Progress in the Application of Machine Learning and Artificial Intelligence To Enhance *EFIT* Equilibrium Reconstruction for Fusion Data Analysis and Real-Time Applications

by
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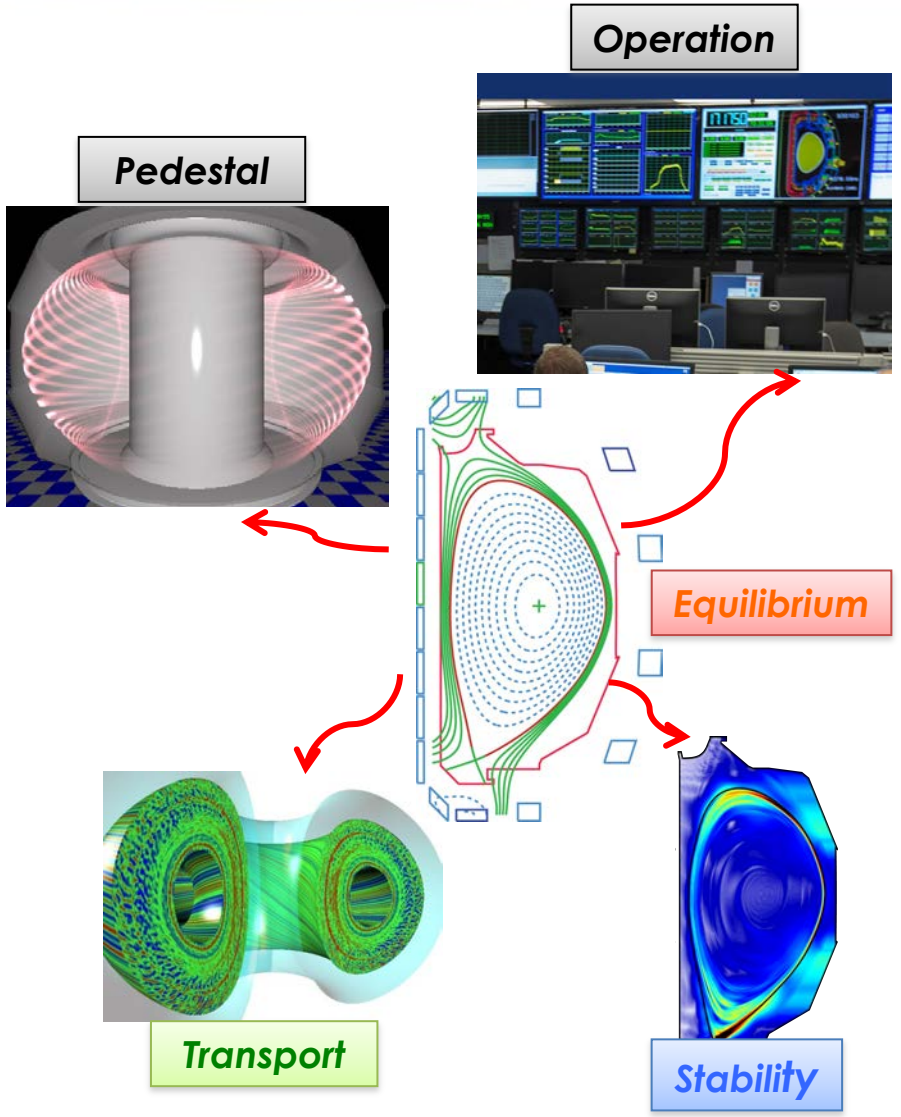
Equilibrium Reconstruction Is Fundamental to Tokamak Research and Operation

- Provides essential magnetic geometry and current and pressure profiles information necessary for tokamak data analysis and interpretation, plasma control, and code and physics model validation
- Contributed to several major tokamak discoveries
  - Experimental verification of β scaling, negative central-shear regime, …
- Burning plasmas with their harsh radiation environment introduce new challenges
- *EFIT* extensively used in many tokamaks worldwide to support plasma operation, real-time control, and data analysis
  - Broad experimental equilibrium reconstruction databases exist
- Recent advance in solving inverse problems and development of machine learning (ML) technologies and advanced hardware can be employed to address these challenges
  - Offers the promise of moving to dynamics and real-time full kinetic equilibrium reconstructions currently limited to off-line analysis



US FES *EFIT-AI* Project Harness Novel ML/AI Algorithms to Enhance Equilibrium Reconstruction for Modeling and Real-Time Applications

- **ML-enhanced Bayesian framework to automate and maximize information from measurements**
- **Model-Order-Reduction (MOR) -based physics-informed ML models to efficiently guide search of solution vector**

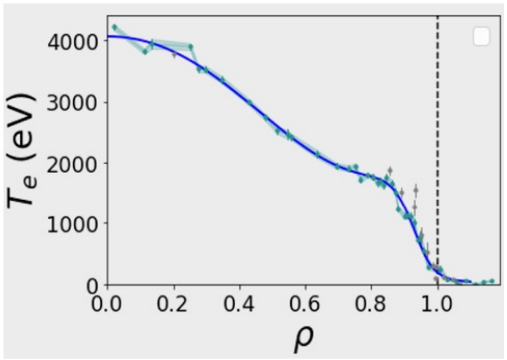
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

