FUSE: digital twin for tokamak fusion power plant design and operations

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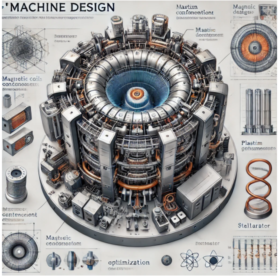
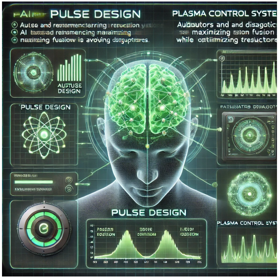
APS DPP
Oct 7th 2024

The BIG THREE digital twins applications of fusion plasmas have noticeable overlaps

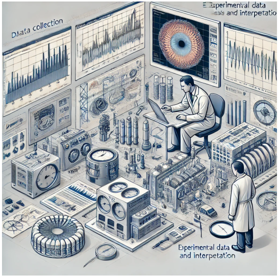
1
MACHINE DESIGN



2
PULSE DESIGN



3
DATA ANALYSIS



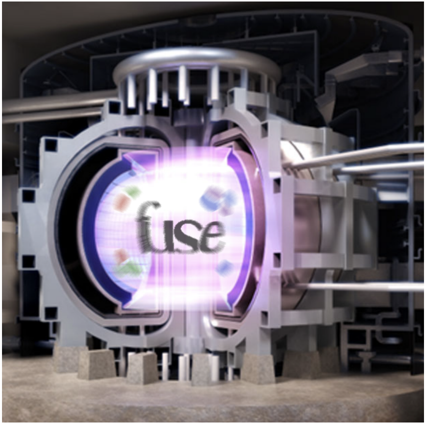
- Same theory-based models
- Same act./diag. models
- Same machine-agnosticity
- Same integrated workflows
- Same data structures
- Same need for speed, always!

Can we build a unified digital twin platform that serves all purposes?

FUsion Synthesis Engine framework was developed from the ground-up to enable such unified digital twin vision

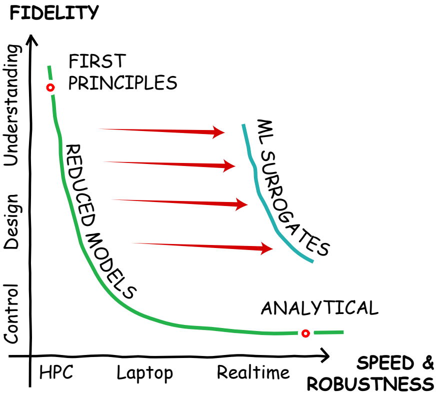
1. First to support of **GA's own FPP design**
2. now focusing on **time dependence and pulse design**
3. with future goal of supporting **integrated data analysis**

- Applying **lessons learned** from GA modeling expertise
  OMFIT, OMAS, STEP, TGYRO, TGLF-NN, EPED-NN, EFIT-AI, TokSys, GASC, ...
- All in one language: **Julia**
  - High-level like Python
  - As fast as C
  - Auto-differentiable
- Built upon the **ITER IMAS** ontology to enable
  - Maximum **interoperability**
  - **Fidelity hierarchy**



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

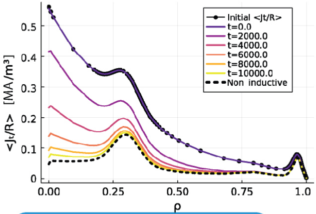
- Want to **capture realistic system dynamics**
  1. Whenever possible, use of **physics-based** (reduced) models
  2. **Sufficient fidelity** to get interfaces between subsystems about right, so higher-fidelity simulations do not upend couplings
- While enabling **rapid design iterations**
  1. **Julia** for high performance
  2. **Tightly coupling** of models
  3. Break efficiency-fidelity tradeoff with **ML surrogates**



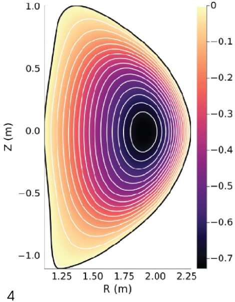
FUSE models span from the plasma core to the site boundary

