Boosting Fusion Reactor Performance With Machine Learning

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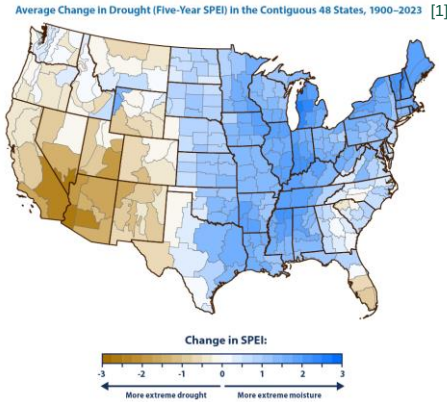
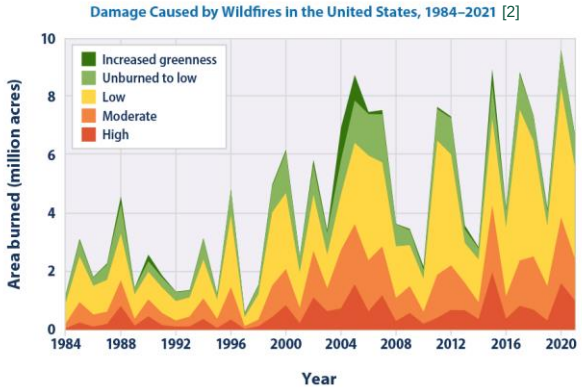
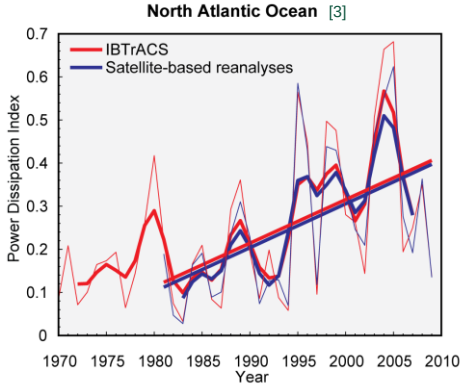
William & Mary
Arts & Sciences

Some Concerning Trends

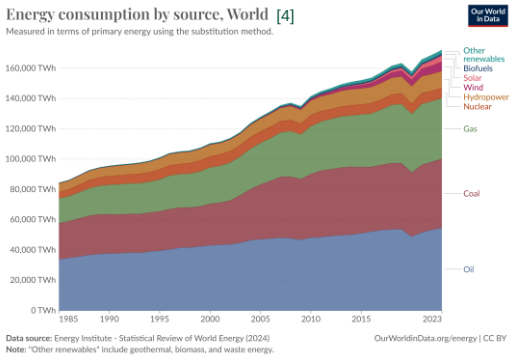
Climate Effects

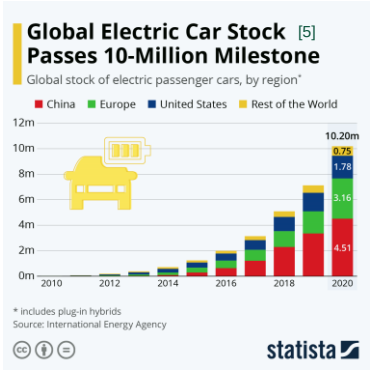


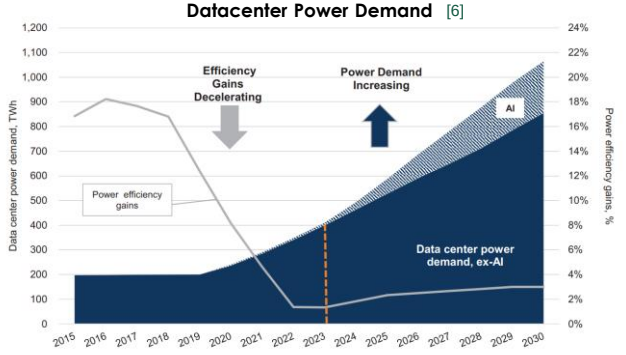




Energy Demand







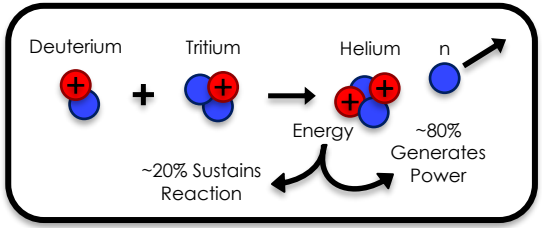
Fusion To The Rescue

What Is Needed?

