The FUSE framework and related IMAS activities

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ITER Modeling Expert Group (IMEG)
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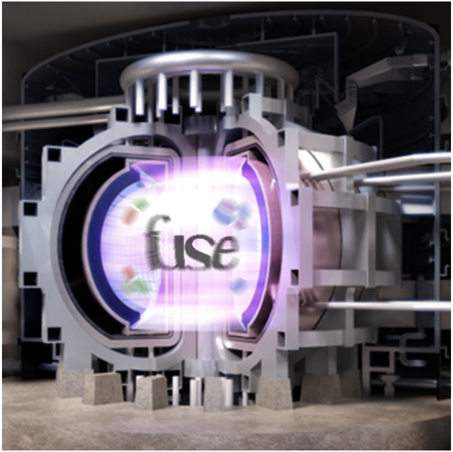
GA's experience with FPP concept design spurred the development of a radically new modeling framework

Needs:

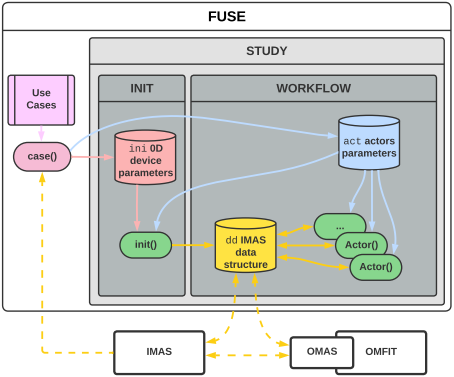
1. Go from idea to concept design in minutes rather than months
2. Evaluate wildly different concepts on same footing
3. Provide different physics and engineering teams a high-quality integrated representation of the design
4. Support modeling needs from machine design to operations

Answer:



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
  - Tightly coupled models
  - ML models also in Julia



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

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 stationary design takes approximately 1 minute

Outline

- Models: plasma
- Models: engineering, plant, costing
- Machine design
- Pulse design
- Wrap up + IMAS considerations

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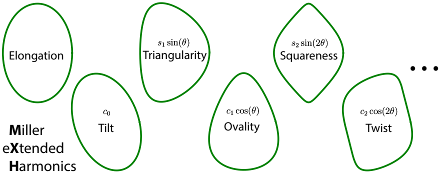
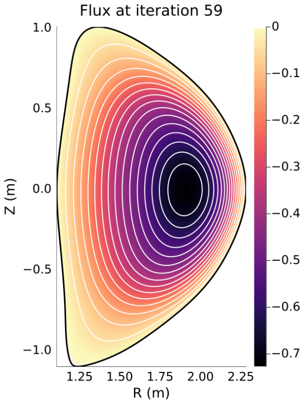
New and efficient equilibrium and current diffusion solvers

- **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





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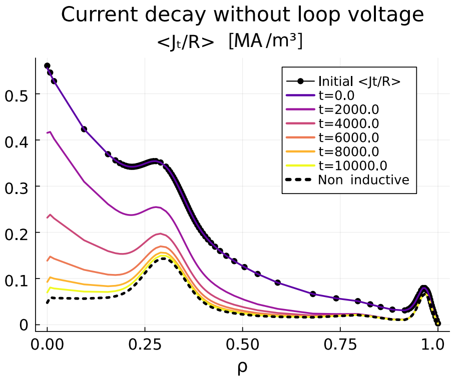
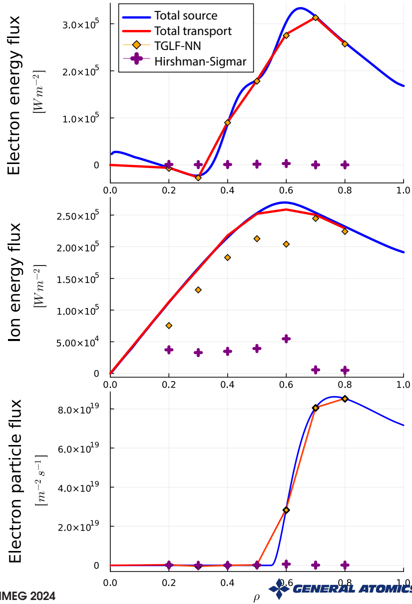


