The FUSE framework and its use for fusion power plant design optimization

O. Meneghini, T. Slendebroek, B.C. Lyons, J. McClenaghan, T.F. Neiser, A. Ghiozzi, J. Harvey, D. Weisberg, L. Stagner, J. Guterl, A. Zalzali, T. Cote, N. Shi, G. Dose, K. McLaughlin, S.P. Smith, B.A. Grierson, R. Nazikian, J.Candy

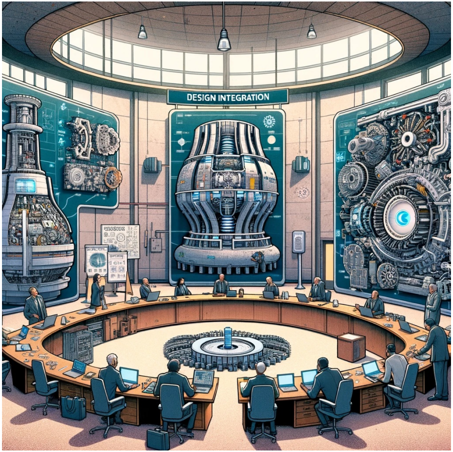
Sherwood Fusion Theory
May 7$^{\text{th}}$ 2024

Using systems code as the starting point of FPP concept designs leads to integration issues!

Traditional concept design workflow:

1. Broad systems code analysis to identify a target design
2. Experts run high-fidelity analyses on each sub-system
3. Issues!

- **Mismatched outcomes** between systems code and experts
  $\Longrightarrow$ Diverging teams
- **Premature design lock-in** limit exploration of alternative designs
  $\Longrightarrow$ Narrow scope
- **Manual integration** of disparate analyses into a cohesive design
  $\Longrightarrow$ Inefficient and costly

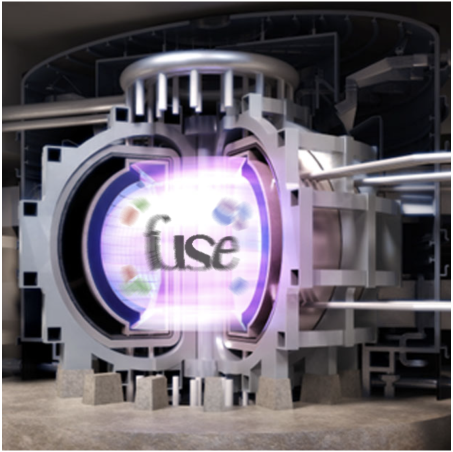


GA's own experience with FPP concept design spurred the development of a radically new modeling framework

Needs:

1. Go from idea to concept design in minutes rather than months
2. Evaluate wildly different concepts on same footing
3. Provide different physics and engineering teams a high-quality integrated representation of the design
4. Support modeling needs from design to operations

Answer:



Outline

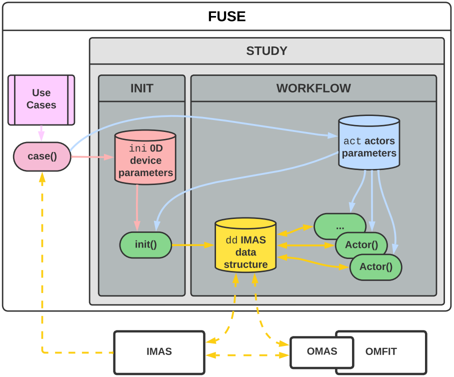
- Framework
- Models: plasma
- Models: engineering, plant, costing
- Machine design
- Pulse design
- Wrap up

Outline

- Framework
- Models: plasma
- Models: engineering, plant, costing
- Machine design
- Pulse design
- Wrap up

The FUsion Synthesis Engine (FUSE) framework

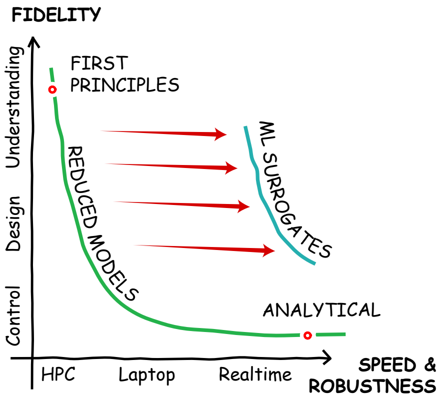
- **Developed from the ground-up** (framework and models) based on GA modeling expertise
- Built around **ITER IMAS*** ontology, enabling **fidelity hierarchy** and maximum interoperability
- All in one language: **Julia**
  - High-level like Python
  - As fast as C
  - Auto-differentiable



* IMAS ontology extended to support machine build, blanket, BOP, costing, ...

