FOCUSED

A Multi-Physics Digital Twin for the Integrated Design and Optimization of an Inertial Fusion Energy Power Plant

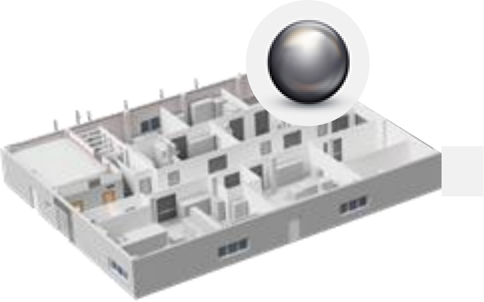
Dr. Valeria Ospina-Bohórquez, Dr. Neil Dhir, Dr. Gavin Friedman

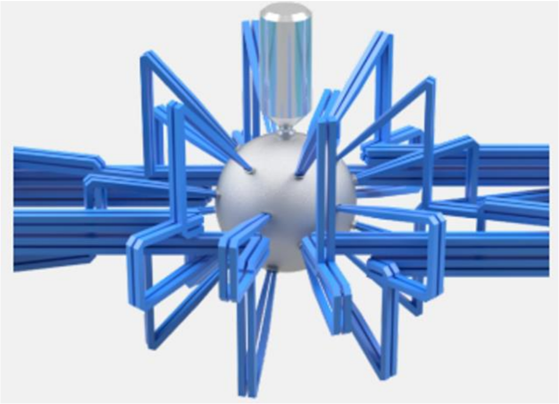
Workshop on Digital Engineering for Fusion Energy Research
Dec 9 – 12, 2025
Cambridge, Massachusetts, USA

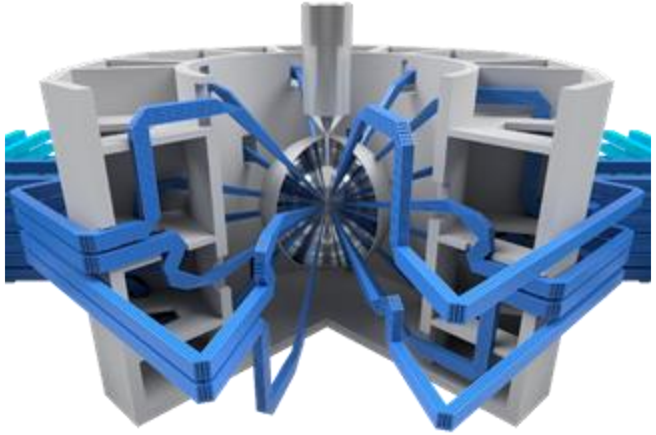
Overview

- ✓ Big picture context: Understanding the overarching goal and strategic importance of Digital Twins applied to Inertial Fusion Energy systems.
- ✓ Digital Twin Architecture: Detail essential modules, components, and data structures necessary for full operational capability and integration.
- ✓ Current Scope and Strategy: Boundaries, technical objectives, and current strategic focus of the project implementation.
- ✓ Optimization Strategy: Bayesian optimization for multivariable optimization

Our Reactor Modeling Roadmap







Computer Aided Engineering for Fusion Reactors
HPC-scale design optimization of reactor chamber components
Flexible and scalable simulation capability supports detailed design work

First Digital Twins of Focused Energy tech

Digital Shadow at intermediate-scale facility
Close model/facility integration and data assimilation at full shot rate
Model-informed experimental planning
Significant reduction in scaling uncertainty to LightHouse

Living Digital Twin at Lighthouse™
Predictive performance monitoring and maintenance
Model-based reactor technology qualification and scaling to FOAK

2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035

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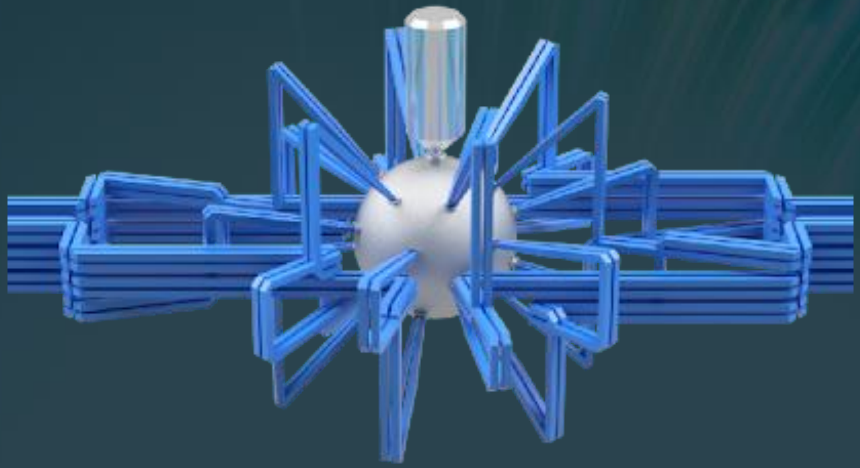
Inertial Fusion Energy Modelling Capabilities that Need Development

Chamber and Target Survival

Fusion Core Physics

System Infrastructure & Engineering

Foundational Data & Cost Assessment



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First Wall Survivability

Predict long-term damage, degradation, and activation.

