FUSE: A Modern Framework for Integrated Fusion Simulations

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fuse

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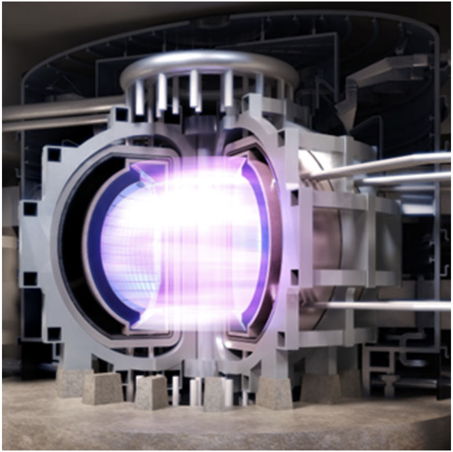
GA is pursuing integrated FPP design based on strongly shaped steady-state advanced tokamak (AT) concept

Commercial viability via high power density steady-state operations

- **High β_t:** making the most efficient use of the expensive superconducting magnets
- **High β_p:** resulting in high bootstrap fraction, and reducing the auxiliary current drive demands
- **Reduced plasma current:** minimize risk of disruptions



AT plasma scenarios require:

- accurate integrated simulations
- advanced control methods

Where were we:

Requirements $\rightarrow$ 0D Scoping $\rightarrow$ 1.5D Stationary $\rightarrow$ Coils $\rightarrow$ HC&D $\rightarrow$ 1.5D Time $\rightarrow$ Control $\rightarrow$ CAD $\rightarrow$ FEM $\rightarrow$ Nuclear $\rightarrow$ ...

Took a team of experts $\sim$ one year to produce a conceptual design

- Design choices made early, with simple models and limited information
- Sub-systems are developed by different groups of people, under different assumptions
- Integration requires coordination among experts, which is slow/costly

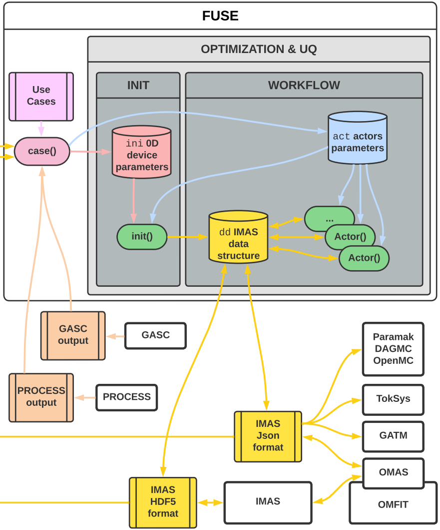
Throughput limited by humans in-the-loop!

Need for a new approach: FUSE

- **Goals**
  - Fast! Throughput to be limited by compute resources, not humans
  - Minimize software maintenance and avoid tech debt
  - Eventually support –ALL– modeling needs
    Scoping, high-fid, stationary, time dep., control, predictive, UQ, exp analyses, ...
  - Evaluate wildly different ideas on same footing
  - Provide to different physics and engineering teams a unified integrated representation of the design (single source of truth)
- **How?**
  - Developed from the ground-up (framework and models) based on GA modeling expertise
    OMFIT, OMAS, STEP, TGYRO, TGLF-NN, EPED-NN, EFIT, TokSys, GASC, GATM, ...
  - Built around ITER IMAS ontology
  - Fidelity hierarchy of tightly (or loosely) coupled models
  - All in one language: Julia (similar to Python yet fast as C/FORTRAN)

High-level view of the FUSE modeling environment

- Physics/engineering *actors*, all operate around (a modified version of) the IMAS data structure
- Data structure can be initialized from 0D parameters
- Everything is machine agnostic, comes with different use-cases (DIII-D, ITER, DEMO, DTT, SPARC, ARC, GA-FPP, ...)
- Use of IMAS maximizes cross-interoperability with existing tools



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Powered by a turbo-charged data structure

"Smart data structures and dumb code works a lot better than the other way around." – *Eric S. Raymond, "The Cathedral and the Bazaar"*