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

- Want to **capture complex system dynamics** while enabling **rapid design iterations**
  1. **Tightly coupling** of models
  2. Rely on **physics-based reduced models**
  3. Break efficiency-fidelity tradeoff with **ML surrogates**



- **Guiding-principle:**
  - **Sufficient fidelity** to get interfaces between subsystems about right, so experts in-depth studies should not upend the whole design...
  - ...after that, **be as fast as possible!**

FUSE models span from the plasma core to the site boundary

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

Typical whole facility simulation takes approximately 1 minute

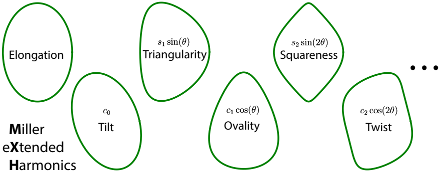
Outline

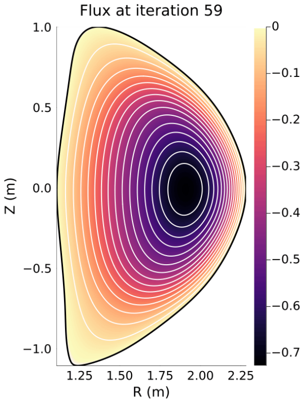
- Framework
- Models: plasma
- Models: engineering, plant, costing
- Machine design
- Pulse design
- Wrap up

New and efficient equilibrium and current diffusion solvers

- **TEQUILA inverse equilibrium**
  - Finite elements radially and Fourier modes poloidally
  - Grid-free flux-surface tracing with **MXH coefficients**
  - Benchmarked Vs CHEASE

- **QED current diffusion**
  - Finite elements and Galerkin method
  - Time-dependent or steady-state, with non-inductive current profiles
  - Benchmarked Vs TRANSP

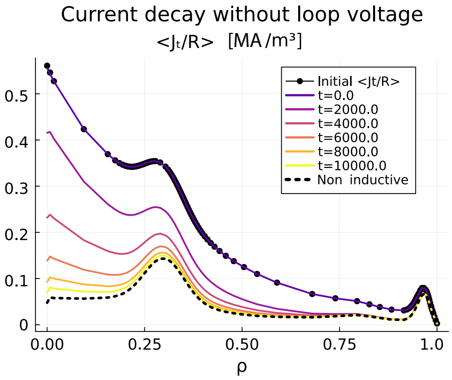




New and efficient equilibrium and current diffusion solvers

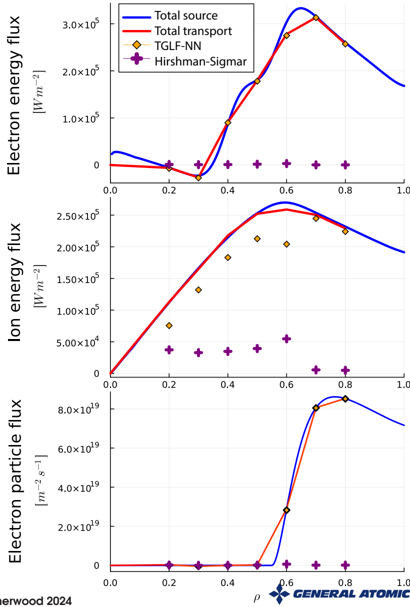
- **TEQUILA inverse equilibrium**
  - Finite elements radially and Fourier modes poloidally
  - Grid-free flux-surface tracing with **MXH coefficients**
  - Benchmarked Vs CHEASE

- **QED current diffusion**
  - Finite elements and Galerkin method
  - Time-dependent or steady-state, with non-inductive current profiles
  - Benchmarked Vs TRANSP



Theory-based core pedestal and transport models are essential for confident extrapolation to new regimes

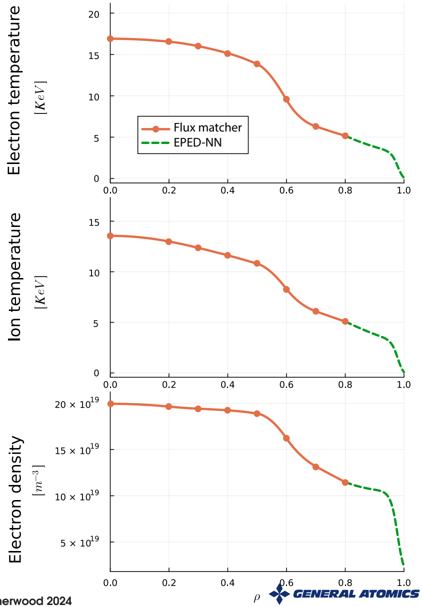
- Core transport solution via **flux-matching**
  - Linear inverse scale length between (few) radial points
  - **Turbulent transport:** TGLF, TJLF, QLGYRO TGLF-NN, QL-NN
  - **Neoclassical transport:** Hirshman-Sigmar, NEO
- Core solution connects to **EPED-NN pedestal model**
  - $n_{\text{e,ped}}$, $z_{\text{eff,ped}}$ as inputs
- **Sources and sinks**
  - Fusion, radiative, exchange
  - Time derivative source term for time dependence
  - External HCD actuators (analytical or RABBIT for NBI)



GENERAL ATOMICS

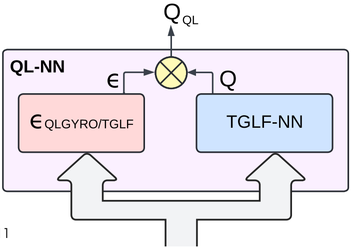
Theory-based core pedestal and transport models are essential for confident extrapolation to new regimes

- Core transport solution via **flux-matching**
  - Linear inverse scale length between (few) radial points
  - **Turbulent transport:** TGLF, TJLF, QLGYRO TGLF-NN, QL-NN
  - **Neoclassical transport:** Hirshman-Sigmar, NEO
- Core solution connects to **EPED-NN pedestal model**
  - $n_{\text{e,ped}}$, $z_{\text{eff,ped}}$ as inputs
- **Sources and sinks**
  - Fusion, radiative, exchange
  - Time derivative source term for time dependence
  - External HCD actuators (analytical or RABBIT for NBI)

