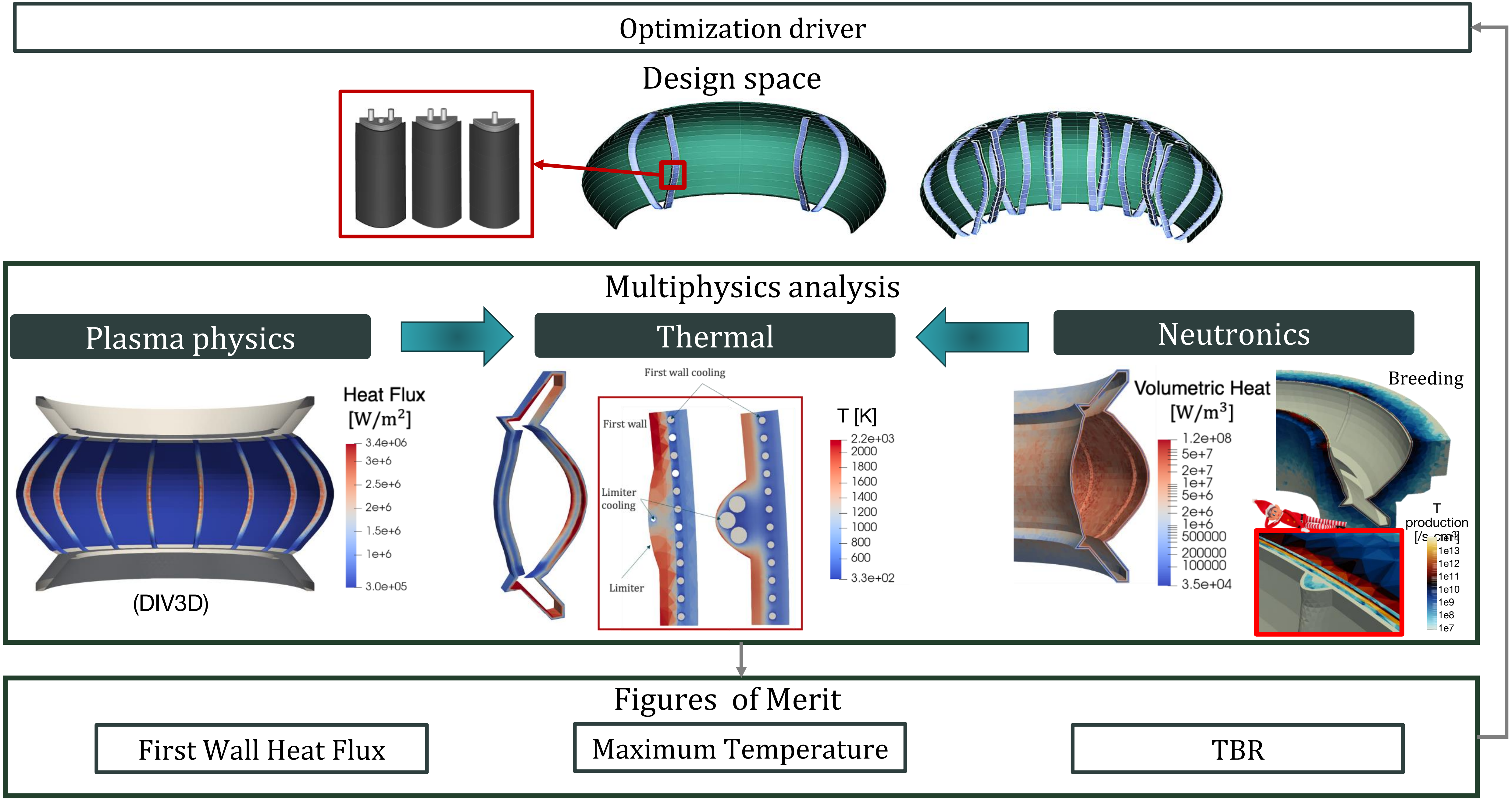


□ *Example first wall shape variations*



PF Coil locations determined
by optimization with FreeGS
[Hassan, IEEE Trans. on Plasma Sci., (submitted)]