- ☑ 24/7 Generation
- ☑ Massive Capacity
- ☑ Low/No Carbon
- ☑ Long-Term Viable
- ☑ Controlled

Fusion Has It All.

How Does It Work?



- Small Atoms → Large Atom
- Opposite of Fission

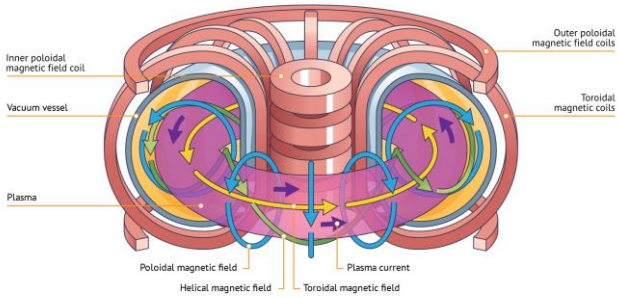
What Is Needed?

- High Density/Pressure/Temperature
- Plasma must be Confined
- Non-Fuel gasses pumped out
- Stable Plasma Structure
- Able to withstand heat loads
- Steady-State Operation

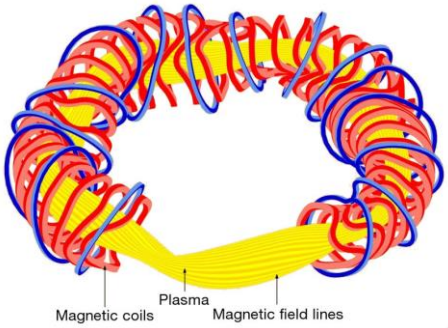
Confinement Is Key!

Magnetic Confinement

Tokamak [7]

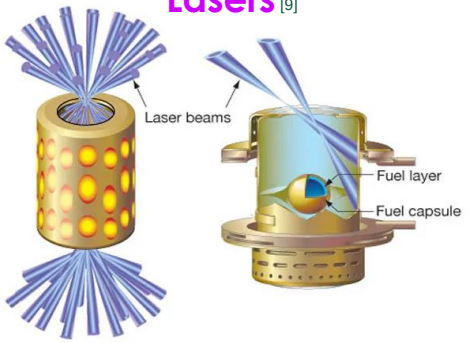


Stellarator [8]



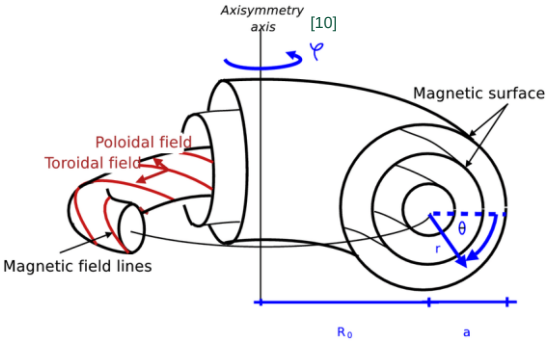
Inertial Confinement

Lasers [9]

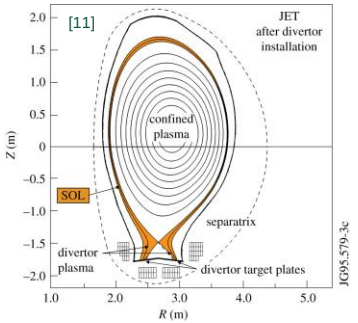


Tokamak Crash-Course

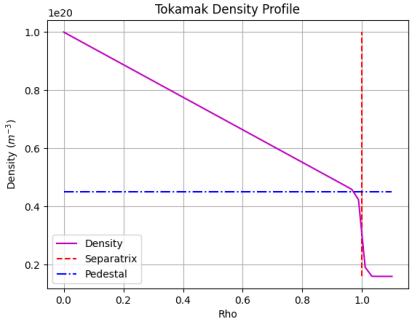
Tokamak Coordinates



Cross-Section



Density Profile Layout



- Field geometry is critical
- Pedestal Shape sets density evolution
- Certain states perform much better
- Steady-State density critical to future reactors