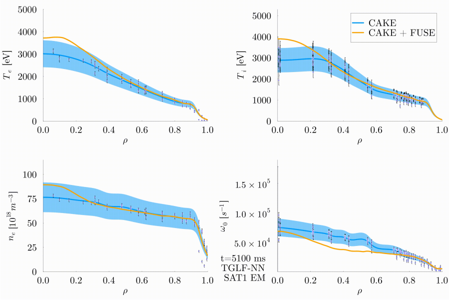


ML-accelerated models are the key to break fidelity-Vs-speed tradeoff and ensure robust convergence

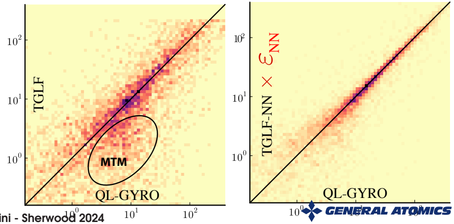
- Battle-tested multi-machine multi-SAT rule **TGLF-NN**
  - DB of 10M TGLF runs
- Beyond gyro-fluid approximation with **QLGYRO**
  - Linear CGYRO spectra with TGLF saturation rules
  - For high β_n and pedestal
- **QL-NN** by transfer-learning TGLF-NN to QLGYRO
  - DB of 10K QLGYRO runs



FUSE TGLF-NN on DIII-D (DOE superfacility project)



QL-NN (DOE Fusion Data Platform project)

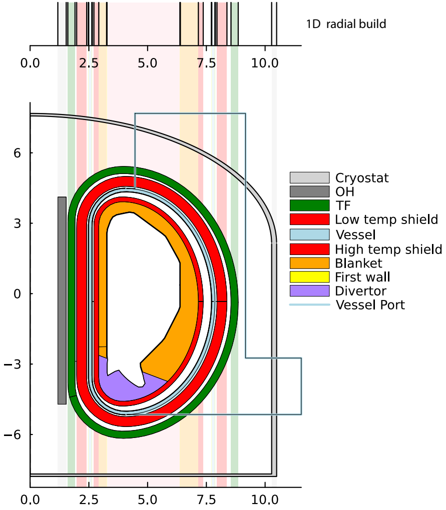


Outline

- Framework
- Models: plasma
- Models: engineering, plant, costing
- Machine design
- Pulse design
- Wrap up

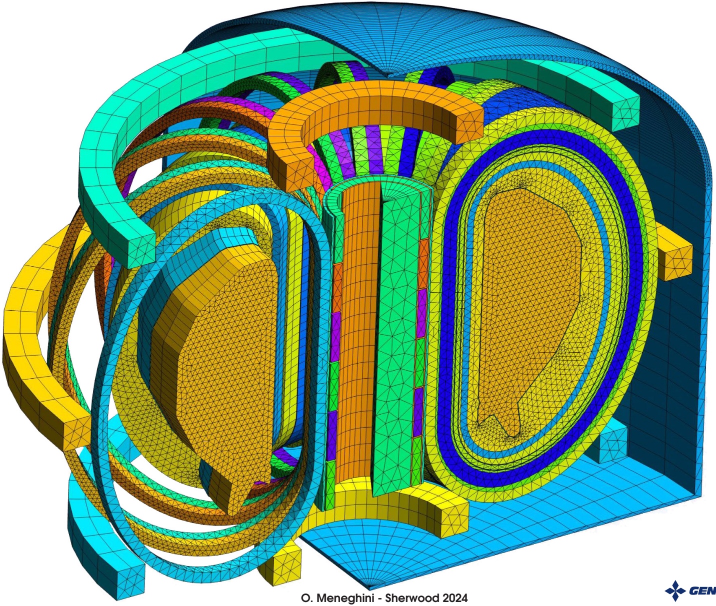
Automated tokamak build: from 1D radial, to 2D cross-section, and 3D CAD

- **Radial build** layer thicknesses based on requirements:
  - Ohmic flux
  - Stress limits
  - Superconductor quench
  - Neutronics TBR and shielding
  - Maintenance
  - TF ripple
- **Automated 2D cross-section** outlines as multiple concentric layers around plasma
  - Support for divertors, blankets, and ports
  - Ports for horizontal and vertical maintenance
- **3D CAD** via Gmsh



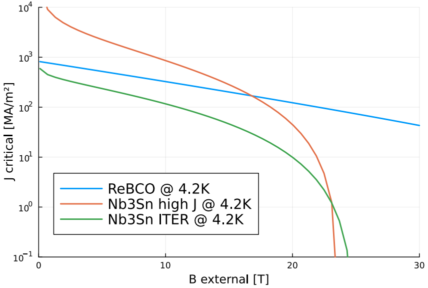
GENERAL ATOMICS

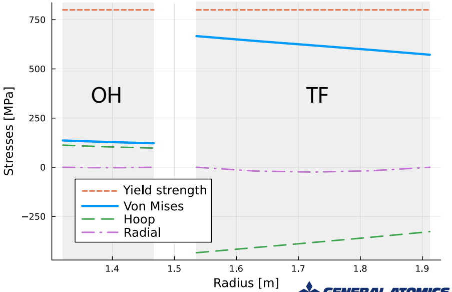
3D CAD and mesh generation opens possibility for future FEA and other high-fidelity simulations