Example Optimization: First Wall Protection Limiters



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Framework & Workflow
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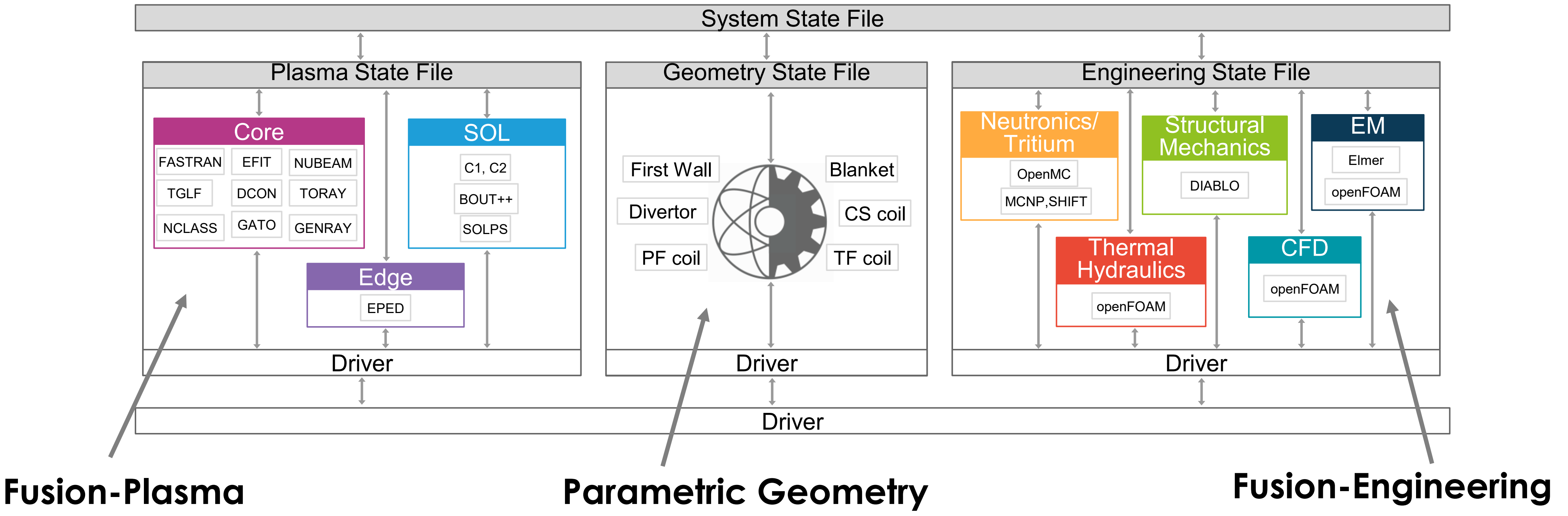
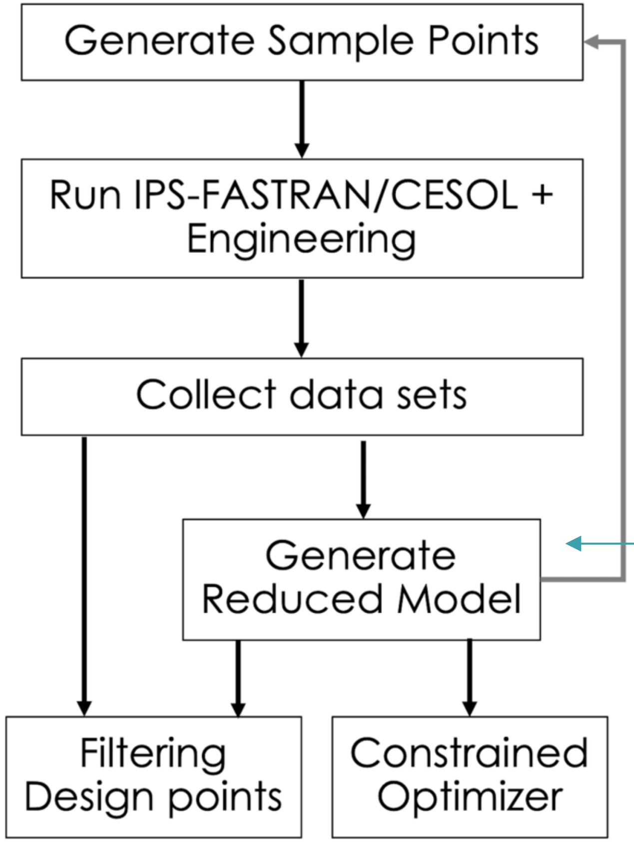
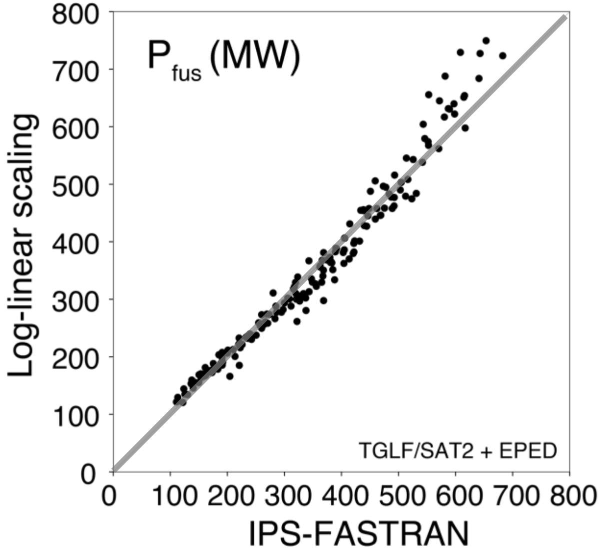