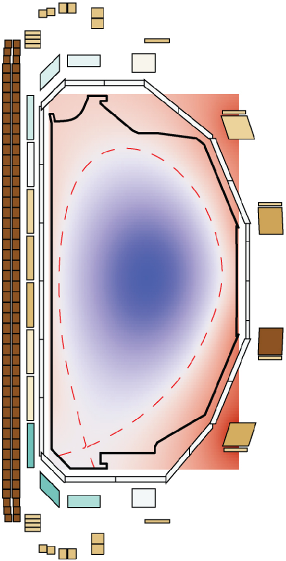
FUSE models span from the plasma core to the site boundary

Current evolution



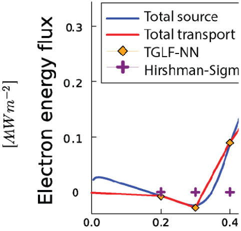
Fixed boundary equilibrium



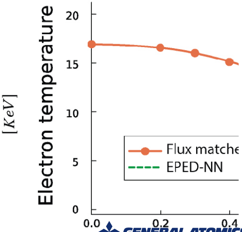


Free boundary equilibrium w/ coil + passive couplings

Flux-Matching tr



Core-pedestal co



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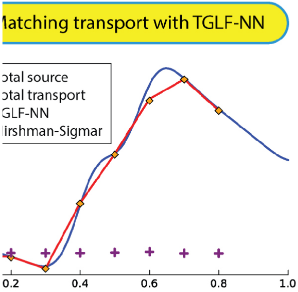
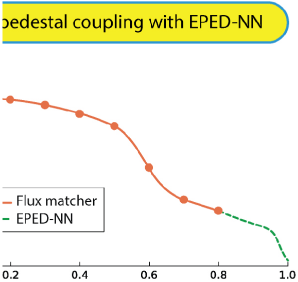
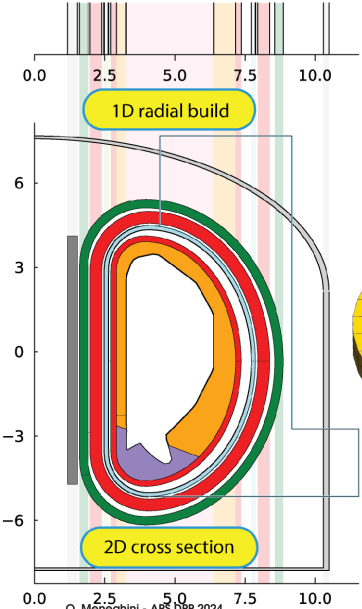
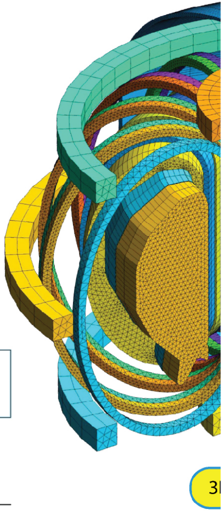
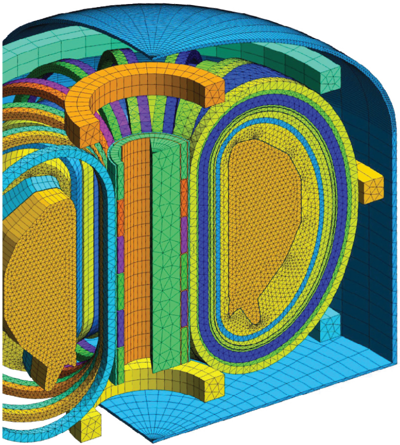