Target Dynamics

Multi-physics modeling of hydrodynamics, radiation transport, and kinetic effects, including instabilities (hydrodynamic, laser-plasma) and hot electron generation

Target Survivability

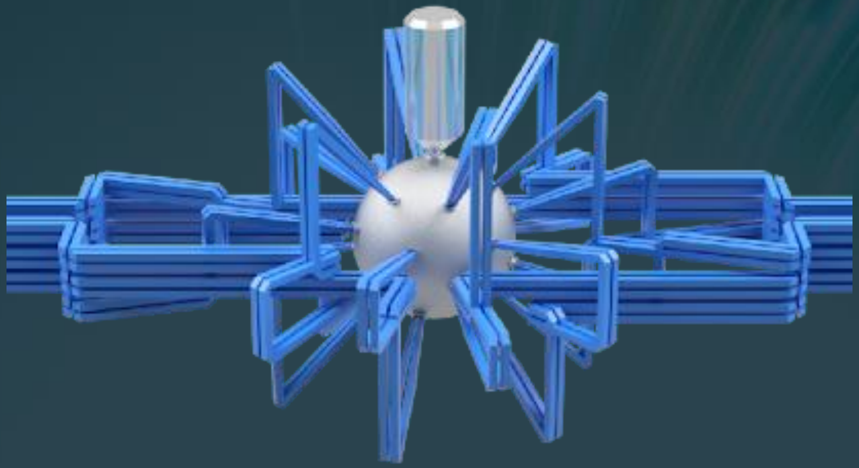
Modeling chamber environment effects (shocks, ablation, irradiation) on target integrity

Laser-Plasma Coupling

Simulations addressing instabilities, spectral effects, smoothing, and energy coupling optimization to ensure efficient laser energy delivery

Chamber Environment

Ensure that the chamber can recover to acceptable conditions between shots



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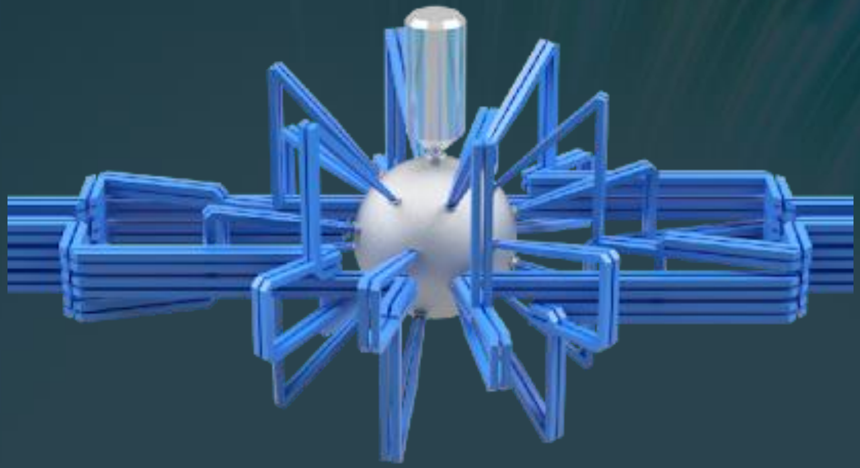

System Infrastructure & Engineering

Fuel Cycle

Modeling the full tritium management loop to ensure regulatory compliance

Blanket Systems

Coupled simulations of fluid flow, heat/mass transfer, and neutronics for tritium breeding and extraction

Laser Chain Simulation

Modeling beam propagation, optics response to high fluence, defect growth, and frequency conversion for performance assessment

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Material Data

Developing accurate material models, including two-temperature equations of state (EOS), opacities, and atomic physics

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Simulations to support lifecycle analysis and regulatory planning for radioactive waste mitigation

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Integrating all component models to evaluate overall reactor performance, reliability, and cost

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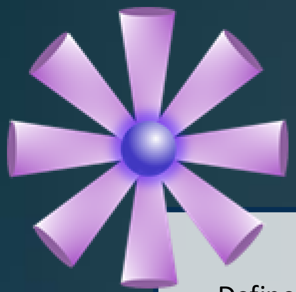
We are developing our Digital Twin physics modules

Ongoing Modeling Activities

Target Illumination & Delivery

Develop a model that can estimate the impact of uncertain laser and target delivery on:

- Implosion symmetry
- Performance



Define the precision and accuracy requirements of key technologies related to laser and target delivery

Fusion Chamber Simulation

Identify viable reactor operating parameters, consistent with first wall survival and capsule survival in-flight, such as:

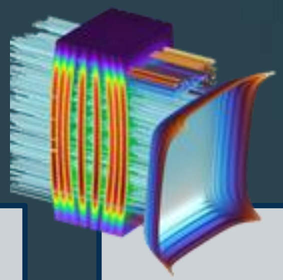
- Target Layering
- Chamber Geometry
- First Wall Survivability

Deliver specifications for in-chamber technologies (gas fill, injection velocity, first wall material, thermal boundaries,…) to inform R&D efforts

Laser Design Optimization

Develop models for laser performance as a function of top-level design parameters:

- Beamlet energy
- Amplifier Design
- Repetition Rate
- Diode Specifications



Inform DPSSL design parameters based on reactor-scale performance metrics

Digital Twin Development: From High-Fidelity Modeling to Global Optimization

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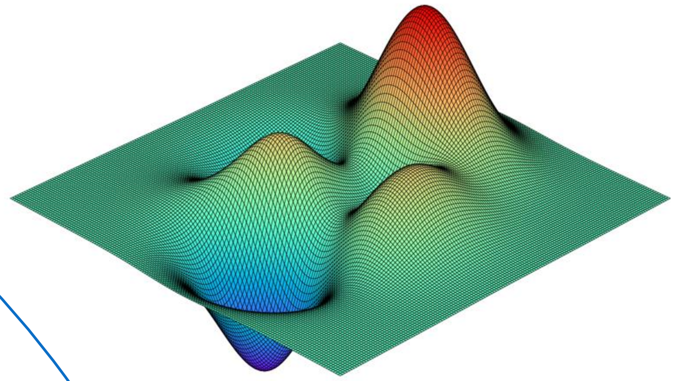
Phase 0
High fidelity physics modeling

Develop theoretical models and equations
Run initial simulations



Phase 1
Surrogate model development

Create faster approximations of complex physics models

Phase 2
Parameter tuning & validation & Local Optimization

Extract data from simulations/experiments
Tune model parameters
Perform verification against datasets

Phase 3
Model coupling & Global Optimization

Integrate separate models accounting for cross-effects
Progress from local optimization to global system optimization

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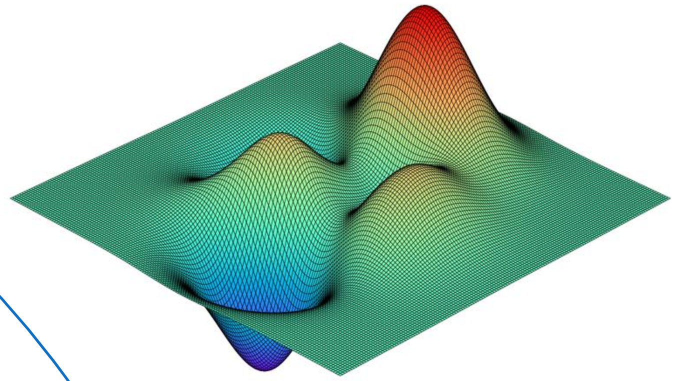

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The Target Illumination module aims at exploring the requirements placed on target injection, tracking, and laser delivery by implosion symmetry constraints

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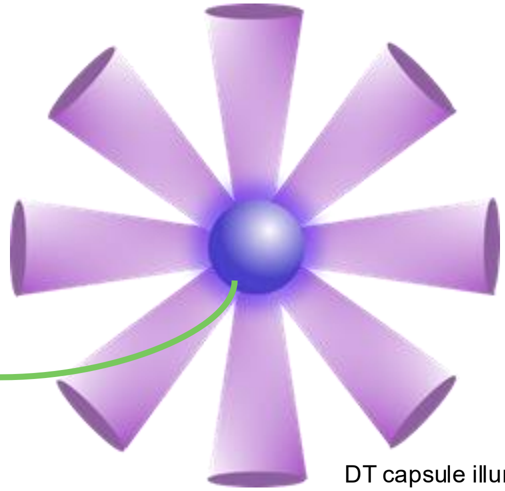
Project Scope

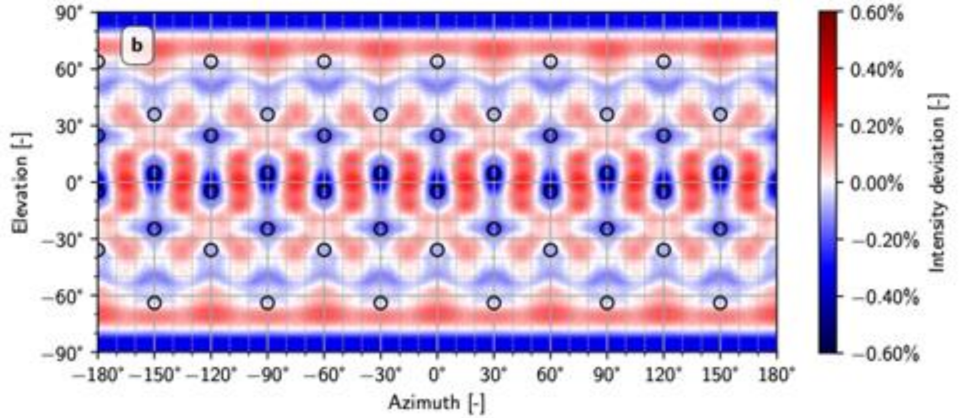
This project is centered on modeling the impact of uncertain target and laser delivery on both implosion symmetry and performance.

Goals

- To define precision and accuracy requirements for key technologies (Target injection, Target tracking, Laser delivery), which will, in turn, motivate necessary R&D efforts across the company.
- R&D Prioritization Question: What are the most impactful R&D efforts needed to significantly increase the performance and robustness of our implosion designs?