Example of large parameter space scan & optimization workflow

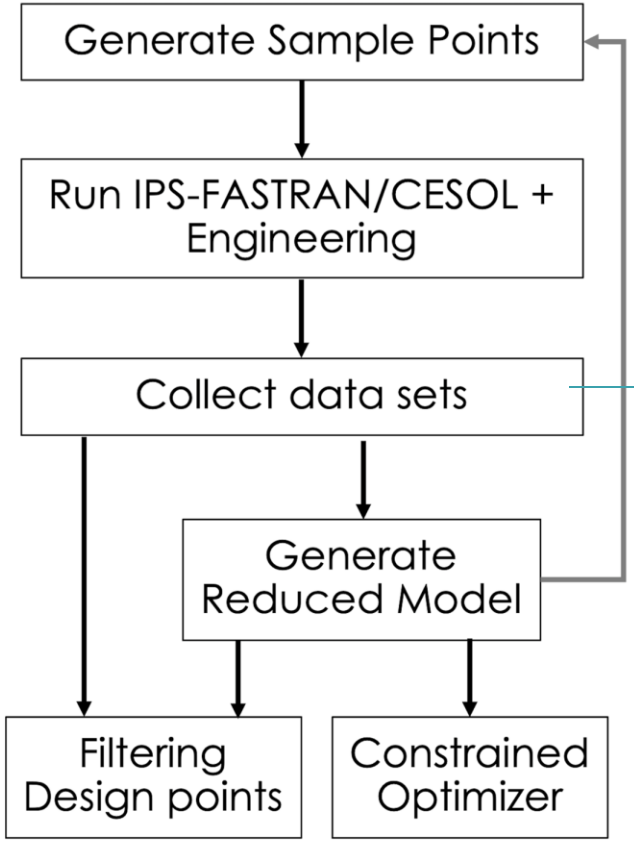


Includes Dakota: Supports a range of ML techniques including Log-linear regression, Gaussian Process, and Neural Network

Example of physics based reduced model fit of P_{fusion} (function of density, plasma current, H&CD power)

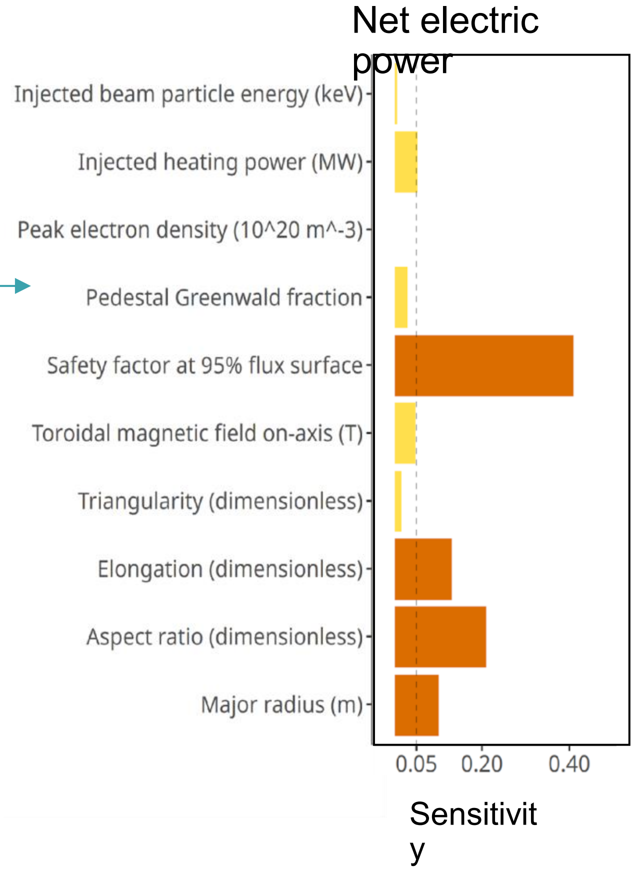


Framework now supports global sensitivity analysis & multi-fidelity UQ

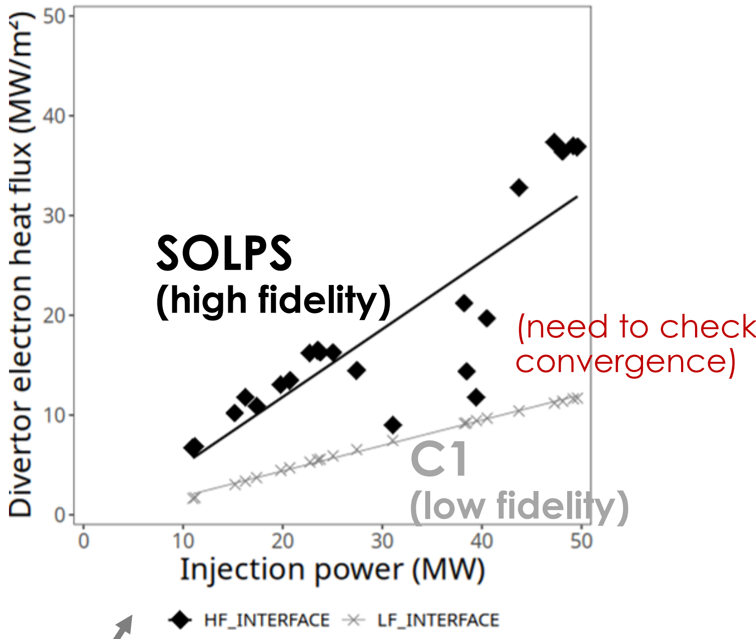


New!