Supercoductors and stress models allow sizing of OH and TF coils to satisfy flux swing and toroidal field requirements

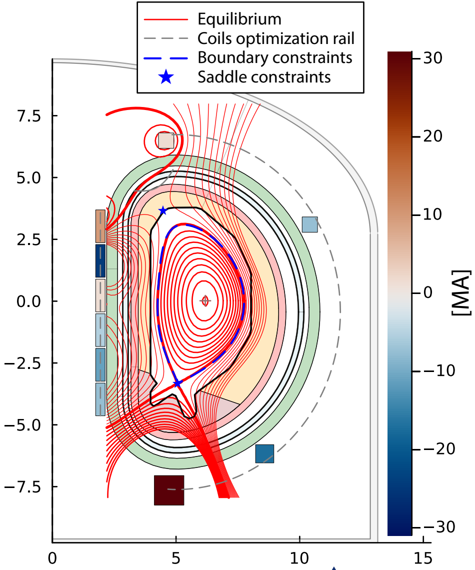
- **Superconductors critical current** models for ReBCO, Nb3Sn, Nb-Ti
- **1D solid mechanics** model of central stack, subject to largest magnetic forces from OH and TF coils
  - Benchmarked against 3D FEM analysis
- Used to **optimize OH and TF** sizes and ratios of steel to superconductors





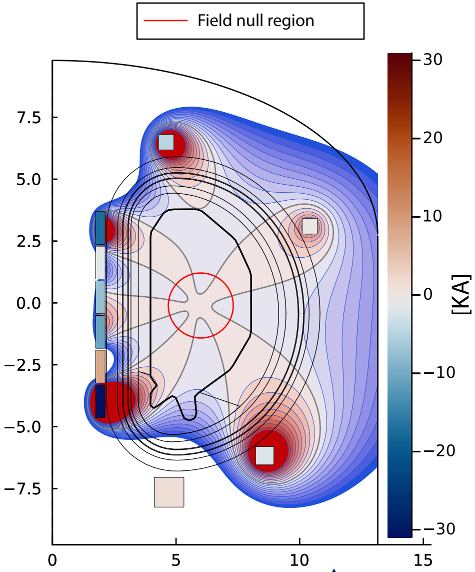
Poloidal field coils placement for optimal shape control

- Machine and pulse design generally **start from a target equilibrium** $(R_0, a, \kappa, \delta, \ldots)$
- FUSE can **extend closed boundary equilibria into the vacuum** region
  - Find coil currents to match boundary, saddle-point, and strike-point constraints
- Green's function grid-free method enables **efficient optimization of PF coils**
  - Optimizes for multiple target equilibria and field nulls
- **Vertical stability** calculation will guide optimization of passive plates position



Poloidal field coils placement for optimal shape control

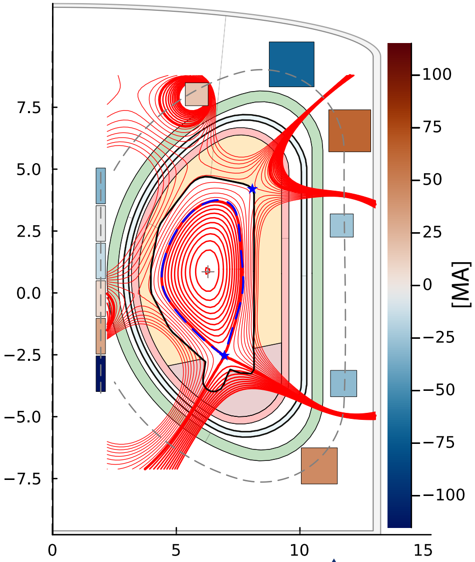
- Machine and pulse design generally **start from a target equilibrium** $(R_0, a, \kappa, \delta, \ldots)$
- FUSE can **extend closed boundary equilibria into the vacuum** region
  - Find coil currents to match boundary, saddle-point, and strike-point constraints
- Green's function grid-free method enables **efficient optimization of PF coils**
  - Optimizes for multiple target equilibria and field nulls
- **Vertical stability** calculation will guide optimization of passive plates position



GENERAL ATOMICS

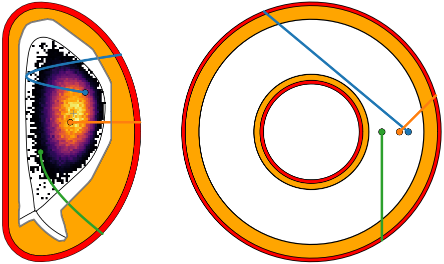
Poloidal field coils placement for optimal shape control

- Machine and pulse design generally **start from a target equilibrium** $(R_0, a, \kappa, \delta, \ldots)$
- FUSE can **extend closed boundary equilibria into the vacuum** region
  - Find coil currents to match boundary, saddle-point, and strike-point constraints
- Green's function grid-free method enables **efficient optimization of PF coils**
  - Optimizes for multiple target equilibria and field nulls
- **Vertical stability** calculation will guide optimization of passive plates position



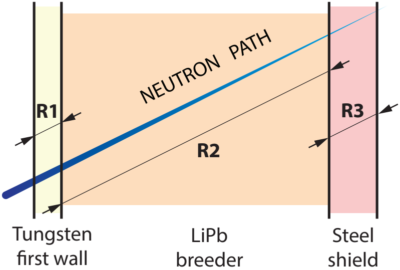
Neutronics surrogate optimizes blanket layers thickness for maximum TBR and minimum neutron leakage