Theory-based core pedestal and transport models are essential for confident extrapolation to new regimes

- **Core** via flux-matching
  - Linear inverse scale length between (few) radial points
  - **Turbulent transport:** TGLF, TJLF, QLGYRO TGLF-NN, GKNN
  - **Neoclassical transport:** Hirshman-Sigmar, NEO
- Core connects to **pedestal**
  - EPED-NN for ELMy H-mode
  - WEPED for L-mode & NT
- **Sources and sinks**
  - Fusion, radiative, exchange
  - Time derivative source term for time dependence
  - External HCD actuators (analytical or RABBIT for NBI)



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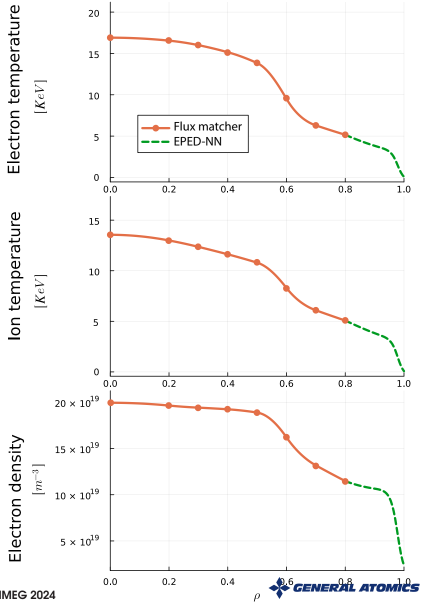

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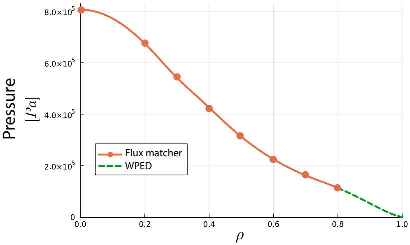
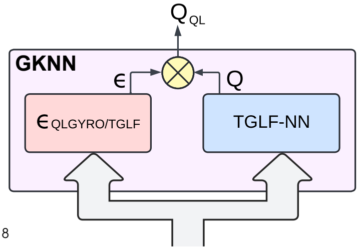


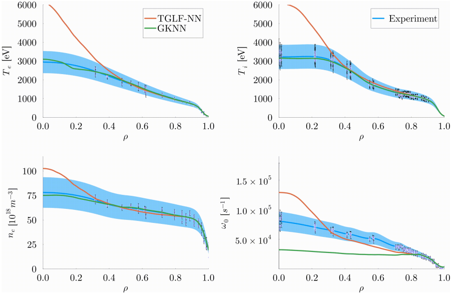
- WPED provides boundary condition for L-mode and negative triangularity (NT) plasmas
- Every tokamak goes through L-mode phase

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

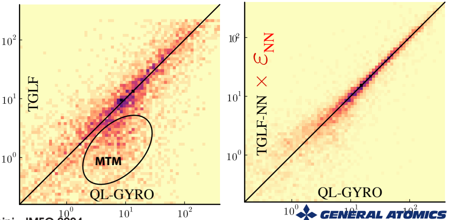
- Battle-tested multi-machine multi-SAT rule **TGLF-NN**
  - DB of 10M TGLF runs
- Beyond gyro-fluid approximation with **QLGYRO**
  - Linear CGYRO spectra with TGLF saturation rules
  - For high β_n and pedestal
- **GKNN** by transfer-learning TGLF-NN to QLGYRO
  - DB of 10K QLGYRO runs



FUSE TGLF-NN / GKNN on DIII-D (DOE IRI project)



GKNN (DOE Fusion Data Platform project)