Plasma Transport

Continuity

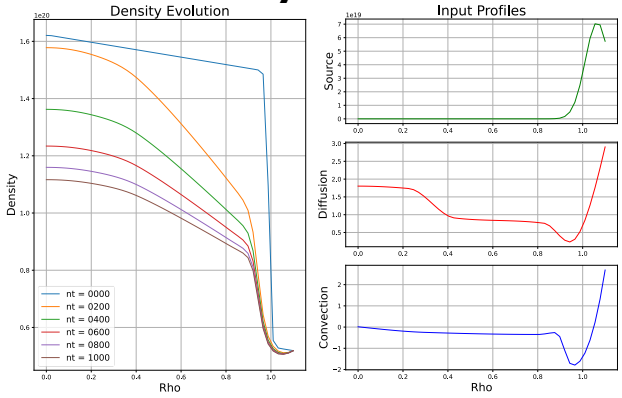
$$\frac{\partial n}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}(r\Gamma) + S$$

D-V Ansatz

$$\Gamma = -D\frac{\partial n}{\partial r} + vn$$

- Plasma modeled as a fluid, radially
- S is Source/Sink term (fueling)
- D and V are transport coefficients
- Cannot be measured directly, analytical methods slow and coarse

Density Evolution



Device Used

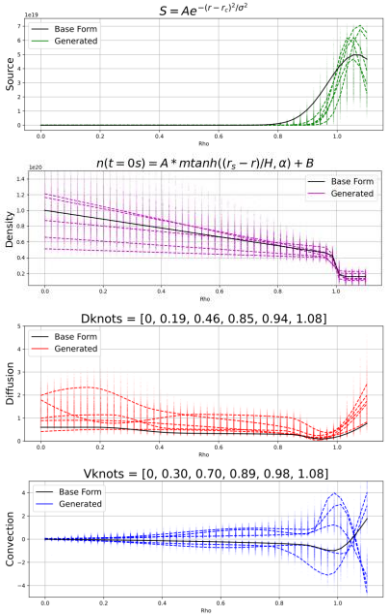
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

GENERAL ATOMICS

Addressing Data Challenges

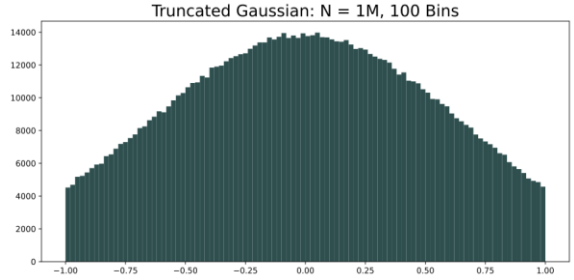
Input Profiles

- ML needs LOTS of data
- Too Little Exp data
- Generate data to mimic experimental data



Generation Considerations

- Truncated Gaussian Kernel Used
- Distribution kept wide to span Experimental Parameter Space
- 100,000 sets generated with no overlap, fully independent

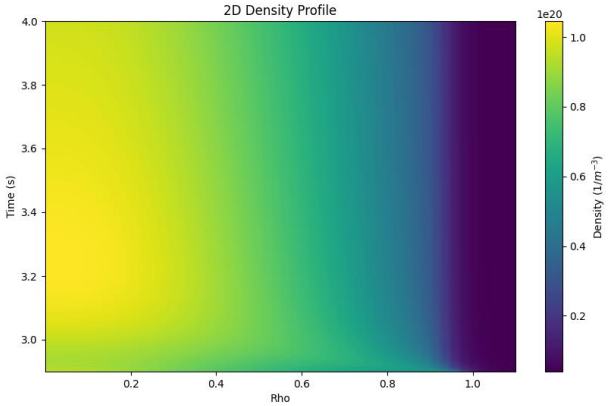


Future Proofing

- Takes any uniform grid size (nt,nr) = (1000,50) used for project
- All steps compatible with non-constant D,V, and S profiles

2D Density Data

- For model to find D and V, need data on density evolution in time
- Finite Diff Solver (Matrix Form)
- existing solvers too slow ~20s per
- Optims and GPU Accel led new solver to ~0.1s per (200x Faster)