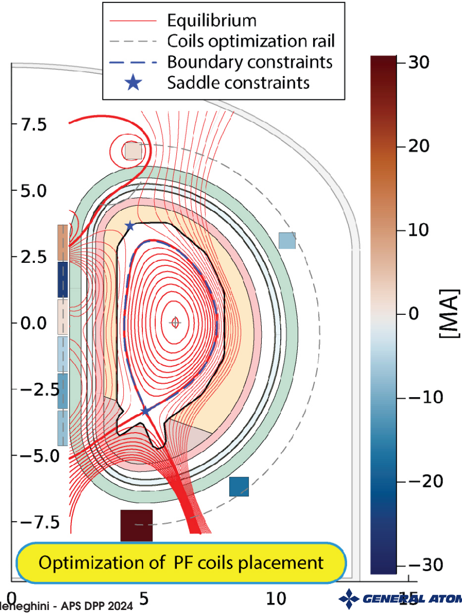




FUSE models span from the plasma core to the site boundary

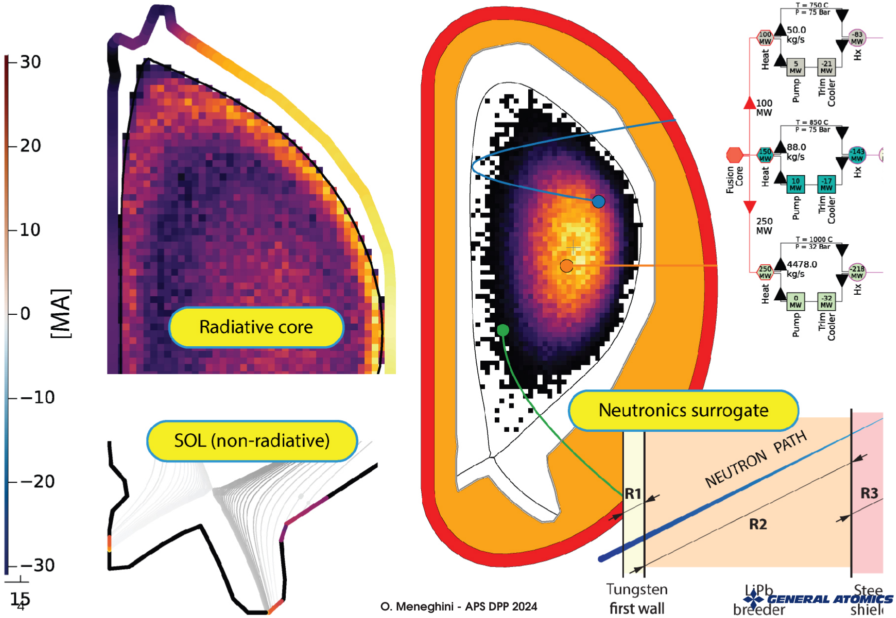


3D CAD and mesh



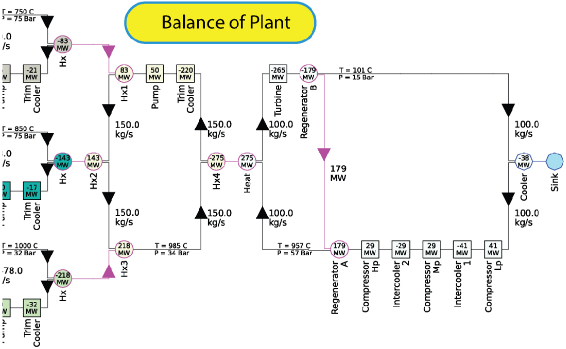
Optimization of PF coils placement

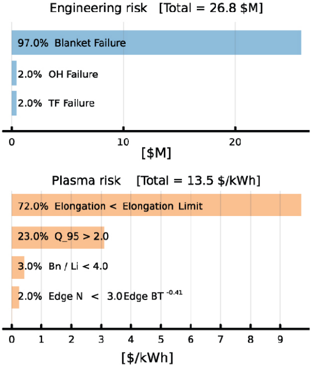
FUSE models span from the plasma core to the site boundary



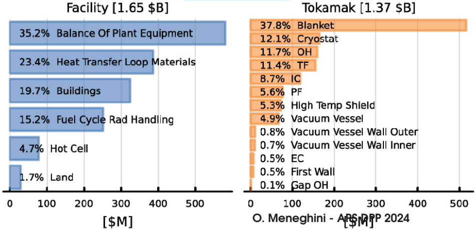
FUSE models span from the plasma core to the site boundary