GENERAL ATOMICS

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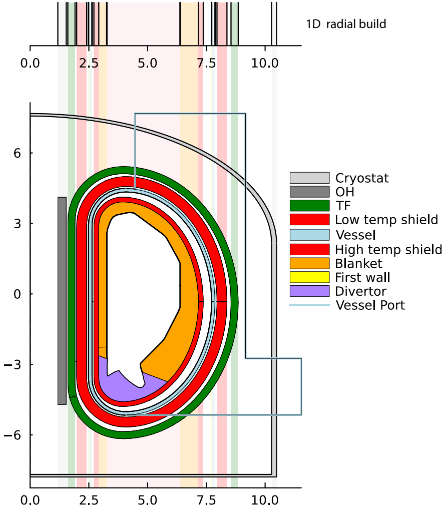
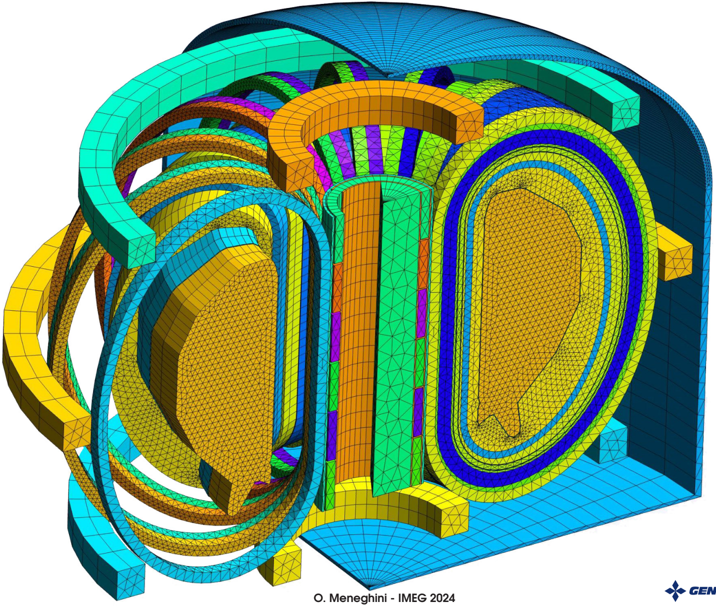
Automated tokamak build:
from 1D radial, to 2D cross-section, and 3D CAD

- **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



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

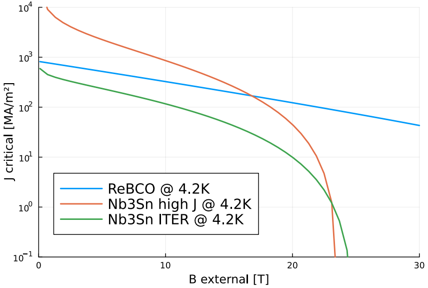


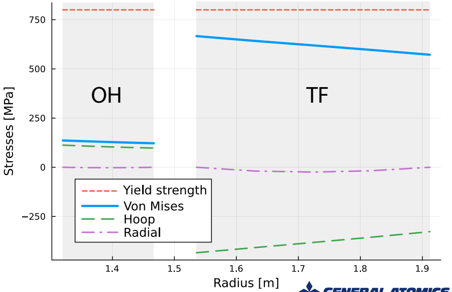
Supercoductors and stress models allow sizing of OH and TF coils to satisfy flux swing and toroidal field requirements

- **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

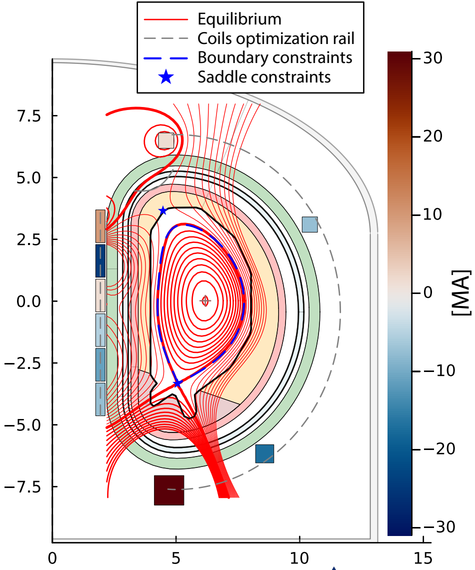
- Used to **optimize OH and TF** sizes and ratios of steel to superconductors