DT capsule illumination



Angular distribution of laser intensity on the target surface

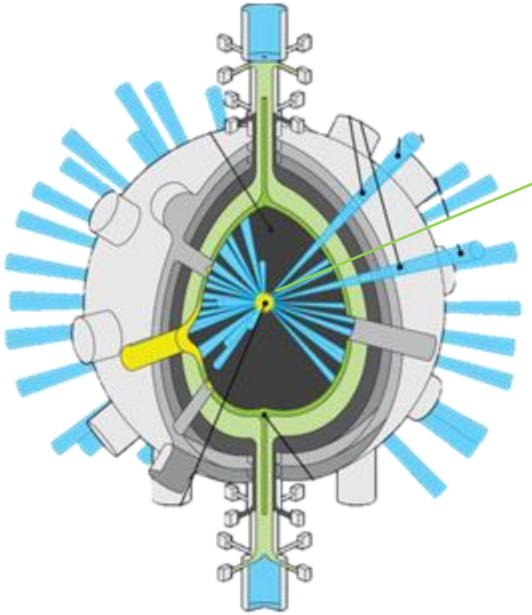
The Fusion Chamber Simulation module will produce viable reactor chamber designs consistent with first wall & capsule survival in-flight

Project Scope

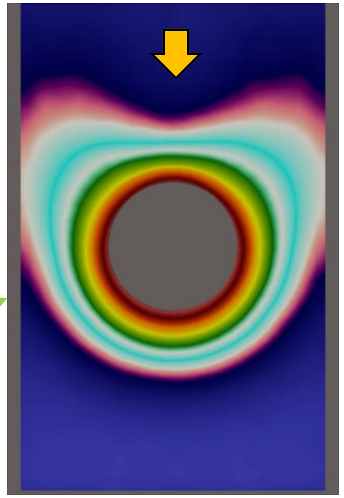
Provide a comprehensive assessment of fuel capsule survivability inside a fusion reactor chamber by modeling the impact of extreme temperatures, radiation, and mechanical stresses on both the capsule and the first wall self-consistently.

Goals

- Identify viable reactor chamber design and operating parameters, consistent with first wall survival, capsule survival in-flight, chamber gas fill response, and other relevant physics constraints.
- Produce specifications for in-chamber technologies to inform R&D efforts.



Fusion Reactor



Simulations of target heating in-flight
C. Fiorina, A. Pagani, Texas A&M

Space capsule re-entrance

Laser performance models are being developed and implemented within the Digital Twin to optimize top-level parameters and guide DPSSL design

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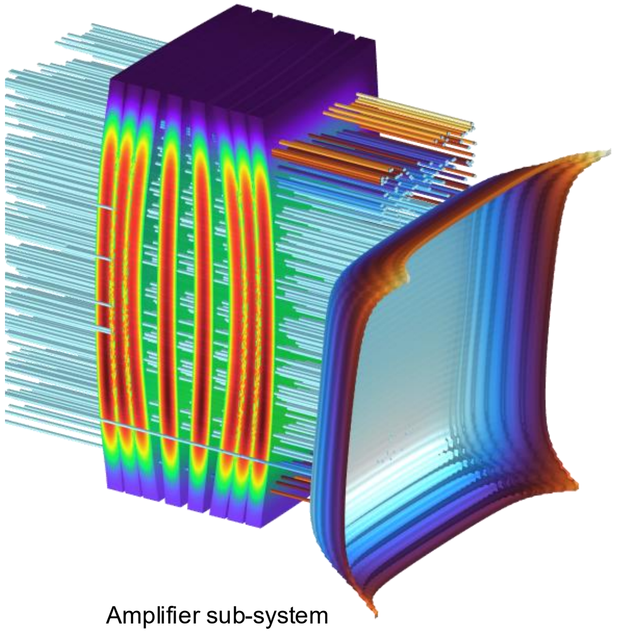
Project Scope

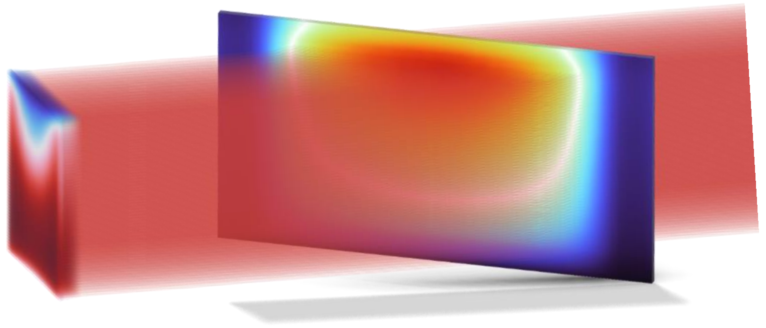
This project will develop models for laser performance as a function of top-level design parameters to inform our diode-pumped solid-state laser (DPSSL) design efforts.

Goals

- Quantify the impact of laser operational parameters (repetition rate, pulse length, etc.) on reactor performance (power output, cost).
- Use the Digital Twin to define a range of design parameters that satisfy FPP performance targets, producing component-level requirements.