- Database of **1D Monte Carlo simulations** with varying
  - R_1: W first wall
  - R_2: LiPb breeder
  - R_3: Steel shield
  - Li_6: enrichment



- Surrogate samples materials according to **neutron path** in 3D geometry (no scattering)

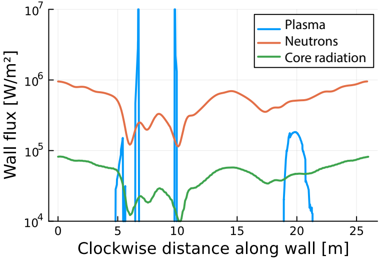
- Verified within 10% of OpenMC for the same 3D geometry and materials

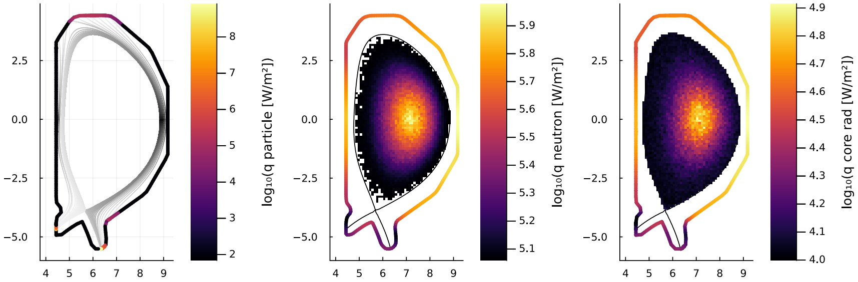


GENERAL ATOMICS

Plasma, neutrons, and radiation fluxes drive first wall design and volume allocated for divertors

- Plasma heat flux
  - Mapped from midplane to target
  - Double exponential decay (eg. λ_{q1} Eich + λ_{q2} ELM)
  - No neutrals dissipation $\rightarrow$ no edge radiation
  - INFUSE w/ LLNL for theory-based ML-accelerated SOL modeling



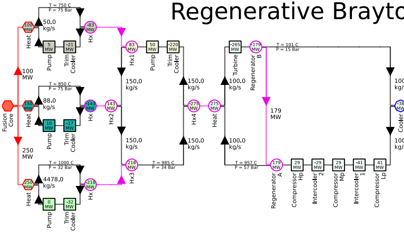


GENERAL ATOMICS

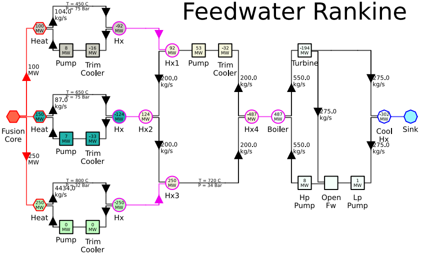
Sophisticated balance of plant model provides realistic thermal conversion efficiencies

- Arbitrary **network of components** (exchangers, turbines, pumps, ...)
  - Stationary or time-dependent
  - Can be run standalone, not only for fusion
  - Verified against Thermoflow
- **Optimize BOP** flows to match operating temperatures, or viceversa
  - Blanket, first wall, divertors as heat sources
  - **Brayton** cycle tends to achieve higher efficiencies than **Rankine** cycle
- Tradeoff tokamak Vs BoP cost?

Regenerative Brayton



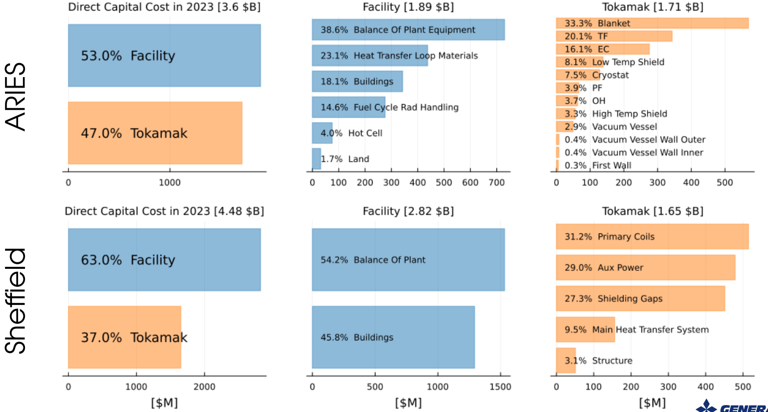
Feedwater Rankine



GENERAL ATOMICS

Cost is what drives design optimization towards compactness and higher plasma performance

- Direct capital, operation, maintenance, decommissioning costs
- Based on **ARIES** (2013) or **Sheffield** (1986, 2016)
  - Updated materials cost and learning rate for different techs (eg. HTS)
  - Inflation adjustment to present-day dollars and projection



Outline

- Framework
- Models: plasma
- Models: engineering, plant, costing
- Machine design
- Pulse design
- Wrap up

FUSE provides a multi-objective optimization workflow for efficient design exploration

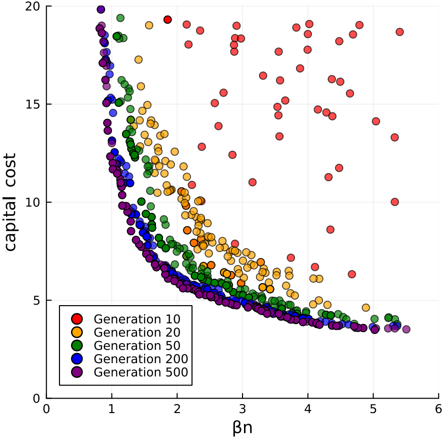
- **Genetic algorithm** steers solution towards the Pareto front

- Exposes **trade-offs** between competing objectives and highlights **complex system dynamics**

- Helps different stakeholders **identify target designs**

  (scientists, investors, policymakers,...)