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



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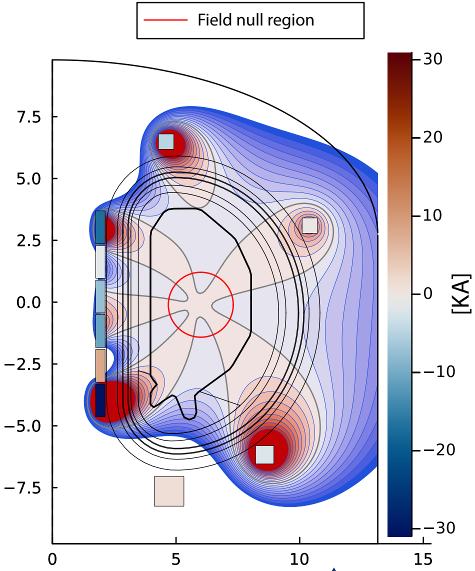

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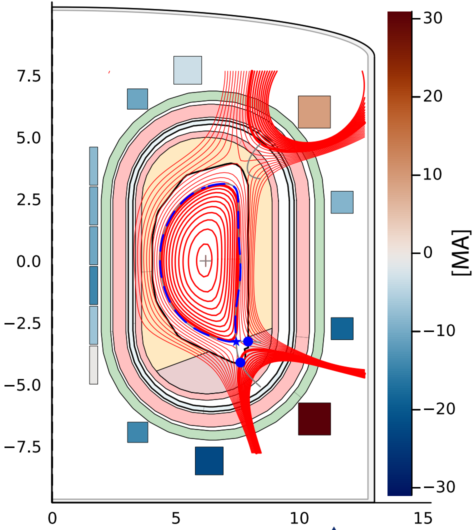
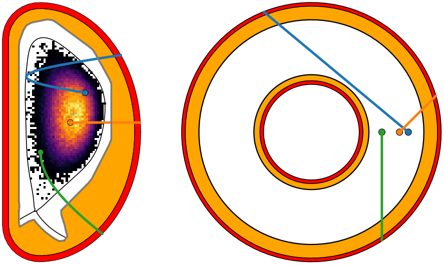


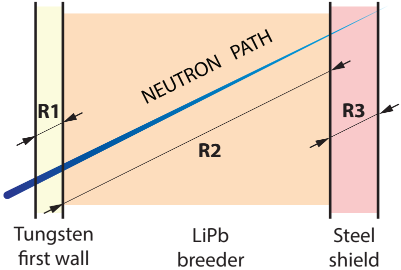
Neutronics surrogate optimizes blanket layers thickness for maximum TBR and minimum neutron leakage

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

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

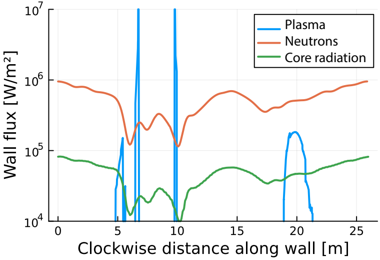
- Verified within 10% of OpenMC for the same 3D geometry and materials

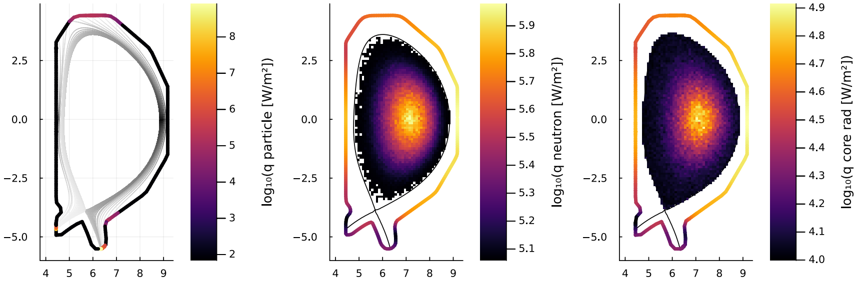




Plasma, neutrons, and radiation fluxes drive first wall design and volume allocated for divertors

- 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

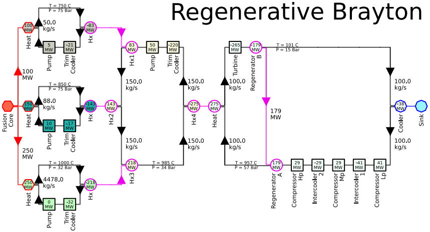


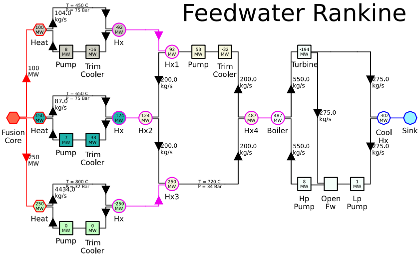


GENERAL ATOMICS

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?