Amplifier sub-system



Transmission optics simulations

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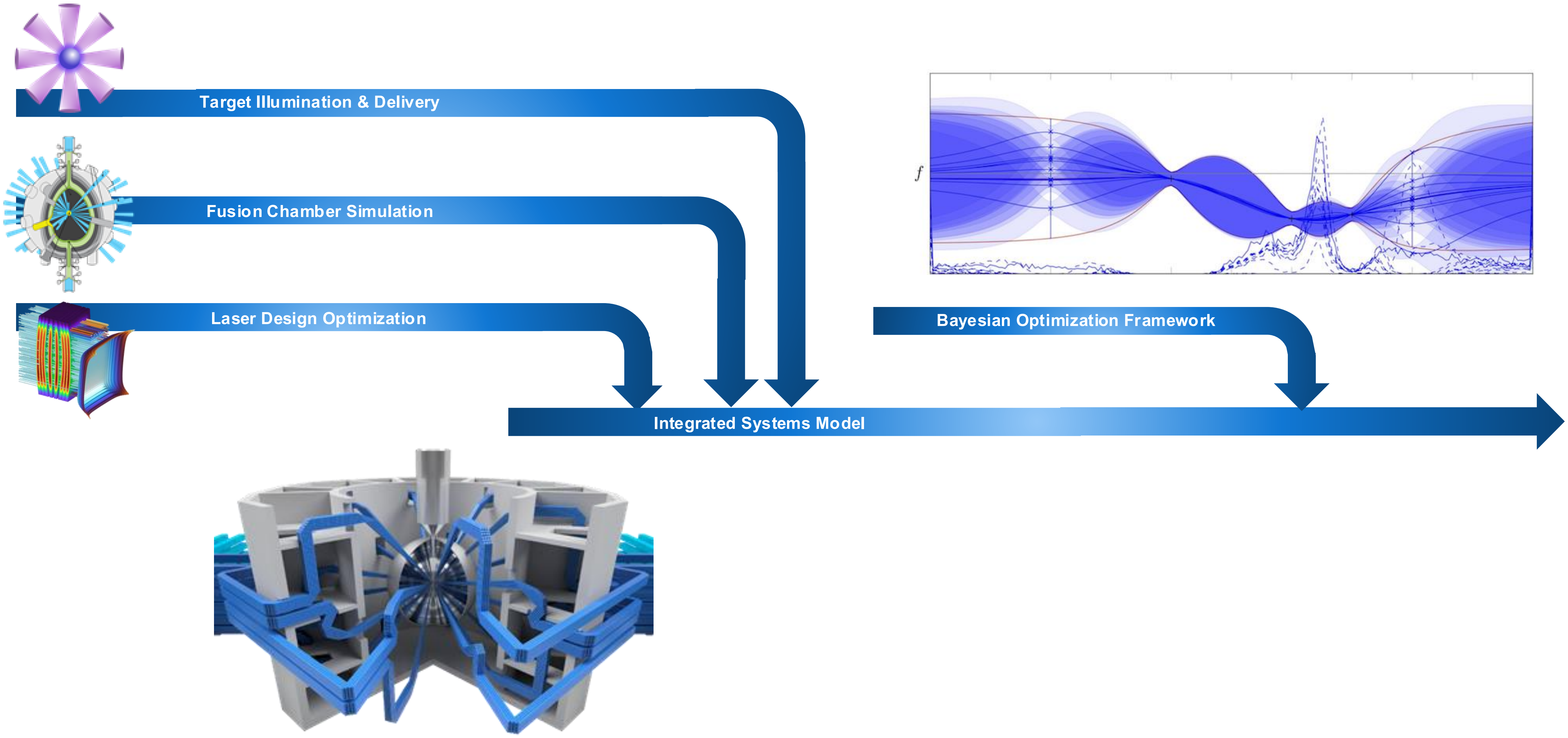
By connecting its modules into a coherent architecture, the Digital Twin enables comprehensive and global optimization of the FPP system



Bayesian Optimization (BO) turns the Digital Twin from a passive model into an intelligent system that actively recommends optimum operating points