Balance of Plant

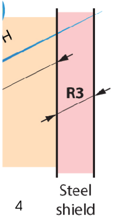




Costing



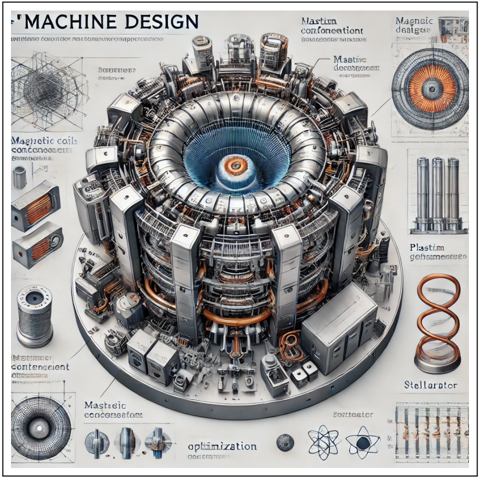
Risk



GENERAL ATOMICS

From idea to pre-conceptual designs in ~~months~~ minutes and evaluate wildly different concepts on same footing

1
MACHINE DESIGN



FUSE uses a multi-objective constrained optimization workflow to enable design explorations and trade studies

OBJECTIVES

1. min capital cost
2. max q_{95}

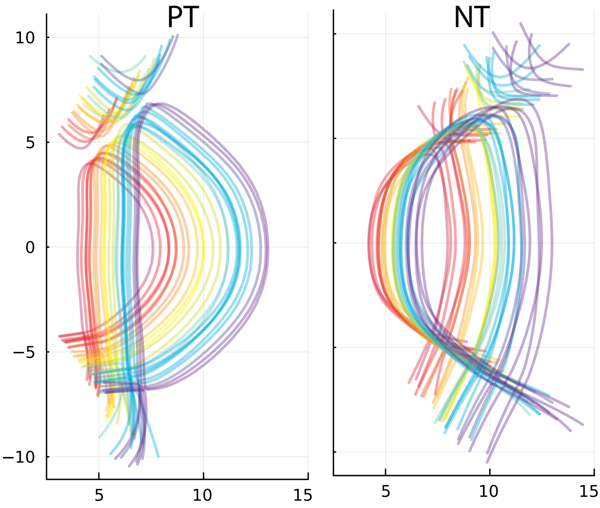
CONSTRAINTS

- $P_{\text{electric}} = 250 \pm 50$ MW
- flattop $= 1.0 \pm 0.1$ (h)
- TBR $= 1.1 \pm 0.1$
- $P_{\text{sol}}/P_{\text{LH}} > 1.1$ (for $+\delta$)
- $P_{\text{sol}}/R < 15$ (MW/m)

ACTUATORS

- $5.0 < R_0 < 10.0$ (m)
- $3.0 < B_0 < 15.0$ (T)
- $4.0 < I_p < 22$ (MA)
- $1.5 < \kappa < 2.2$
- $|\delta| < 0.7$
- $1.1 < z_{\text{eff,ped}} < 3.5$
- $0.4 < f_{\text{GW,ped}} < 0.85$
- Impurity: Ne, Ar, Kr
- $0 < P_{\text{EC}} < 100$ (MW)
- $0 < \rho_{\text{EC}} < 0.9$
- $0 < P_{\text{NB}} < 50$ (MW)

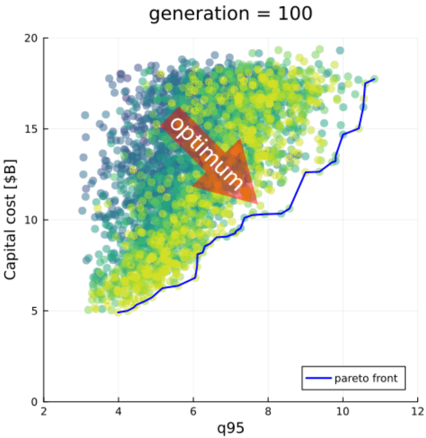
eg. Trade study for positive-δ VS negative-δ FPP



FUSE multi-objective constrained optimization workflow enables designs exploration and trade studies

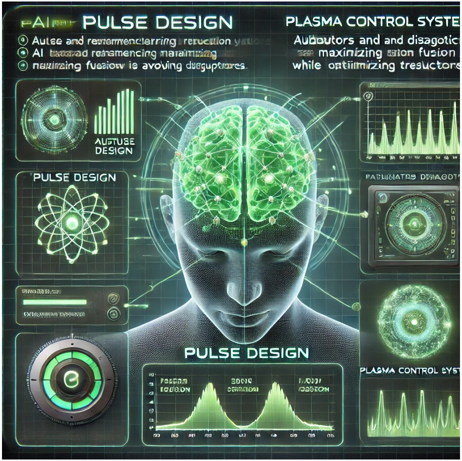
A **Genetic algorithm** steers solution towards the **Pareto front**