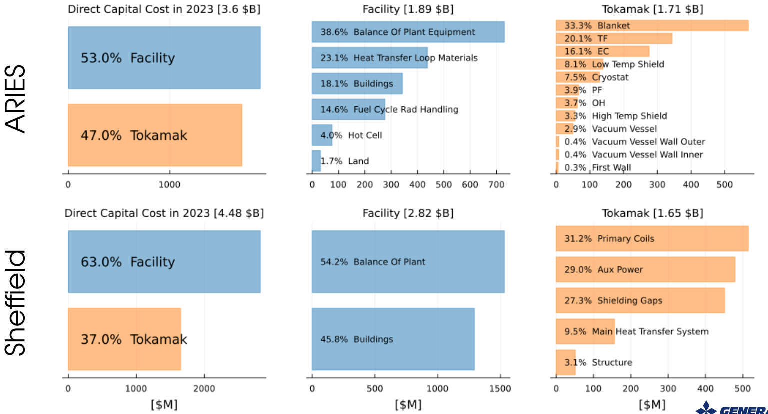




GENERAL ATOMICS

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 costs
  - Inflation adjustment to present-day dollars and projection



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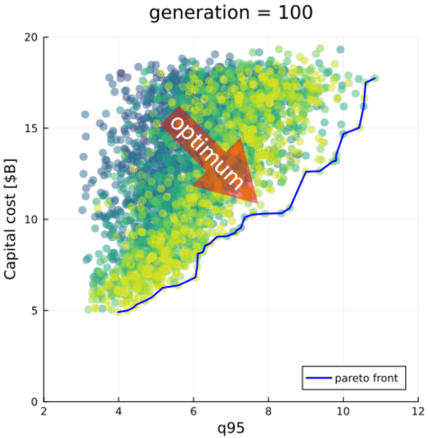
FUSE multi-objective constrained optimization workflow enables designs exploration and trade study

- **Genetic algorithm** steers solution towards the <u>Pareto front</u>
- 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
- A **formidable stress-test** of models' robustness!



eg. Trade study for positive-δ VS negative-δ FPP by running separate optimizations and compare pareto fronts

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)
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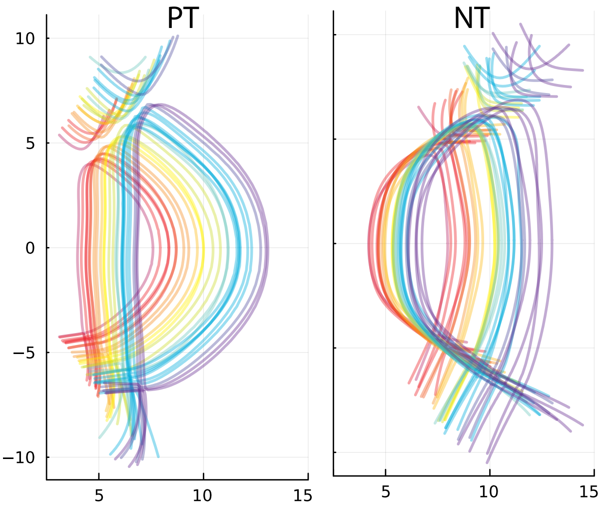

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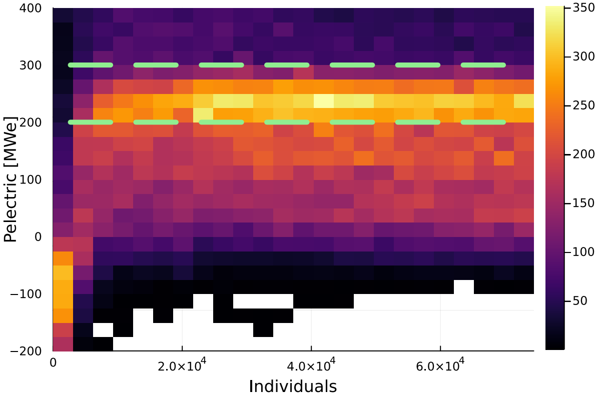

