Boosting Fusion Reactor Performance Through Machine Learning Predictions

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Motivation

Climate Change & The Electrical Grid

Weather Disaster Costs[1] — 2000 → 4x → 2025

Future Energy Needs[2] — 2025 → 3x → 2050

"The Energy of The Future"

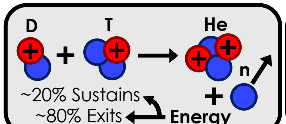
Challenges
- ☒ Reliability →
- ☒ Capacity →
- ☒ Emissions →
- ☒ Economics →
- ☒ Support →

What's Needed?
- ☑ 24/7 Baseload
- ☑ High Scalability
- ☑ Low/No Carbon
- ☑ Long-Term Viable
- ☑ Safe & Controlled

*Fusion Energy **Alone** Can Be All*

Background

Fusion Reactors Emulate The Sun



Plasmas
- 4th State of Matter
- Usually VERY hot
- Behaves like Fluid
- Must Be Controlled

Tokamaks Help Sustain Plasma

"Spinning Plasma"

Upcoming "Pilot" Plants

SPARC — U.S. (2026)

iter — E.U. (2039)

Tokamak Plasma "Moves" As Fluid

Diffusion(D)
Spreading Out No "Direction"

Convection(V)
Moving Around One "Direction"

The Strengths of D&V Determine Plasma Behavior

General Approach

Opportunity For Improvement

Current SOTA: Inaccurate, Hard, Complicated, Slow, Bespoke → **ML Benefits**: Exact, Easy, Simple, Fast, Generalized

Implementation Workflow

Data Generation
- Gather Exp. Data
- Generate More
- Verify Coherence

→ **Preprocessing**
- Filter Out Noise
- Calculate Density
- Create Database

→ **ML Model**
- Create Network
- Optimize Model
- Make Predictions

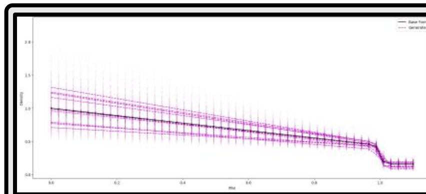
→ **Validation**
- Test Predictions
- Score Results
- Improve Model

Data Challenges

Fusion Data Is Expensive

1000s Of "Shots" → 100s Of Million$

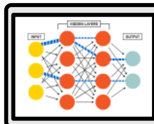
Additional Data Must Be Generated



Experimental Data Is Tweaked "Randomly"

Machine Learning Methodology

Machine Learning Implementation

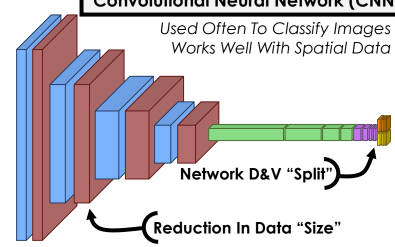


Neural Networks
- Represents Relationships
- Learns Weights For Each
- Learning Is Data-Driven
- Can Represent Anything

Neural Network Architecture Used

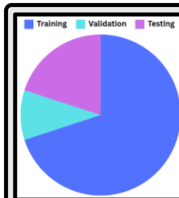
Convolutional Neural Network (CNN)

Used Often To Classify Images
Works Well With Spatial Data



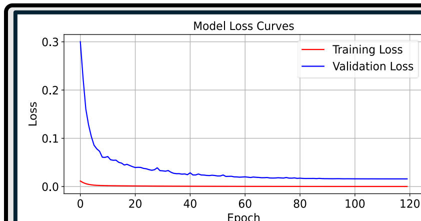
"Compressing" Input To Relevant Data Only

Model Training Process



Considerations
- Data Split For Testing
- Trained On 100k Samples
- Training Takes ~2hr
- Model Run On Single PC
- Scored On Diff From Exp.
- Weights Outliers Heavily

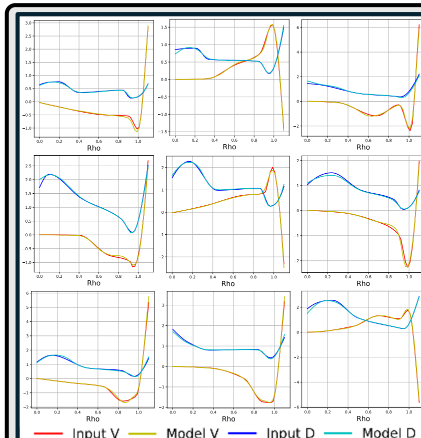
Model Performance



Results

Model Predicting Reactor Behavior

(Existing Methods' Error 10-20%)



Samples Selected Randomly

Impacts

Better Predictions Are Very Powerful

Better Predictions → Higher Performance → Faster Progress → Deeper Understanding

Acknowledgements

[1]: A. B. Smith 2024, NOAA NCEI 10.25921/sktw-7w73
[2]: Denholm et al. 2022 NREL 6A40-81644
[1] S. Mordijck 2020 Nucl. Fusion 60 082006
[2] E. Stefanikova et al 2016 Rev. Sci. Instrum. 11E536
[3] A.M. Rosenthal et al 2024 Nucl. Fusion 64 036006

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