Example GSA analysis



Multi-fidelity UQ strategically launches high fidelity runs

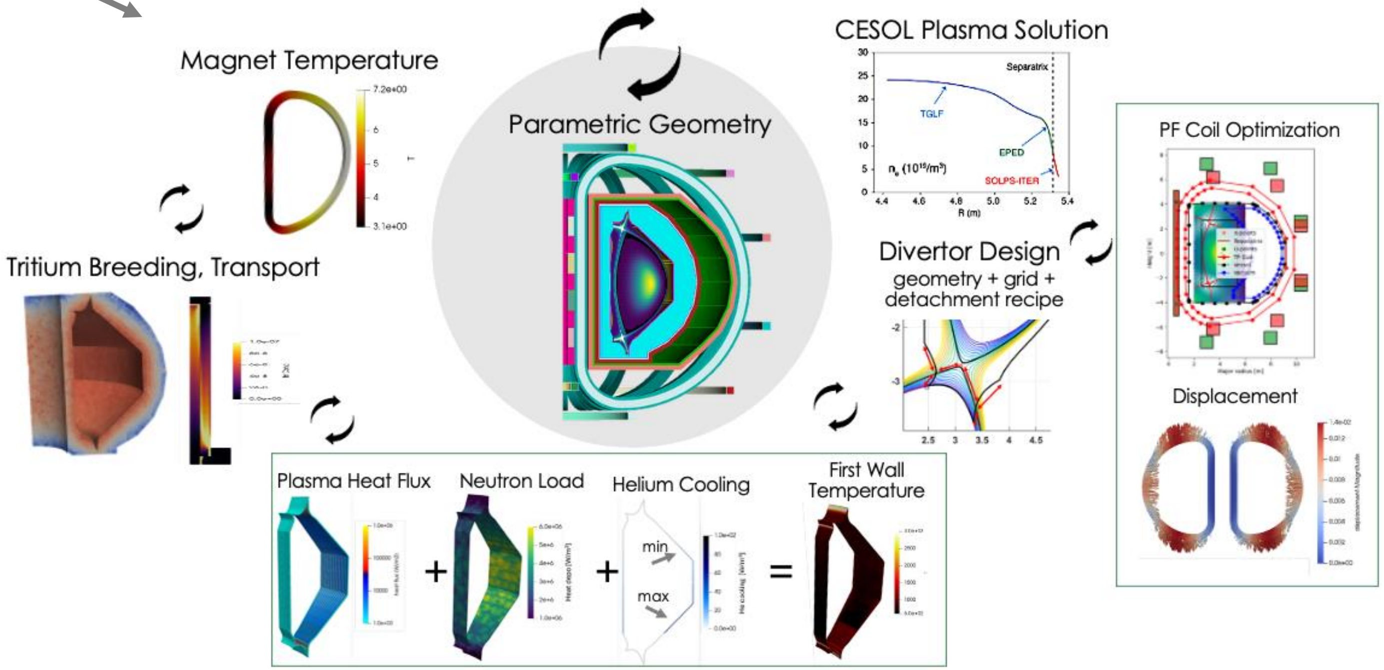


Use MFUQ to reduce variance, or can apply linear correction to lower fidelity model…

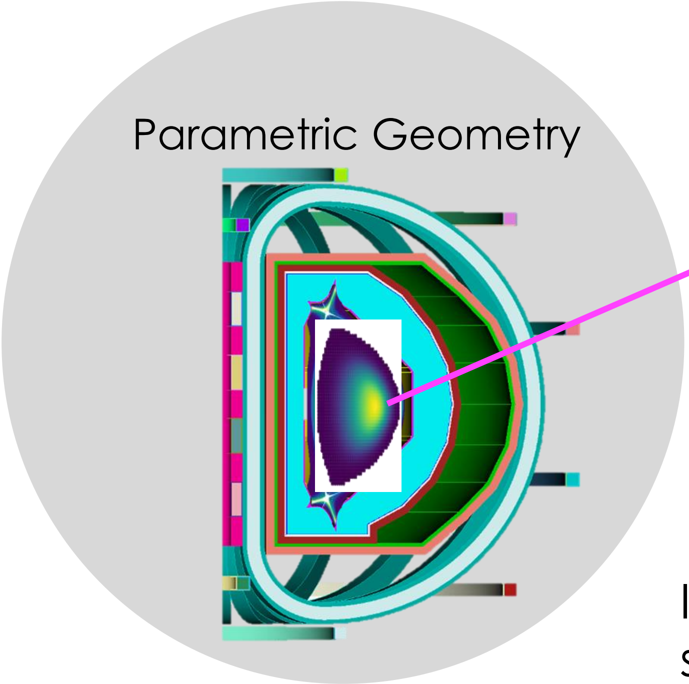
FREDA is supporting a number of efforts

- Delivered FY25 DOE/FES Theory & Simulation Performance Target report (next slides)
- Private efforts are using FREDA-IPS ensemble scans, parametric divertor tool (Tokamak Energy, KDEMO, Type One, Thea)
- FREDA-FERMI for Arpa-E project on nested pebble bed blanket
- Newly funded proposals (FIRE, tokamak research, LDRD)
- Smolentsev SciDAC shares CAT equilibria, divertor structure, and first wall geometry.
- Rapid surrogate model generation for AI/ML pulse simulator (De Pascuale)
- Students: grad (H. Wilson), SULI (A. Irvin), even high school

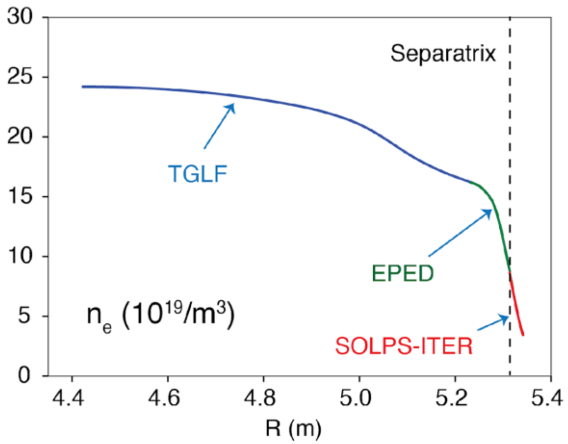
We practice on this example case:
Compact Advanced Tokamak with a DCLL-type blanket