- **Extends IMAS IDSs** to support reactor design

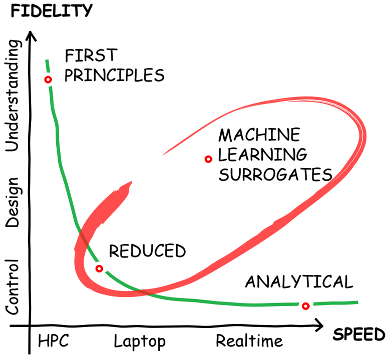
  `balance_of_plant, blanket, build, costing, neutronics, requirements, solid_mechanics, stability`
- **Dynamically evaluates** derived quantities
  - Ensures data consistency
  - Enables true plug & play of different models
- Designed to easily and efficiently handle large **time dependent** simulations
- Provides contextual, composable **plots** with multiple backends
- **Fast numerical efficiency** thanks to Julia

Whole fidelity spectrum is supported, but generally try to balance fidelity with speed and use ML when advantageous

- **Medium-fidelity benefits**:
  - Balance of computational efficiency and intricate detail
  - Ideal for understanding complex system dynamics
  - Rapid yet meaningful design optimization

- **Using ML surrogates**:
  - Speed of analytical models with accuracy of high-fidelity simulations
  - Perfect for rapid design iterations

- **Uniform fidelity**:
  - Models fidelity commensurate to simulation input uncertainties

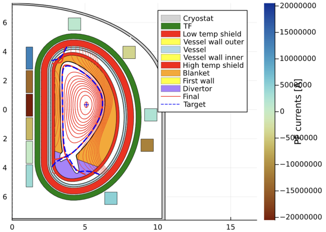


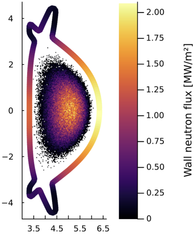
New reduced models and ML surrogates being built into FUSE to support GA FPP design

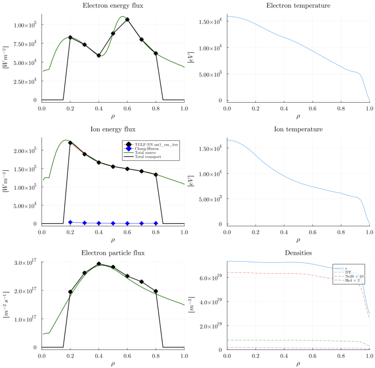
FUSE models from the plasma core to the site boundary

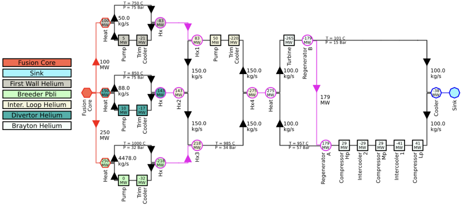
Core, Pedestal, SOL, HC&D, Build, Divertors, Coils, Neutronics, Blankets, BOP, Costing

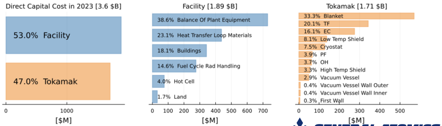
Time depends on models used, but a typical whole facility sim ~ 1 min











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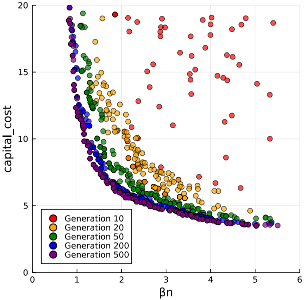
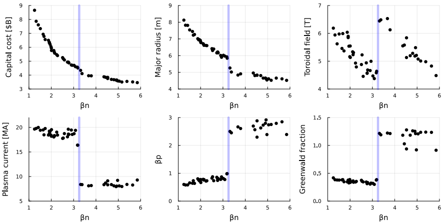
FUSE provides a robust workflow for deep design exploration

Rely on **Multi-objective optimization** to balance competing objectives:

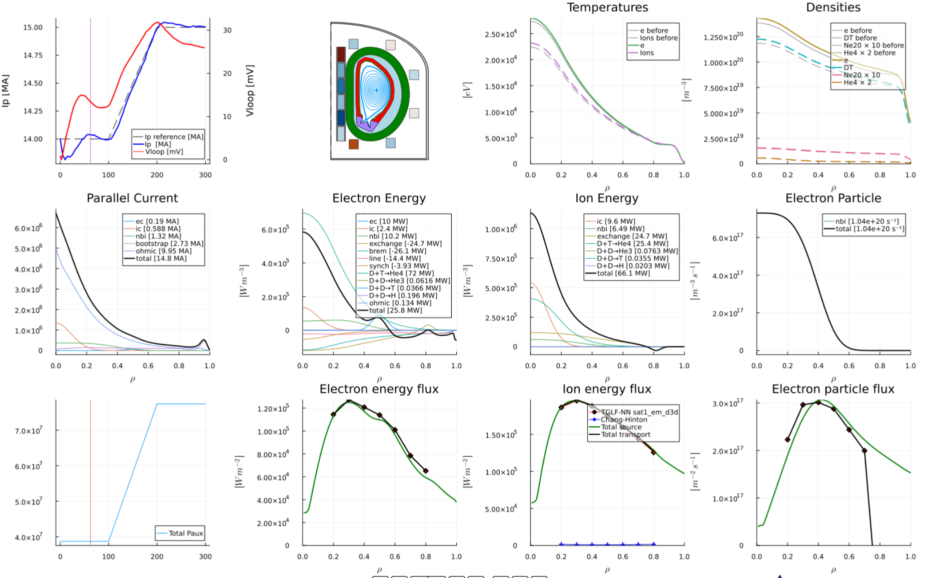
- MOOPT **genetic algorithm** guides solution towards the Pareto front
- Illustrates **trade-offs** and highlights **complex system dynamics**
- Helps **select designs** aligning with different stakeholder priorities (engineers, investors, policymakers,...)
- **Scalable parallel execution** allows running 100k+ cases in few hours on small cluster



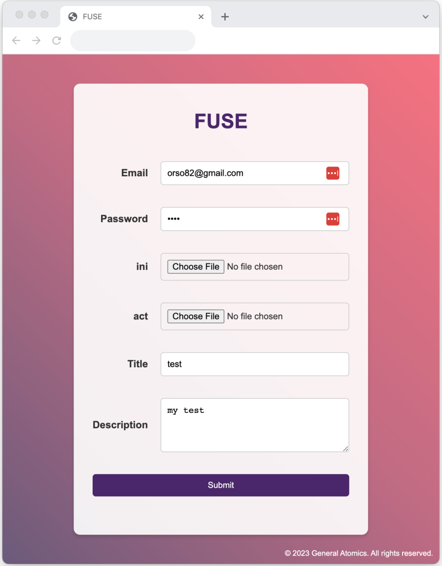


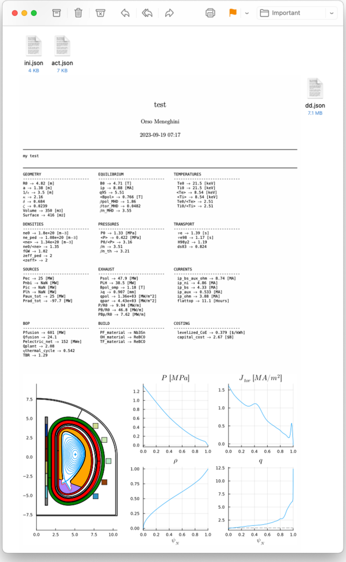
Recent focus has been on time dependent simulations with the goal of enabling rapid and effective control design

$\sim 30s$ per time-slice on a laptop, implicit time stepping



FUSE portal and web API are under development to eventually enable community use





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Conclusions

- FUSE is a modern modeling framework, built from the ground up
  - Based on the ITER IMAS ontology
  - Leverages machine learning models for enhanced performance
  - Supports fidelity spectrum, yet focus on balancing fidelity and speed
  - Utilizes the Julia language for efficiency and speed
- With FUSE, GA is leading the way in pursuing integrated FPP design based on the advanced tokamak (AT) concept
  - The traditional approach of conceptual design is slow and costly
  - FUSE aims to optimize the process by minimizing human bottlenecks
  - Future endeavors will focus on further expanding the capabilities of FUSE and enhancing its integration with control systems
- Rapid medium-fidelity integrated simulations that are IMAS compatible could be applied cross-validate ITER IMAS workflows
  - Scenario and pulse design
  - Plant model for testing and development of control algorithms