- **Each point is a full machine design** that takes ~ 1 min to run
- Highlights **complex system dynamics** and exposes **objectives trade-offs**
- Helps different stakeholders **identify a target design**
  (scientists, investors, policymakers,...)
- **Scalable parallel execution** runs 10k+ cases in few hours on small cluster



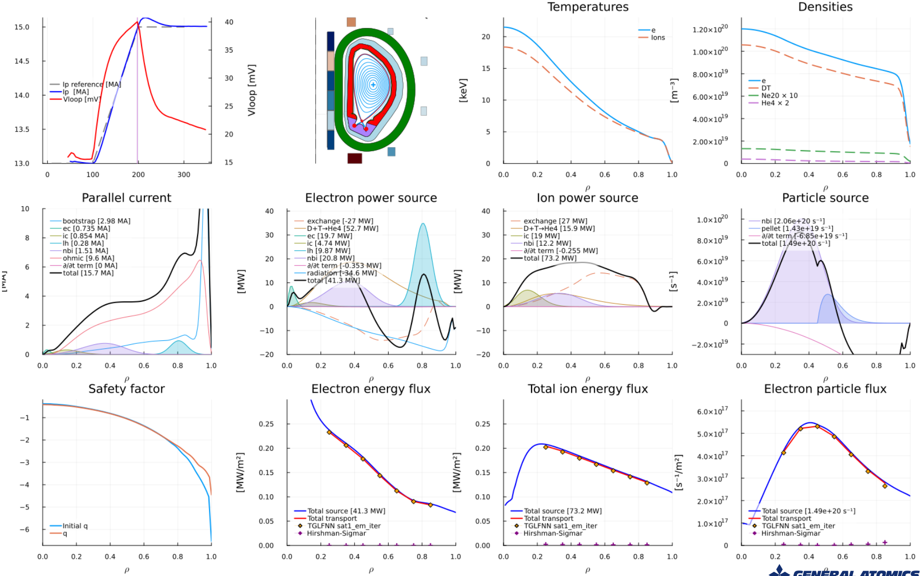
Time-dependent capabilities that enable fast, high-fidelity, and machine-agnostic pulse design with PCS integration

2
PULSE DESIGN



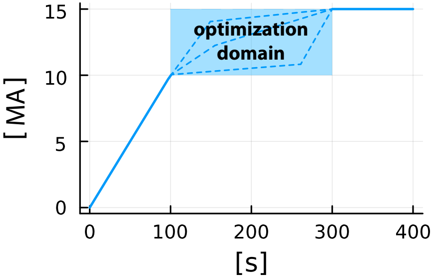
By leveraging its ML models FUSE can efficiently perform feed-forward high-fidelity time-dependent simulation

300 s simulation of ITER discharge in 600 s on a laptop (eq. solve is the main bottleneck)