Compact Advanced Tokamak Reactor: Plasma Feasibility



P_{net}=200 MWe Plasma Solution using CESOL



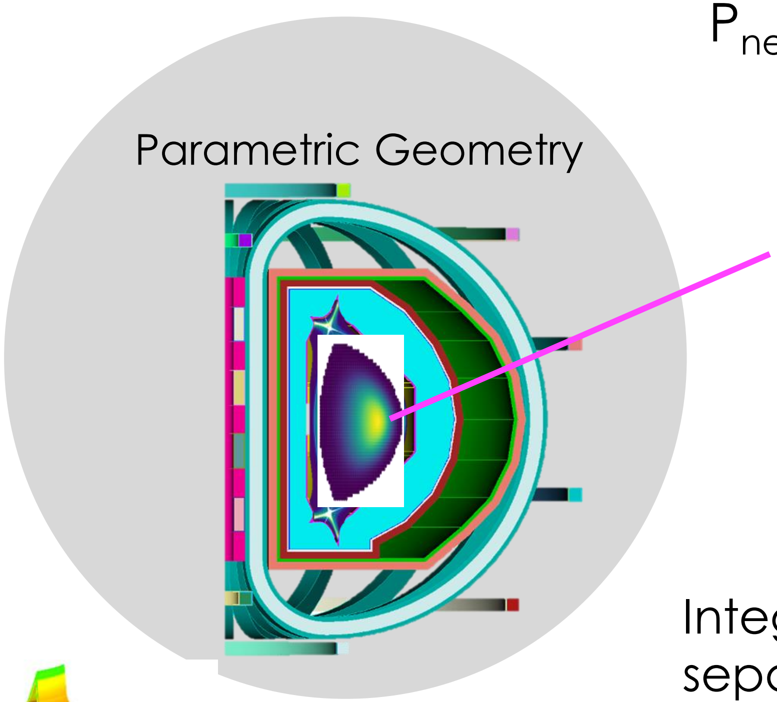
Integration matters: CESOL predicted separatrix density is higher than the EPED assumption of 1/4 ne_{ped}

- **CESOL predicts improved performance**

OAK RIDGE National Laboratory

Compact Advanced Tokamak Reactor: Plasma Feasibility

We couldn't find fully detached divertor with initial geometry; **need automation** for checking SOLPS/BOUT++ convergence and geometry iteration



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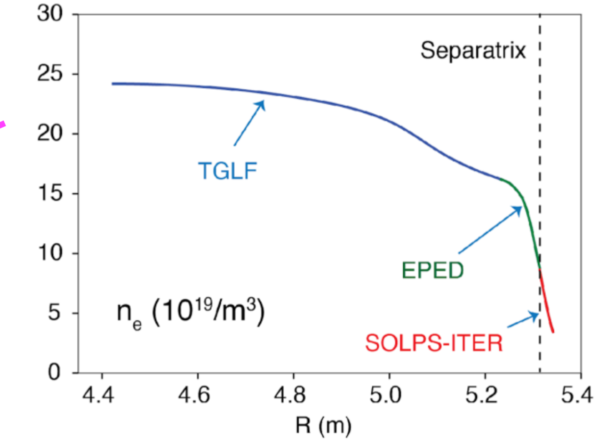

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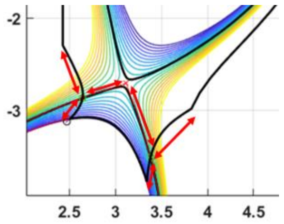
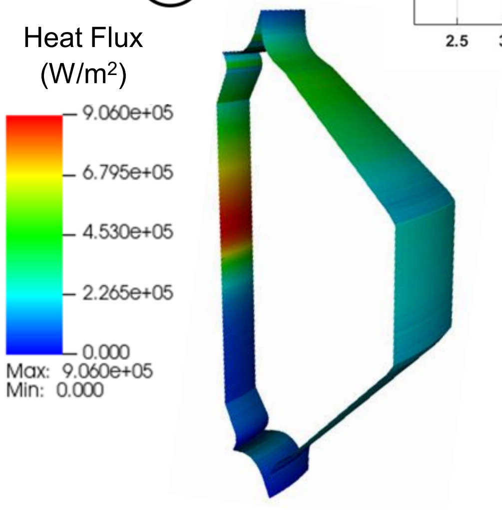
 CESOL predicts improved performance

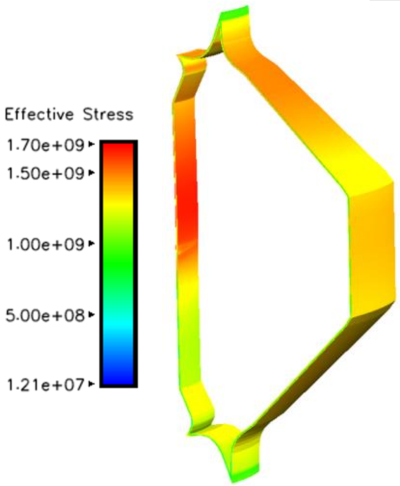
Divertor Design

geometry + grid + detachment recipe



Asymmetric detachment

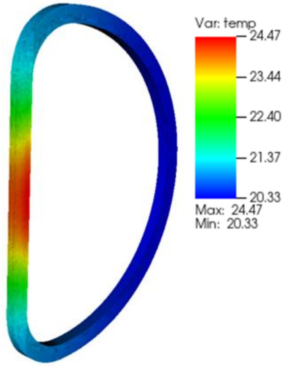


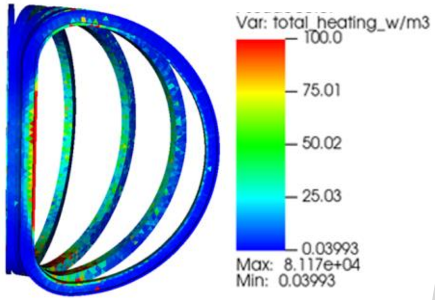


Thermal-stress on RAFM steel >1700 MPa, well above the expected yield stress of 400-600 MPa