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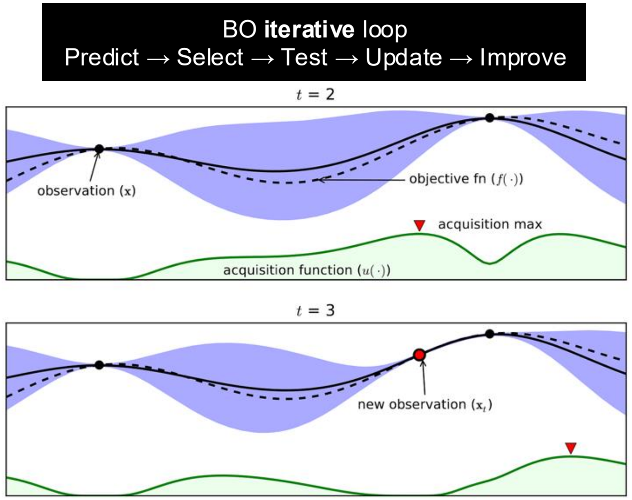
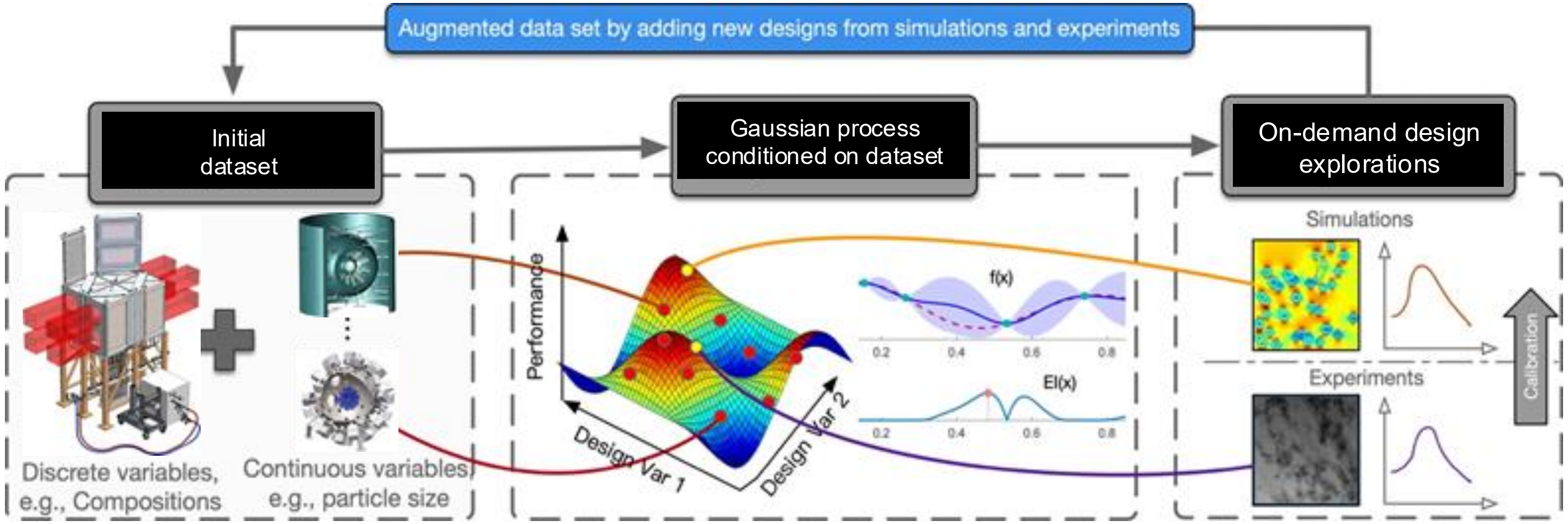
Find multi-variable optimal operating conditions efficiently (injection, timing, steering, laser parameters)

Reduce experimental cost by minimizing the number of required data points

How It Works:

- Surrogate Model: Learns a probabilistic approximation of system response & incorporates **uncertainty**
- **Acquisition Function**: Guides the next optimal experiment
- Balances *exploration* vs *exploitation*





The Digital Twin will enable global optimization to identify key reactor parameters and achieve commercial goals

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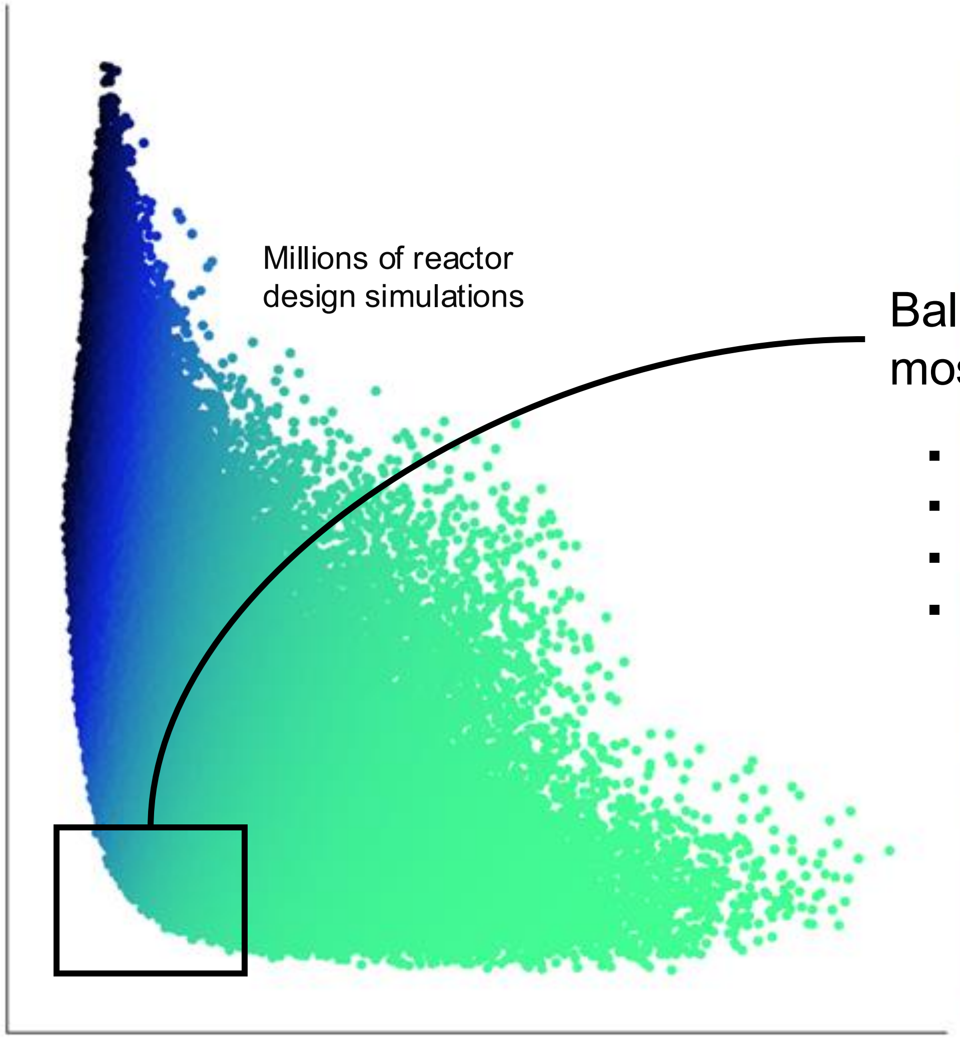
Multiple Cost Metrics