2×50k+ runs, **each a full FPP design**

- 1.5D transport + build + eng + bop + cost

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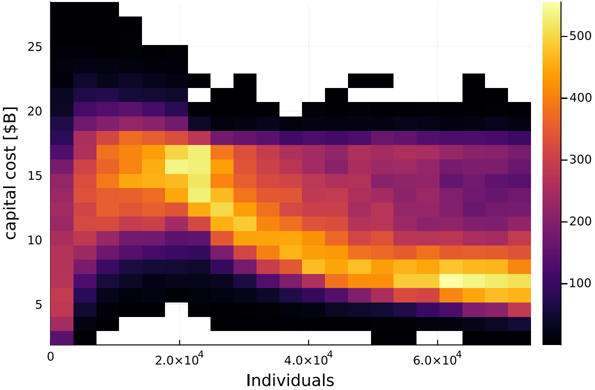

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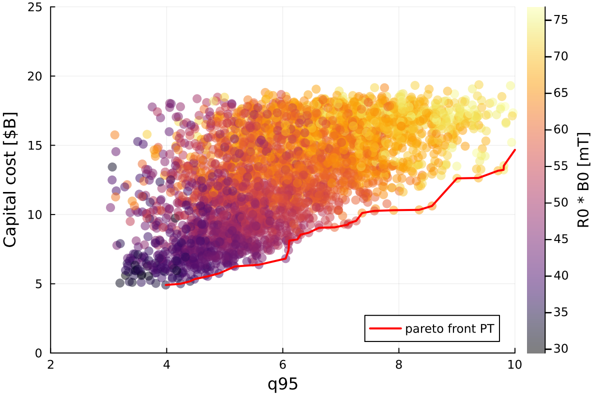

Plasma safety can be bought with:

- Larger devices
- Higher field

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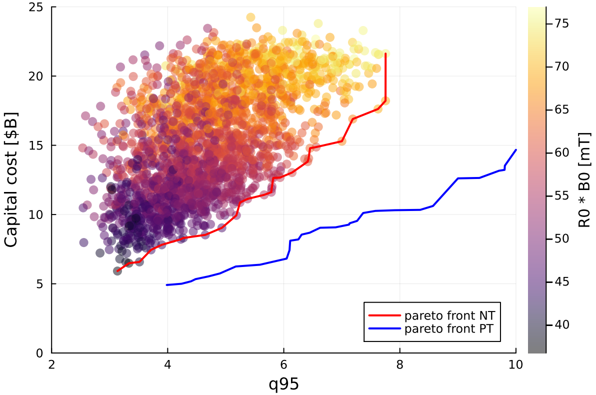

$\sim 50\%$ higher cost for NT advantages:

- Consistent ELM-free operations
- Edge compatible with radiative divertor

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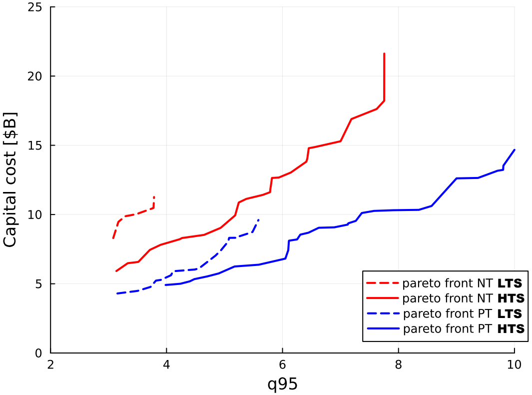
- $0 < \rho_{\text{EC}} < 0.9$
- $0 < P_{\text{NB}} < 50$ (MW)



LTS design space is narrower compared to HTS

- Using similar cost for LTS and HTS
- LTS with ITER technology

Outline

- Models: plasma
- Models: engineering, plant, costing
- Machine design
- Pulse design
- Wrap up + IMAS considerations