Magnet Feasibility

Magnet cooling representation & analysis

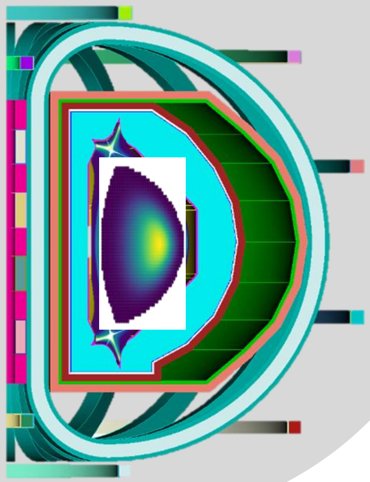




neutron heat deposition on magnet case

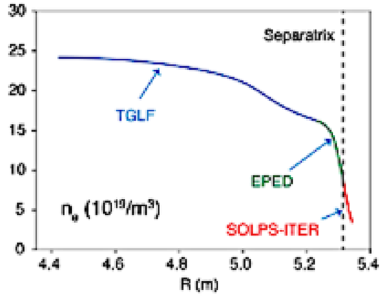
Heat extraction ~200 W per coil. Insulation is key; if thermal efficiency of the insulator surrounding the magnet coils was reduced from 99% to 90%, temperature increased >200 K

Parametric Geometry



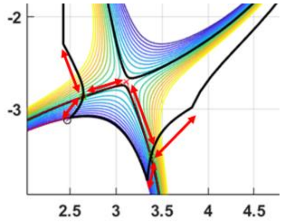
Magnet stress analysis

Plasma Solution

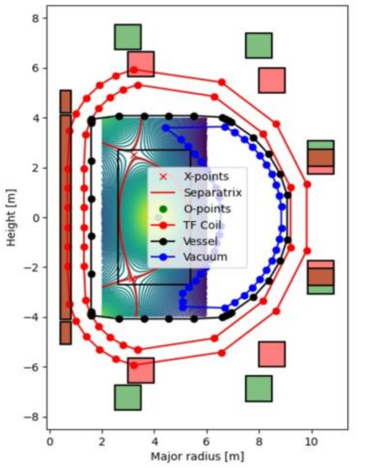


Divertor Design

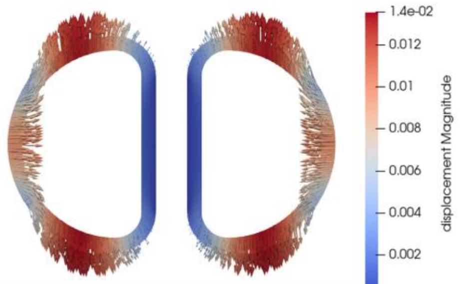
geometry + grid + detachment recipe



PF Coil Optimization



Displacement



- Will PF coils create the shape for the whole discharge within stress, current limits? ✓
- Do TF coils experience too much stress, displacement? 14 mm vertical displacement

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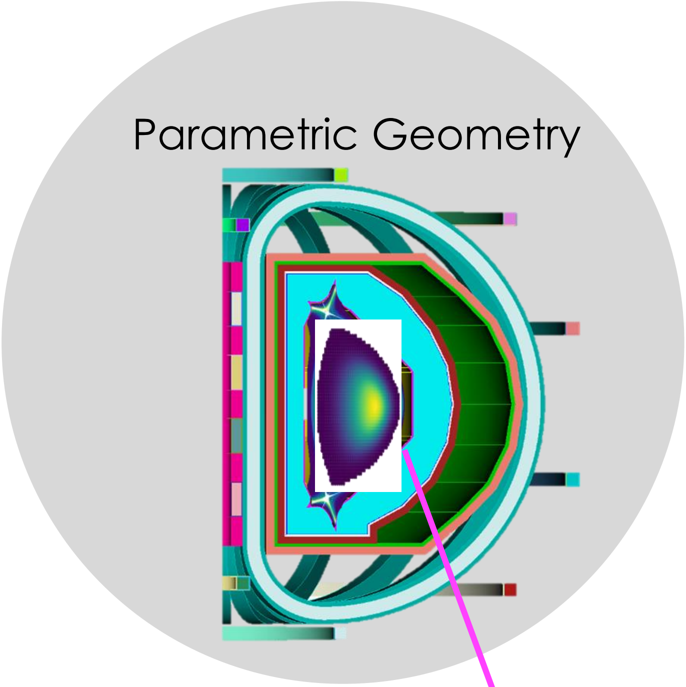
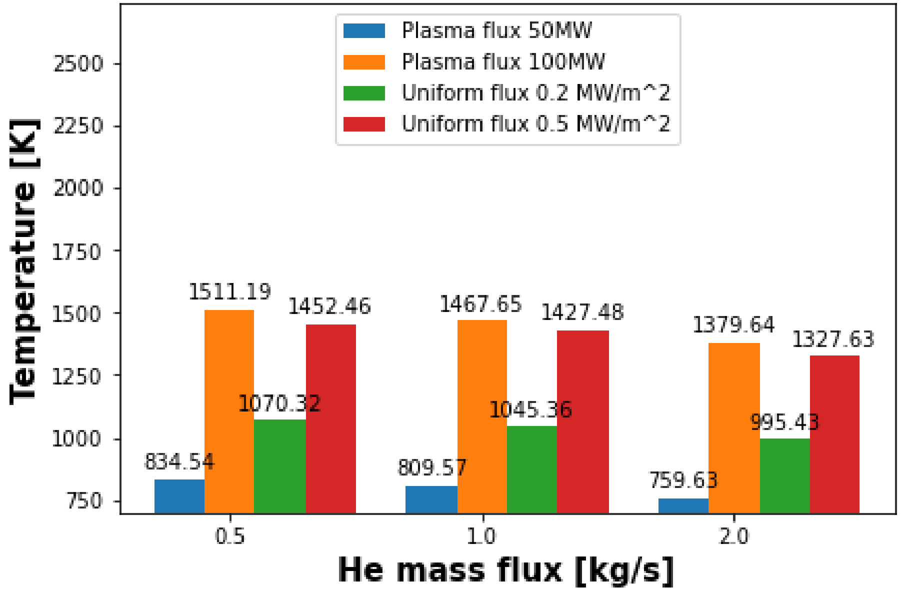
PFC heat handling feasibility