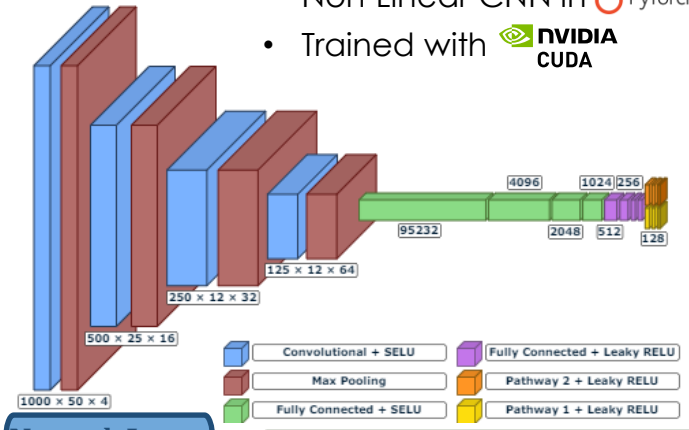


- 2D array paired with input arrays
- Saved into database file (40GB)
- Generating parameters stored as well

Model Creation and Training

Model Architecture

- Non-Linear CNN in PyTorch
- Trained with NVIDIA CUDA



Network Inputs

Rho: 1D
Time: 1D
Source: 1D
Density: 2D

Network Outputs

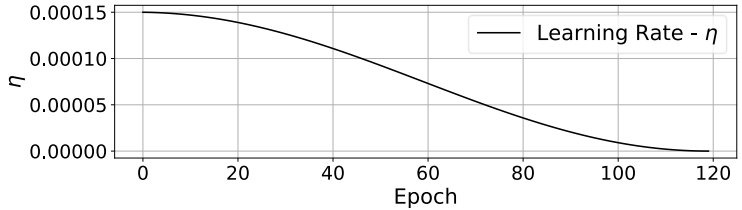
Diffusion: 1D
Convection: 1D

Network Characteristics

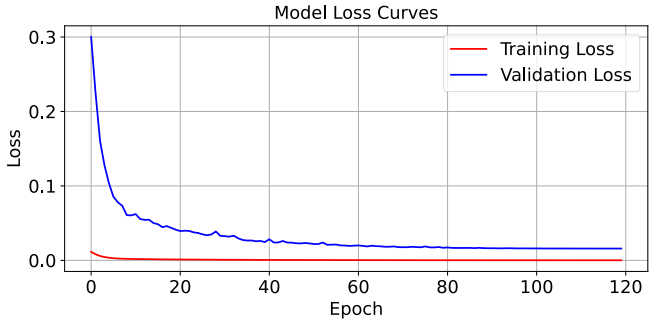
- ❑ Non-Linear Activation Functions
- ❑ Split Output Data Pathways
- ❑ Learning-Rate Scheduler
- ❑ Huberloss Criterion (delta = 0.75)
- ❑ AdamW optimizer function
- ❑ Data Standard Scaling
- ❑ Optimized Runtime

Training Process

- Training/Validation/Test Split of 70/10/20 Implemented
- Trains in ~1hr, 120 epochs (RTX 4090, 7950x3d, 128GB RAM)



Training Loss	Validation Loss	Test Loss
0.0042	0.0159	0.0168

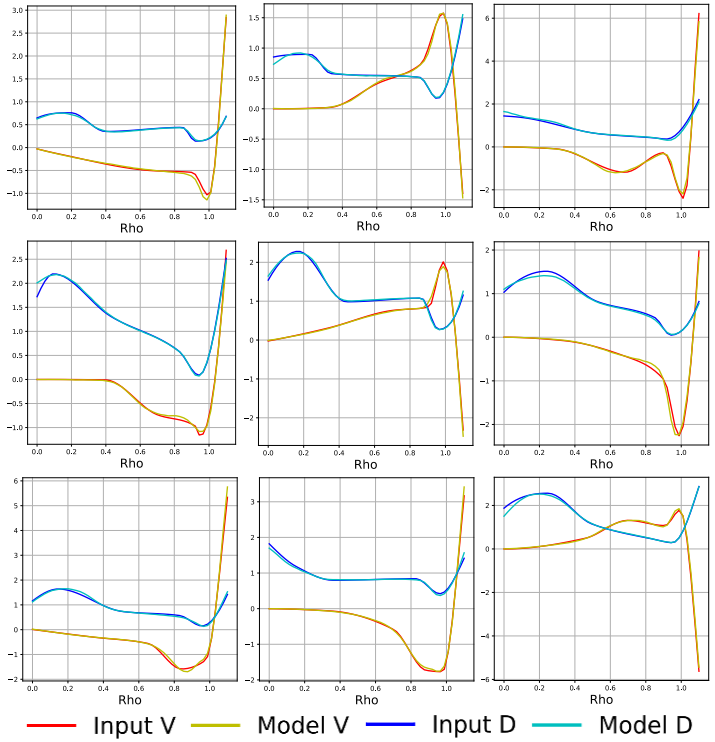


- Gap between losses suggests overfitting
- Saturated at ~60 epochs training
- Model error is exceedingly low