Capital Cost, LCOE, …



Balance cost & risk to find the most attractive design

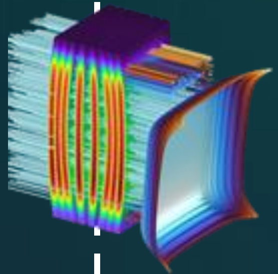
- Reactor power output
- Fusion gain & Repetition Rate
- Ignition concept & threshold
- Self-consistent R&D targets

Multiple Risk Metrics

TRL Level, Sensitivities, Cost of Failure, …

Our R&D Facilities will become our first Digital Twin demos

Experimental Facilities

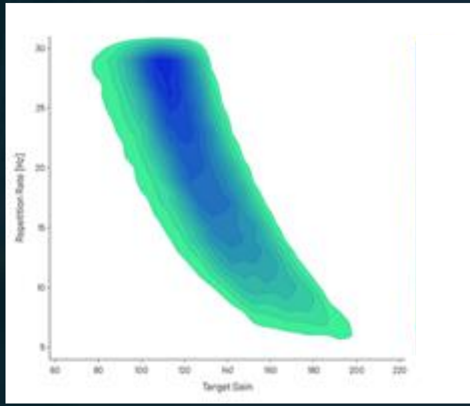


Digital Twin

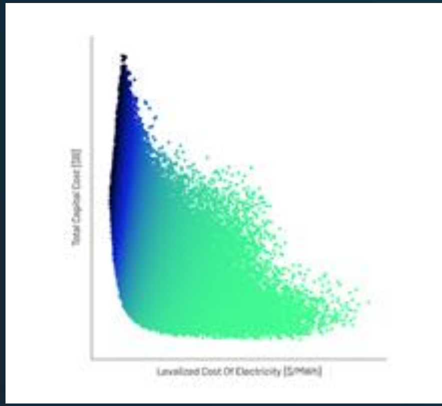
Carefully inform

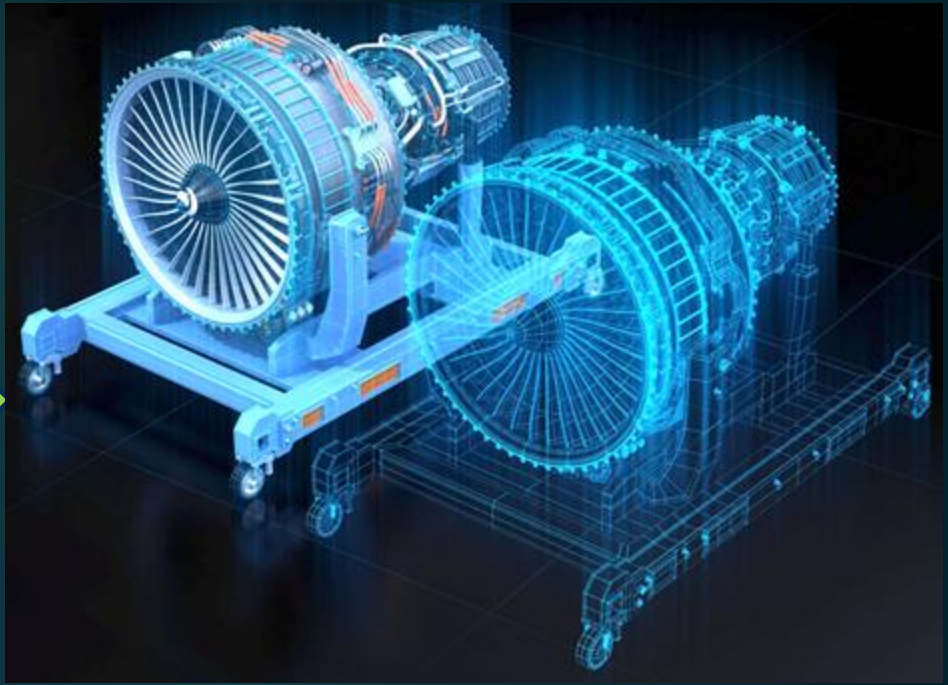
Optimal reactor designs that minimize risks

Rep Rate vs Target Gain



Total Capital Cost vs LCOE





https://sybridge.com/digital-twin-technology/

Thank you for your attention

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Inertial Fusion Energy Modelling Capabilities that Need Development

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Chamber and Target Survival

First Wall Survivability
Predict long-term damage, degradation, and activation.