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

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

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

DYNAMIC

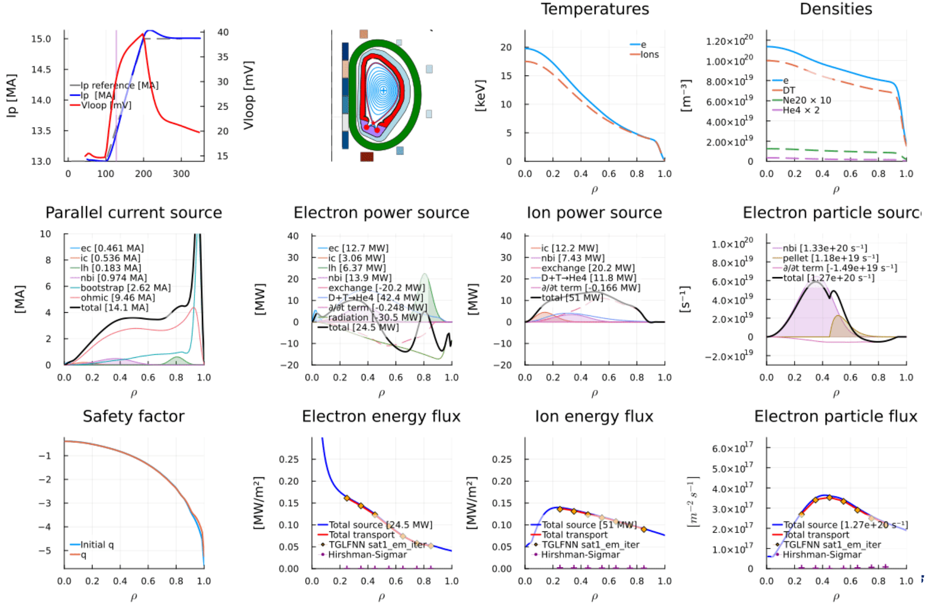
- Flux matching with time-derivative source

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

- Implicit time stepping, allows taking larger steps

Time dependence example on ITER
Ip 13 MA→15 MA and heating 40 MW → 80 MW

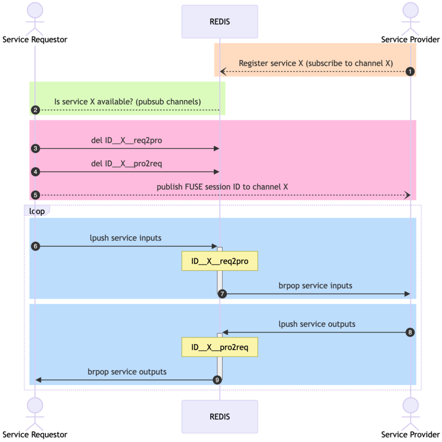
300 s of simulation in 10 mins on a laptop



Near term focus for FUSE development is on pulse-design

- Add models for **rampup and L-H transition**
- Develop **Grad-Hogan** solver
  - New free-boundary solver
  - Add inductive dynamics of PF coils and conducting structures
- FXP for co-simulation w/ TokSys
  - Built on top of **Redis**
  - Widely used internet data caching system
  - **Fast!** ~ 0.2 ms latency when run locally
- Go faster, if necessary via ML

Fuse eXchange Protocol (FXP)



GENERAL ATOMICS

Outline

- Models: plasma
- Models: engineering, plant, costing
- Machine design
- Pulse design
- Wrap up + IMAS considerations

GA is open-sourcing FUSE to provide community with a powerful platform for integrated simulations

A complete fusion modeling ecosystem in Julia

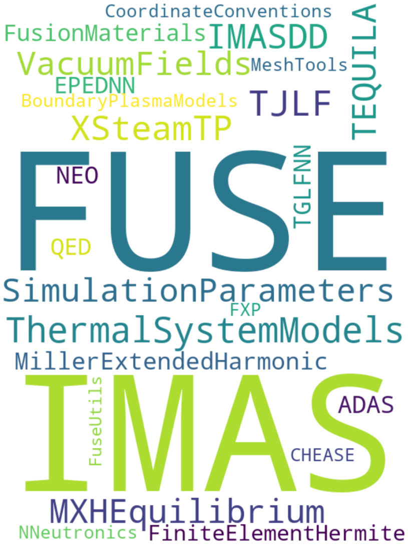
- 25+ packages
- 200K+ lines of Julia code
- Apache 2.0 licensed
- https://github.com/ProjectTorreyPines
- Email me for early access