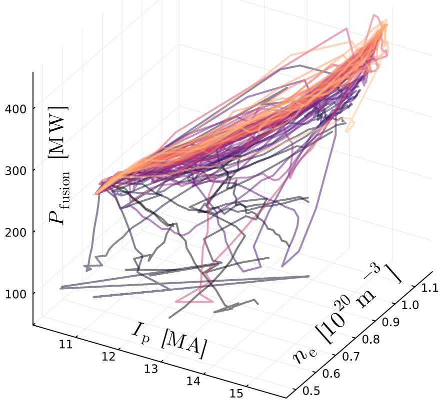


Combining time-dependence with multi-objective optimization enables pulse design

eg. Find optimal Ip and n_e ramp rates to max ITER fusion energy



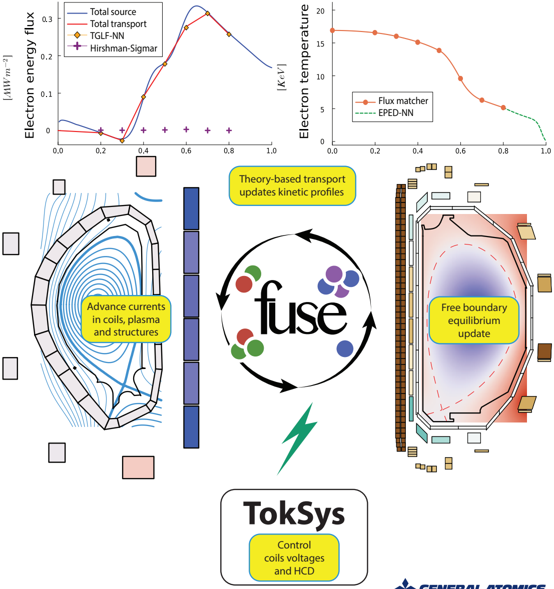
- Define optimization domains for multiple time traces
- Support for multiple time-depedent objectives
- Take full advantage of HPC



Best solutions keeps plasma sufficiently hot to sustain fusion throughout

A new Grad Hogan solver is under development to model plasma dynamics in combination with control system

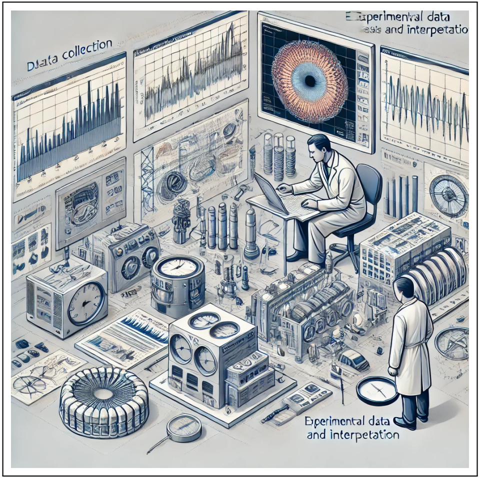
- Working on integration:
  1. Free-boundary solver
  2. Theory-based transport
  3. Inductive coupling of plasma, PF coils, and conducting structures
- Co-simulation w/ TokSys
  - Via Redis technology $\sim$ 0.2 ms latency
- Equilibrium acceleration via ML (like EFIT-AI) will enable use for between shot planning



GENERAL ATOMICS

Models fast enough to inform operators between-shots and enable Bayesian integrated data analysis

3
DATA ANALYSIS



FUSE has the potential to address key bottlenecks and limitations of today's data analyses techniques

Long experience automating data analyses on DIII-D and other tokamaks

eg. Kinetic equilibrium reconstructions on DIII-D:

	2013	2017	2019	2023
Manual	**KineticEFIT**	**KineticEFITtime**	**CAKE**	**CAKE @ NERSC**
Days	Hour	Hours	Hour	20 minutes
1 timeslice	1 timeslice	10 timeslices	50 timeslices	50 timeslices

Three main limitations:

1. Reaching speed limit with legacy serial codes and loose couplings
2. Machine specific workflows
3. Mostly classical data analysis (IDA being developed)

FUSE can address all of these:

1. Faster, with tight coupling and higher degree of parallelism
2. IMAS-based and machine-agnostic
3. Fast ML-based forward models in Bayesian data analysis

Conclusion: FUSE is an adaptable framework, able to satisfy broad range of plasma digital twin needs

Roadmap:

1. **MACHINE DESIGN** - well developed
   - Can rapidly go from concept to pre-conceptual design
   - Will continue to include more physics and subsystems

2. **PULSE DESIGN** - in development
   - Development of Grad Hogan solver with control system integration is near complete
   - To support development of control algorithms in data-poor environments

3. **DATA ANALYSIS** - to be developed
   - Will leverage ML models to enable between-shots Bayesian data analyses
   - To inform operators and enable high-quality statistical model validations

FUSE is now open-source, enabling collaboration on a digital twin platform for next-generation fusion systems

A complete fusion modeling ecosystem in Julia

- 25+ packages
- 200K+ lines of Julia code
- Regression tested
- Documented
- Preprint on Arxiv

Apache 2.0 licensed

- Free for anyone to use
- Supports commercial use

1st community code camp

- Dec 9th-13th
- In person @ General Atomics
- 40 seats max, register! ⟶

http://fuse.help