- **Scalable parallel execution** allows running 10k+ cases in few hours on small cluster



- A **formidable stress-test** of FUSE's robustness!

FUSE enables complex optimization studies eg. preliminary 3-obj optimization machine design study

OBJECTIVES

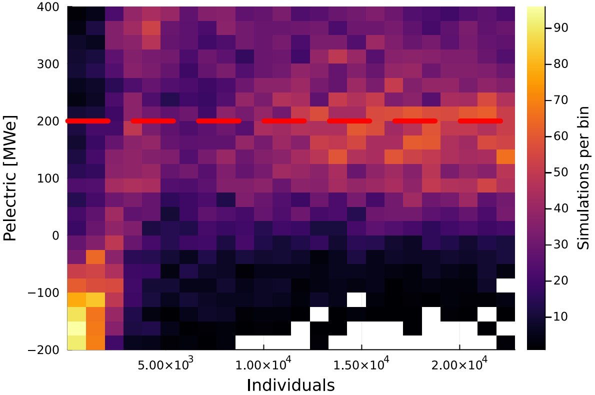
1. min capital cost
2. min β_N
3. max q_{95}

CONSTRAINTS

- $P_{\text{electric}} > 200$ MW
- flattop $= 1.0$ (h)
- TBR $= 1.1$
- $q_{95} > 3.5$

ACTUATORS

- $5.0 < R_0 < 10.0$ (m)
- $3.0 < B_0 < 15.0$ (T)
- $4.0 < I_p < 22$ (MA)
- $1.5 < \kappa < 2.2$
- $-0.7 < \delta < 0.7$
- $1.1 < z_{\text{eff,ped}} < 3.5$
- $0.4 < f_{\text{GW,ped}} < 0.85$
- BOP: Rankine, Brayton
- SC: ReBCO, Nb3Sn
- $0 < P_{\text{EC}} < 100$ (MW)
- $0 < \rho_{\text{EC}} < 0.9$
- $0 < P_{\text{NB}} < 50$ (MW)
- $0.1 < E_{\text{NB}} < 2$ (MeV)



- 24k simulations, **each a full FPP design**
- 1.5D transport + build + eng + bop + cost

FUSE enables complex optimization studies
eg. preliminary 3-obj optimization machine design study

OBJECTIVES

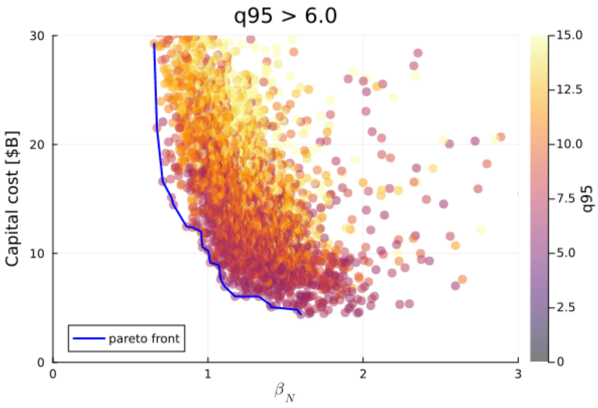
1. min capital cost
2. min β_N
3. max q_{95}

CONSTRAINTS

- $P_{\text{electric}} > 200$ MW
- flattop $= 1.0$ (h)
- TBR $= 1.1$
- $q_{95} > 3.5$

ACTUATORS

- $5.0 < R_0 < 10.0$ (m)
- $3.0 < B_0 < 15.0$ (T)
- $4.0 < I_p < 22$ (MA)
- $1.5 < \kappa < 2.2$
- $-0.7 < \delta < 0.7$
- $1.1 < z_{\text{eff,ped}} < 3.5$
- $0.4 < f_{\text{GW,ped}} < 0.85$
- BOP: Rankine, Brayton
- SC: ReBCO, Nb3Sn
- $0 < P_{\text{EC}} < 100$ (MW)
- $0 < \rho_{\text{EC}} < 0.9$
- $0 < P_{\text{NB}} < 50$ (MW)
- $0.1 < E_{\text{NB}} < 2$ (MeV)



Plasma safety can be bought...