Documentation:

- https://fuse.help

Publication:

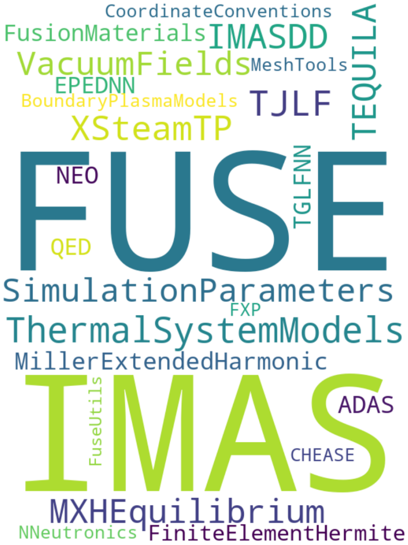
- Submitted to arXiv
- https://tinyurl.com/FUSEpaper



GA is open-sourcing FUSE to provide community with a powerful platform for integrated simulations

IMAS.jl enables IMAS-compatible models in Julia

- Much **faster** than OMAS (Python)
- **Native tensorized h5 I/O** without IMAS as dependency
- Lots of **physics functions**, shared among actors
- **Dynamic derived quantities** $(180+$ expressions)
- Handling of **non-uniform time**
- Flexible, multi-backend, actor-agnostic **plotting**



GENERAL ATOMICS

FUSE uses an extended IMAS data dictionary

See additions here: `https://tinyurl.com/fuseimasextras`

- Minor changes to original IDSs, eg.:
  - MHX parametrization to `equilibrium` and `pulse_schedule`
  - Support for `pellets` with layers of materials
  - HCD conversion/transmission/coupling efficiencies
- Whole new IDSs, eg.:
  - `build`, `neutronics`, `blanket`, `balance_of_plant`, `costing`, `solid_mechanics`, `requirements`

Would like to start opening JIRA PRs to make things “official” ...
... but a bit worried about the time and effort it will take!

Many US activities look at extending IMAS (even not tokamaks...)

1. Does IO want to grow/maintain IMAS beyond ITER?
2. International coordinating committee?
3. Alternative standards?

Strategies for transition from IMAS data dictionary v3 to v4

1 Rapid, exclusive

- Packages switch from one standard to the other
- Dependencies! Must convert everything to have a working system
- Viable if one controls everything, and change can be done quickly

- eg. Like Sweden changed driving direction in 1967
- FUSE could do this now… maybe more difficult later
- Could IMAS achieve this in one big code-camp?

2 Gradual, cross-compatible

- Packages support both standard (at least for some time)
- Keeps working, transition can be slow, but lots of complexity!
- Necessary when change cannot be coordinated

- eg. Like Python packages during 2→3 transition (2008–2020)
- Would like to avoid this complexity and performance hit for FUSE
- Maybe, accelerate community transition by only open-sourcing v4?

COCOS 11 $\rightarrow$ 17 is surely the biggest hurdle to v4
`https://jira.iter.org/browse/IMAS-3836`

COCOS 11

- B_p has sign $\nabla\phi \times \nabla\psi$
- ψ is as a "bowl" for Ip>0

COCOS 17

- B_p has sign $\nabla\psi \times \nabla\phi$
- ψ is as a "hill" for Ip>0

1. **Fix all codes by hand**
   - How many codes? people? hours? dollars?
   - Who will pay? The IO, the DAs, both?
2. **Automated COCOS translation**
   - Store/fetch data to/from DD in any COCOS
   - At that point IMAS COCOS becomes irrelevant
   - OMAS does this!!! Inescapable performance hit due to allocations
3. **Keep COCOS 11 and carry on**
   - 11, 17, or any other COCOS, it's just a convention (it's in the name)
   - Avoid bugs, complexity, and performance hits
   - Save a few million dollars, and keep community happy
   - Accelerate deployment of IMAS v4
   - Avoid forking of IMAS standards: `IMAS_v4_cocos11` anyone?