JET

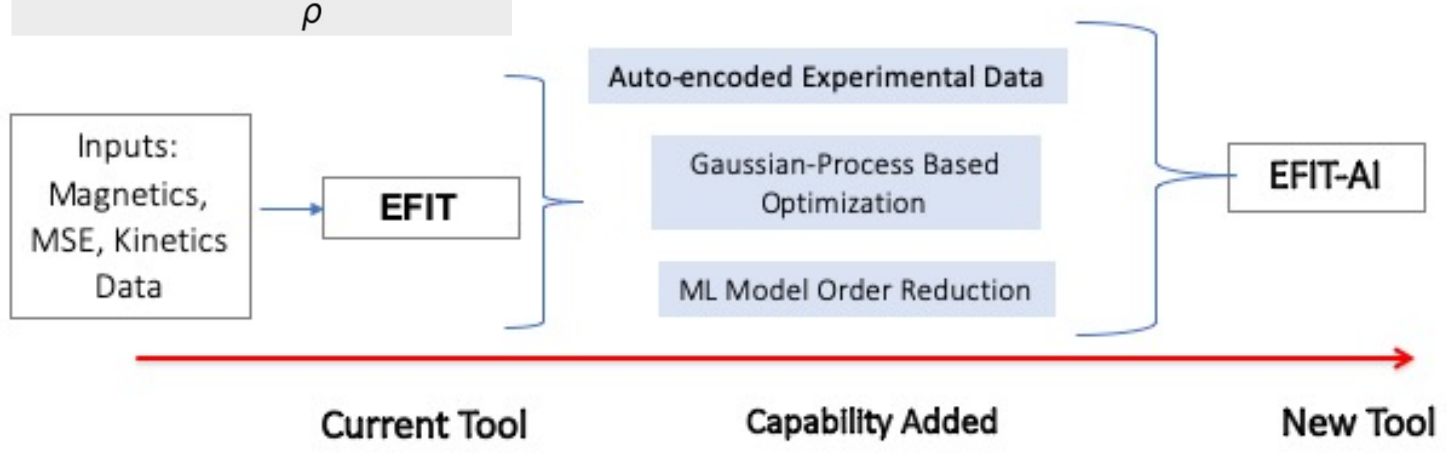
KSTAR

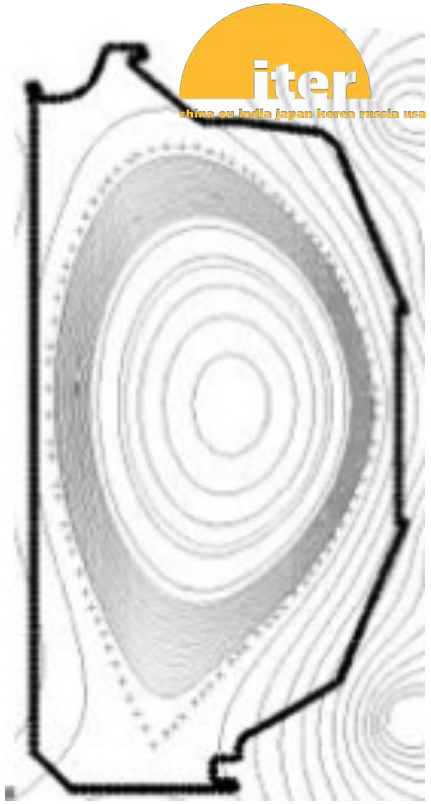
EAST

NSTX



ML uses DIII-D and other tokamak data to enhance equilibrium reconstruction and control