Results and Project Future

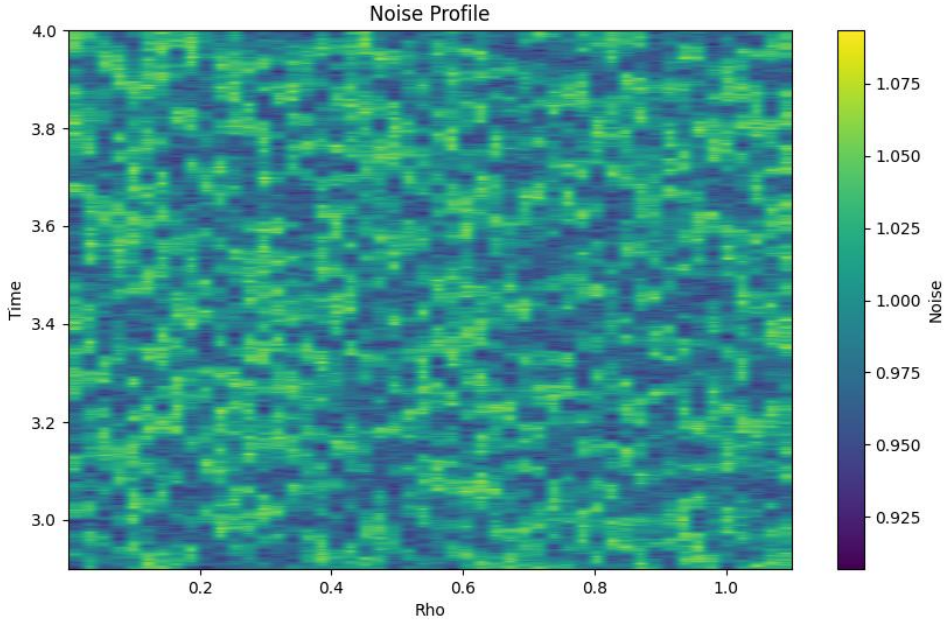
Results

- Fit is exceptional as Data Error ~10%
- Small deviations in D profile near the core



Ongoing & Future Work

- Benchmark Model on additional Experimental Data
- Inject Noise into data and verify model still functions
- Extract trends and relationships from model weights
- Incorporate Recurrent elements for real-time inference



Thanks For Listening!

Collaboration

Open and FAIR Fusion For Machine Learning Applications

William & Mary Arts & Sciences

Massachusetts Institute of Technology PSFC Plasma Science and Fusion Center

AUBURN UNIVERSITY

EPFL

UK Atomic Energy Authority

College of Engineering UNIVERSITY OF WISCONSIN–MADISON

The HDF Group

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN

Project Mascots

Leo, age 3mo.

Houdini, age 8mo.

Very helpful when coding…

References

Figures

[1]: *(Climate Change Indicators: Drought | US EPA, 2024)*
[2]: *(Climate Change Indicators: Wildfires | US EPA, 2024)*
[3]: *(2014 National Climate Assessment | NCA, 2014)*
[4]: *(Ritchie et al. United States Energy |OWID, 2022)*
[5]: *(Richter, Global Electric Car Ownership | Statistica, 2021)*
[6]: *(Singer et al. GS Sustain Datacenter Growth | Goldman Sachs, 2024)*
[7]: *(Nuclear Fusion, Tokamak Main Principles | Energy Encyclopedia, 2024)*
[8]: *(Bovet, Suprathermal Ion Transport | University of Zurich, 2015)*
[9]: *(Obenschain, Tutorial On ICF | Naval Research Lab, 2015)*
[10]: *(Nguyen, MHD Activity and Energetic Particles | IP Paris, 2009)*
[11]: *(Costley, Compact Spherical Tokamak PP | Tokamak Energy, 2019)*

Resources

- PPPL Intro to Plasma Course
- A Short Introduction to Plasma
- Github Site (Under Construction)

Papers

[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*
[4]: *F. Sciortino 2021 MIT Libraries 142810*

Acknowledgement

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