FUSE enables complex optimization studies eg. preliminary 3-obj optimization machine design study

OBJECTIVES

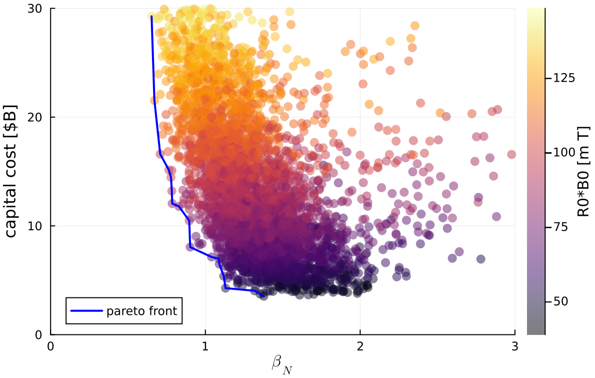
1. min capital cost
2. min β_N
3. max q_{95}

CONSTRAINTS

- $P_{\text{electric}} > 200$ MW
- flattop $= 1.0$ (h)
- TBR $= 1.1$
- $q_{95} > 3.5$

ACTUATORS

- $5.0 < R_0 < 10.0$ (m)
- $3.0 < B_0 < 15.0$ (T)
- $4.0 < I_p < 22$ (MA)
- $1.5 < \kappa < 2.2$
- $-0.7 < \delta < 0.7$
- $1.1 < z_{\text{eff,ped}} < 3.5$
- $0.4 < f_{\text{GW,ped}} < 0.85$
- BOP: Rankine, Brayton
- SC: ReBCO, Nb3Sn
- $0 < P_{\text{EC}} < 100$ (MW)
- $0 < \rho_{\text{EC}} < 0.9$
- $0 < P_{\text{NB}} < 50$ (MW)
- $0.1 < E_{\text{NB}} < 2$ (MeV)



... with larger and higher field devices

FUSE enables complex optimization studies eg. preliminary 3-obj optimization machine design study

OBJECTIVES

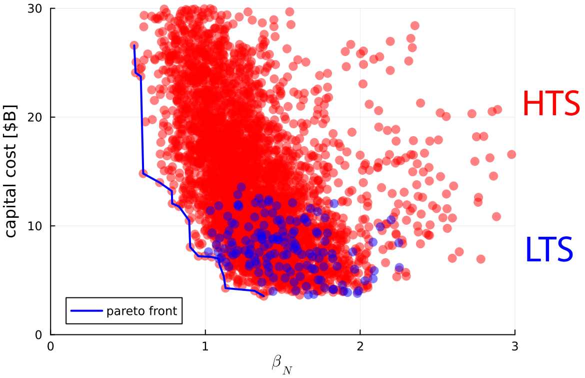
1. min capital cost
2. min β_N
3. max q_{95}

CONSTRAINTS

- $P_{\text{electric}} > 200$ MW
- flattop $= 1.0$ (h)
- TBR $= 1.1$
- $q_{95} > 3.5$

ACTUATORS

- $5.0 < R_0 < 10.0$ (m)
- $3.0 < B_0 < 15.0$ (T)
- $4.0 < I_p < 22$ (MA)
- $1.5 < \kappa < 2.2$
- $-0.7 < \delta < 0.7$
- $1.1 < z_{\text{eff,ped}} < 3.5$
- $0.4 < f_{\text{GW,ped}} < 0.85$
- BOP: Rankine, Brayton
- SC: ReBCO, Nb3Sn
- $0 < P_{\text{EC}} < 100$ (MW)
- $0 < \rho_{\text{EC}} < 0.9$
- $0 < P_{\text{NB}} < 50$ (MW)
- $0.1 < E_{\text{NB}} < 2$ (MeV)



HTS Vs LTS trades:

- Higher unit cost, for
- Smaller size and less SC material

FUSE enables complex optimization studies
eg. preliminary 3-obj optimization machine design study

OBJECTIVES

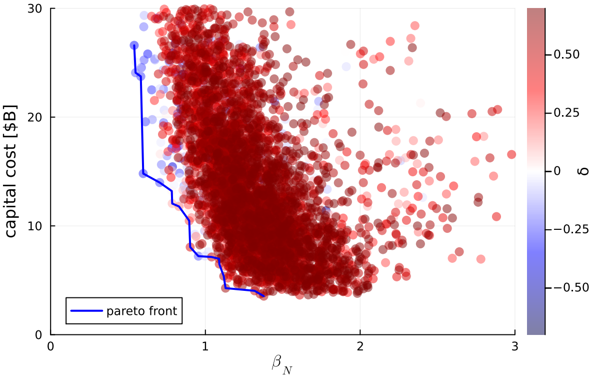
1. min capital cost
2. min β_{N}
3. max q_{95}

CONSTRAINTS

- $P_{\text{electric}} > 200$ MW
- flattop $= 1.0$ (h)
- TBR $= 1.1$
- $q_{95} > 3.5$

ACTUATORS

- $5.0 < R_0 < 10.0$ (m)
- $3.0 < B_0 < 15.0$ (T)
- $4.0 < I_p < 22$ (MA)
- $1.5 < \kappa < 2.2$
- $-0.7 < \delta < 0.7$
- $1.1 < z_{\text{eff,ped}} < 3.5$
- $0.4 < f_{\text{GW,ped}} < 0.85$
- BOP: Rankine, Brayton
- SC: ReBCO, Nb3Sn
- $0 < P_{\text{EC}} < 100$ (MW)
- $0 < \rho_{\text{EC}} < 0.9$
- $0 < P_{\text{NB}} < 50$ (MW)
- $0.1 < E_{\text{NB}} < 2$ (MeV)



Several attractive NT results at lower β_{N}

- Lower risks of NT not yet captured by FUSE
- Need for a generalized *risk metric*

Outline

- Framework
- Models: plasma
- Models: engineering, plant, costing
- Machine design
- Pulse design
- Wrap up

FUSE is designed to seamlessly handle both stationary and time-dependent simulations