PFC temperature check
Plasma predicts:
1-20 kW/m2 first wall
15 MW/m2 divertor
Engineering calculates:
760K first wall
...3000K divertor

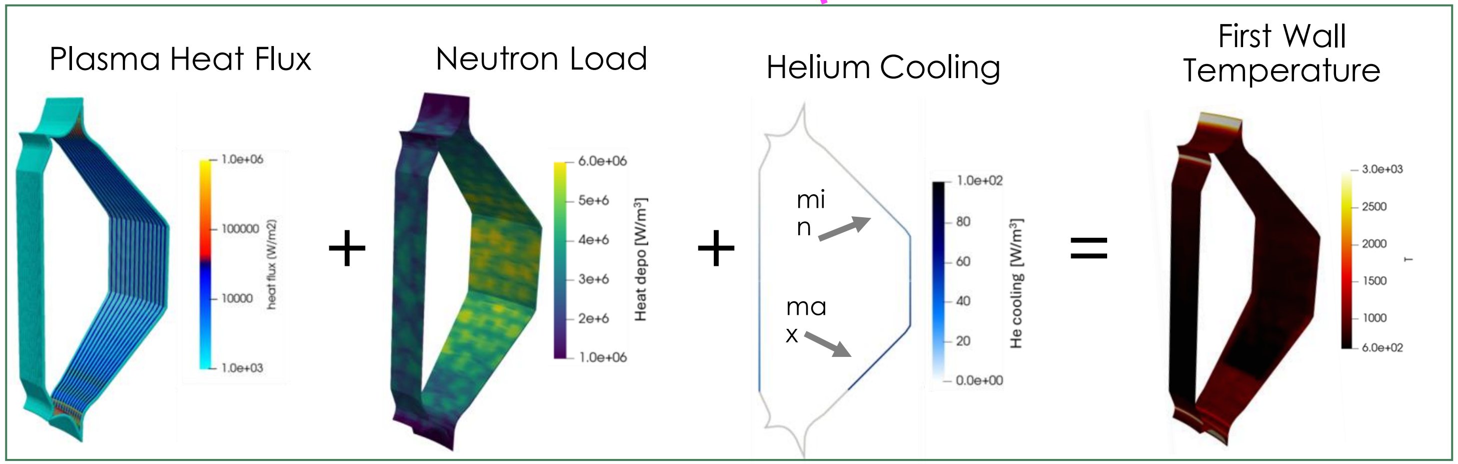
- Change the plasma?
- Engineer better heat transfer?