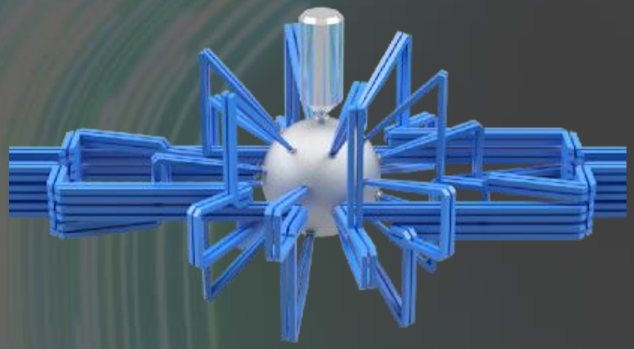
Target Survivability
Modeling chamber environment effects (shocks, ablation, irradiation) on target integrity

Chamber Environment
Ensure that the chamber can recover to acceptable conditions between shots

Fusion Core Physics

Target Dynamics
Multi-physics modeling of hydrodynamics, radiation transport, and kinetic effects, including instabilities (hydrodynamic, laser-plasma) and hot electron generation

Laser-Plasma Coupling
Simulations addressing instabilities, spectral effects, smoothing, and energy coupling optimization to ensure efficient laser energy delivery



System Infrastructure & Engineering

Fuel Cycle
Modeling the full tritium management loop to ensure regulatory compliance

Blanket Systems
Coupled simulations of fluid flow, heat/mass transfer, and neutronics for tritium breeding and extraction

Laser Chain Simulation
Modeling beam propagation, optics response to high fluence, defect growth, and frequency conversion for performance assessment

Foundational Data & Cost Assessment

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Developing accurate material models, including two-temperature equations of state (EOS), opacities, and atomic physics

Activation and Waste
Simulations to support lifecycle analysis and regulatory planning for radioactive waste mitigation

Reactor Cost
Integrating all component models to evaluate overall reactor performance, reliability, and cost

Inertial Fusion Energy Modelling Capabilities that Need Development

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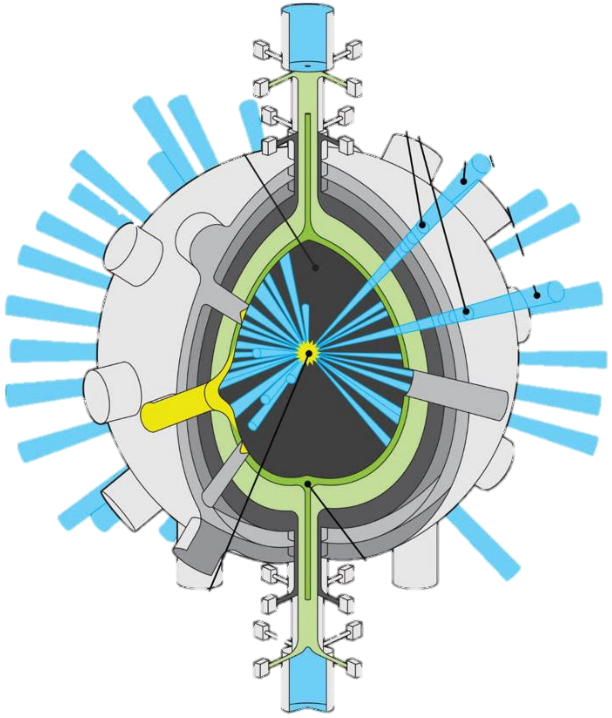
Chamber & Target Survival

- **First Wall Survivability:** Coupling particle transport (neutrons/gamma) with material response to predict long-term damage, degradation, and activation.
- **Target Survivability:** Modeling complex chamber environment effects (shocks, ablation, irradiation) on target integrity using fluid-gas dynamics and structural mechanics.
- **Chamber Environment & Recovery:** Simulating gas/liquid dynamics, ablation, material compatibility, heat transfer, ensuring the chamber can recover to acceptable conditions (e.g., vacuum pumping, debris mitigation) between shots.

Fusion Core Physics (High-Fidelity Modeling)

- **Target Dynamics:** Comprehensive multi-physics modeling of hydrodynamics, shocks, radiation/laser transport, and kinetic effects, including instabilities (hydrodynamic, laser-plasma) and hot electron generation.
- **Laser-Plasma Coupling:** Critical simulations addressing instabilities, spectral effects, smoothing, and energy coupling optimization to ensure efficient laser energy delivery.



Fusion reactor

System Infrastructure & Engineering

- **Tritium Inventory and Fuel Cycle:** Modeling the full tritium management loop, including processing times, contamination, and balance-of-plant interactions to ensure operational and regulatory compliance.
- **Blanket Systems:** Coupled simulations of fluid flow, heat/mass transfer, and neutronics for tritium breeding, extraction, and power optimization.
- **Laser Chain Simulation:** Modeling beam propagation, optics response to high fluence, defect growth, and frequency conversion for performance and reliability assessment.

Foundational Data & Cost Assessment

- **Material Data:** Developing accurate material models, including two-temperature equations of state (EOS), opacities, and atomic physics.
- **Material Activation and Waste:** Simulations to support lifecycle analysis and regulatory planning for radioactive waste mitigation.
- **Reactor Cost Performance:** Integrating all component models to evaluate overall reactor performance, reliability, cost, and incorporating physics outputs into economic models.