- IMAS data structure supports time dependence
- All FUSE actors operate at a globally defined simulation time
- Transport via flux-matching approach for both problems:

$$\frac{\partial}{\partial t} + \langle \nabla \cdot \Gamma \rangle = S$$

STATIONARY

- No time dependence

$$t \to \infty \text{ and } \frac{\partial X}{\partial t} = 0$$

$$\cancel{\frac{\partial}{\partial t}} + \langle \nabla \cdot \Gamma \rangle = S$$

DYNAMIC

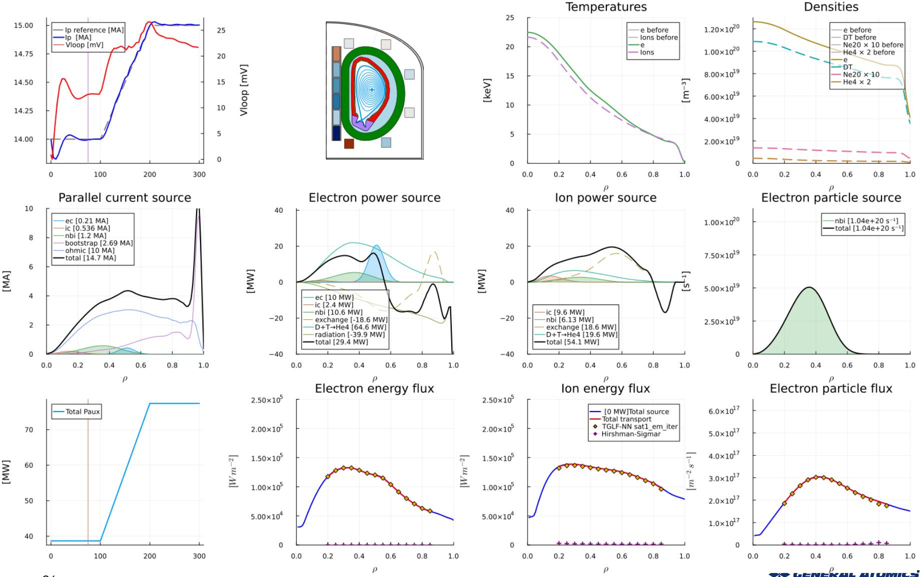
- Flux matching with time-derivative source

$$\langle \nabla \cdot \Gamma \rangle = S - \frac{\partial}{\partial t}$$

- Implicit time stepping, allows taking larger steps

Time dependence example on ITER
Ip 14 MA→15 MA and heating 40 MW → 80 MW

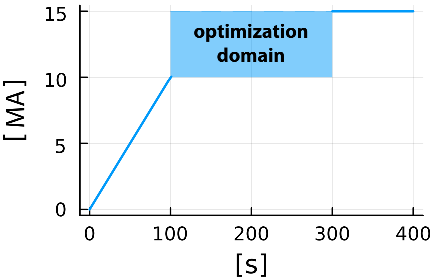
300 s of simulation in 30 mins on a laptop (w/ ample room for improvement)



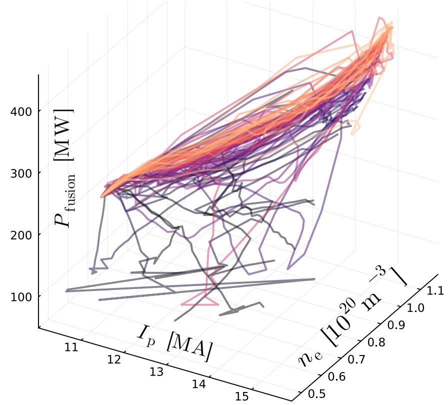
GENERAL ATOMICS

Combining time-dependence with multi-objective optimization enables trajectory optimization (ie. 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



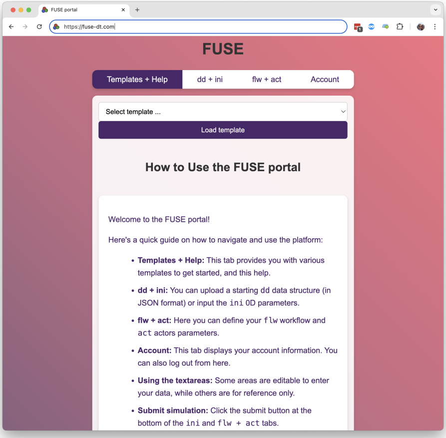
Best solutions keeps plasma sufficiently hot to sustain fusion throughout

Outline

- Framework
- Models: plasma
- Models: engineering, plant, costing
- Machine design
- Pulse design
- Wrap up

Web portal will provide community with turnkey access and GA plans to open-source FUSE

https://fuse-dt.com to request early access



Open-sourcing:

- To provide the community with a powerful platform for integrated simulations
- Will start with IMAS + framework + plasma models
- `IMASDD.jl` already made public with Apache 2.0 license

FUSE is a major leap in whole facility modeling capabilities

- A **modern** framework, **built from the ground up** in **Julia**
  - Central to GA's mission **to accelerate fusion commercialization**

- It enables **integrated whole facility tokamak FPP designs** with unprecedented combination of <u>speed</u>, <u>fidelity</u>, and <u>robustness</u>
  - Comprehensive **stationary** solution in **less than one minute**
  - Extensive **multi-objective constrained optimizations** are practical **on a small cluster**, evaluating wildly different designs on same footing
  - **Time dependent simulations** and **trajectory optimization**

- There's always **more to do**! In the near term:
  - Apply, include UQ and risk, scout for ever better reduced models