First wall is too hot



scanned He flow rate



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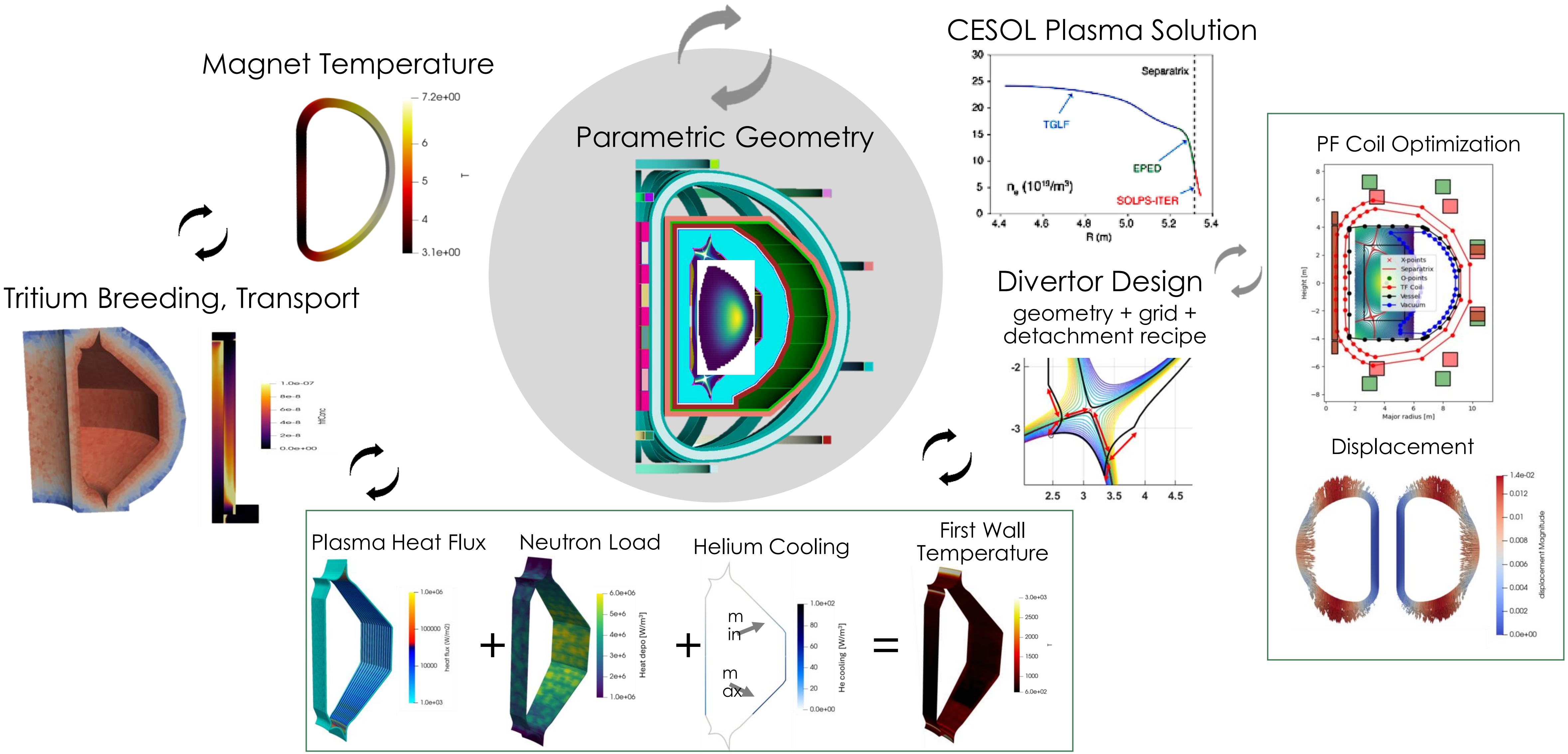
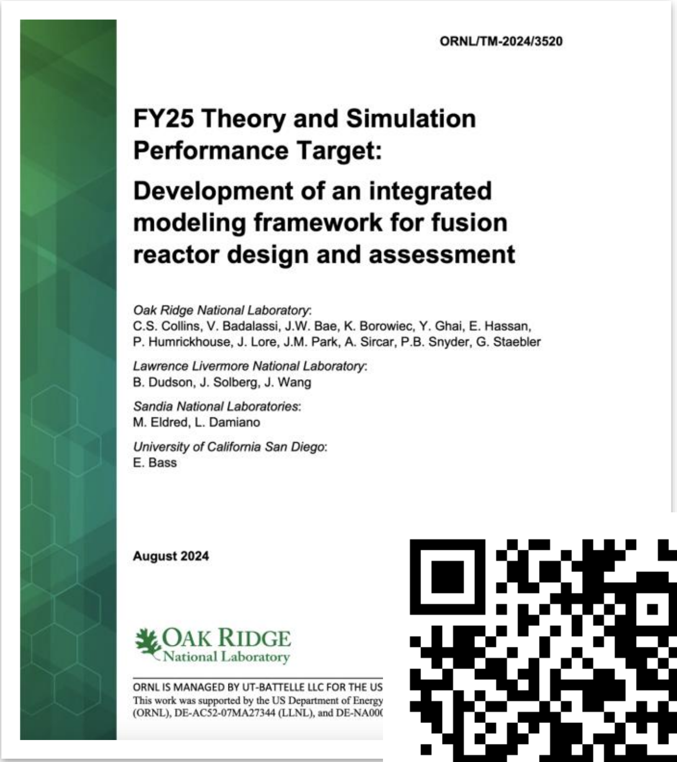
FY26 FREDA goal: iteration to find a steady-state AT reactor solution



utilize plasma loading for thermal analysis

Summary: Fusion Reactor Design and Assessment (FREDA) SciDAC connects plasma+engineering modeling for **self-consistent, multi-fidelity, iterative optimization**

- Initial focus: connecting plasma to PFCs for engineering analysis
- **FY25 TSPT report available**
  - It is a major challenge to find suitable balance between the plasma solution, wall and divertor loads, neutron heating, and practical limits of PFC cooling.
- FREDA future development directions
  - Incorporation of materials models (SLAG, cracking)
  - Transient plasma+engineering
  - Provenance tracking


ORNL/TM-2024/3520

FY25 Theory and Simulation Performance Target:

Development of an integrated modeling framework for fusion reactor design and assessment

Oak Ridge National Laboratory:
C.S. Collins, V. Badalassi, J.W. Bae, K. Borowiec, Y. Ghai, E. Hassan, P. Humrickhouse, J. Lore, J.M. Park, A. Sircar, P.B. Snyder, G. Staebler

Lawrence Livermore National Laboratory:
B. Dudson, J. Solberg, J. Wang

Sandia National Laboratories:
M. Eldred, L. Damiano

University of California San Diego:
E. Bass

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OAK RIDGE National Laboratory

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Full report here

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