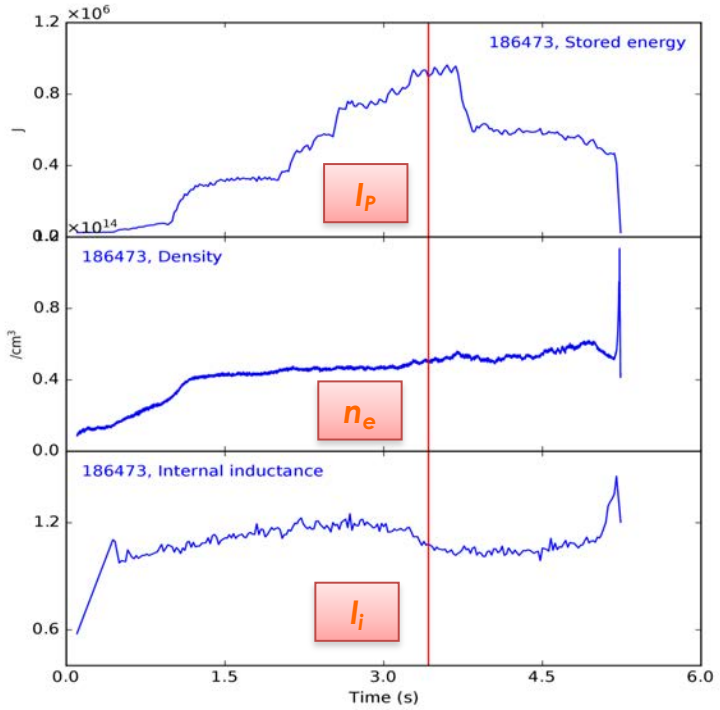
Outline / Summary

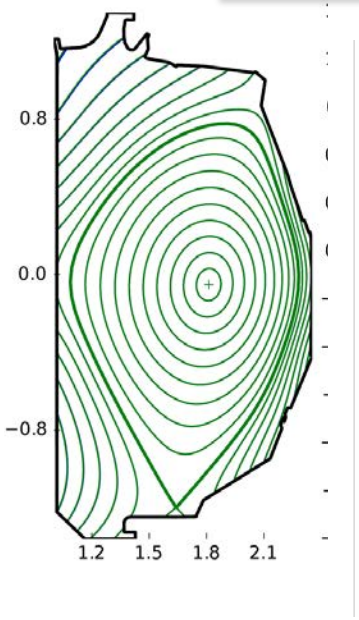
EFIT-AI project are organized around 4 major research-development topics: *Core Equilibrium Solver, EFIT MOR, Bayesian Framework, and 3D Perturbed Equilibrium*. Progress in these areas includes:

- **A MPI device-independent portable core equilibrium solver to ease adaptation of ML enhanced reconstruction algorithms has been created and successfully tested on several platforms with various compilers**
  - **Performance tests look promising achieving ~ 7x speed-up with aggressive optimizations and more cores**
  - **Single version runs on multiple tokamak devices: DIII-D, NSTX-U, EAST, ITER, BEST**
- **A large *EFIT* database comprising of DIII-D magnetic, MSE, and kinetic reconstruction data is being generated for developments of EFIT-MOR surrogate models to speed up the search of solution vector**
  - **NN-based MOR representations are being trained and tested with encouraging results**
- **A Gaussian-Process Bayesian framework is being developed and tested to improve processing of experimental input data**
  - **GPFlow change-point kernel can adapt its many hyperparameters to fit L-mode, H-mode, and H-mode with ITBs**
- **A 3D perturbed equilibrium database from toroidal full MHD linear response modeling with the MARS-F MHD code has been constructed for developments and testing of 3D-MOR surrogate models**
  - **SVD-based MOR techniques provide accurate representation of MARS-F computed 3D perturbed equilibria**

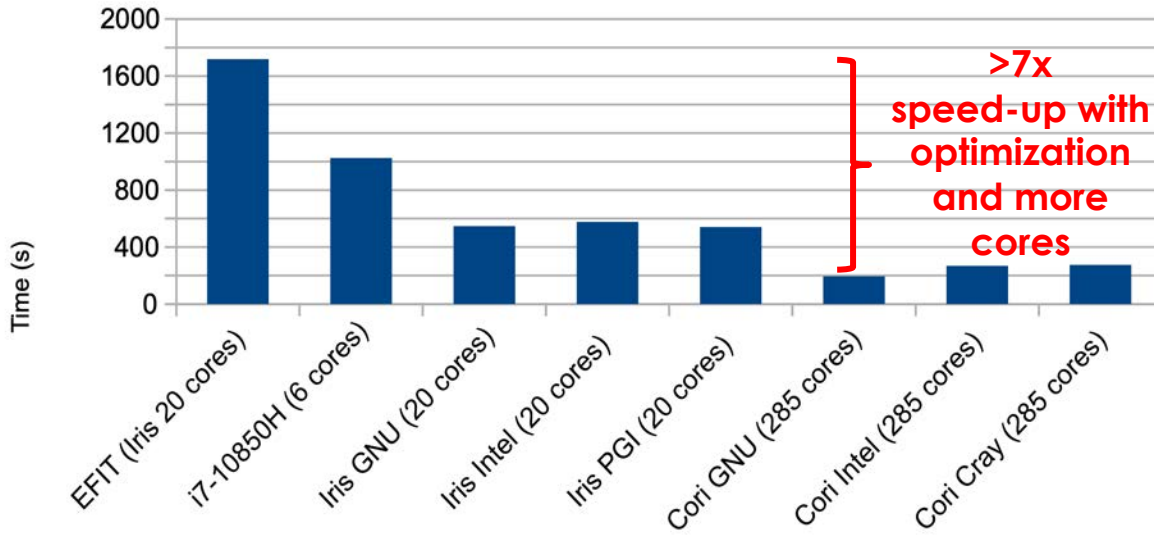
A MPI Device-Independent Portable Core Equilibrium Solver Has Been Created Based on *CMake* and Successfully Tested on Several Platforms and Tokamak Devices

- Successfully ported to multiple clusters and personal machines and built with GNU, Intel, PGI, and Cray compilers
- Compilation has been made possible with coding improvements and aggressive optimization
- High resolution equilibria (2049 × 2049 grid) can be run on machines with large memory (128GB)
- Successfully tested for DIII-D, NSTX, EAST, ITER, and BEST devices
- Installations are available to users on GA Iris, NERSC Cori, and PPPL Portal
- Additional layers of parallelism is being explored to further leverage exa-scale systems



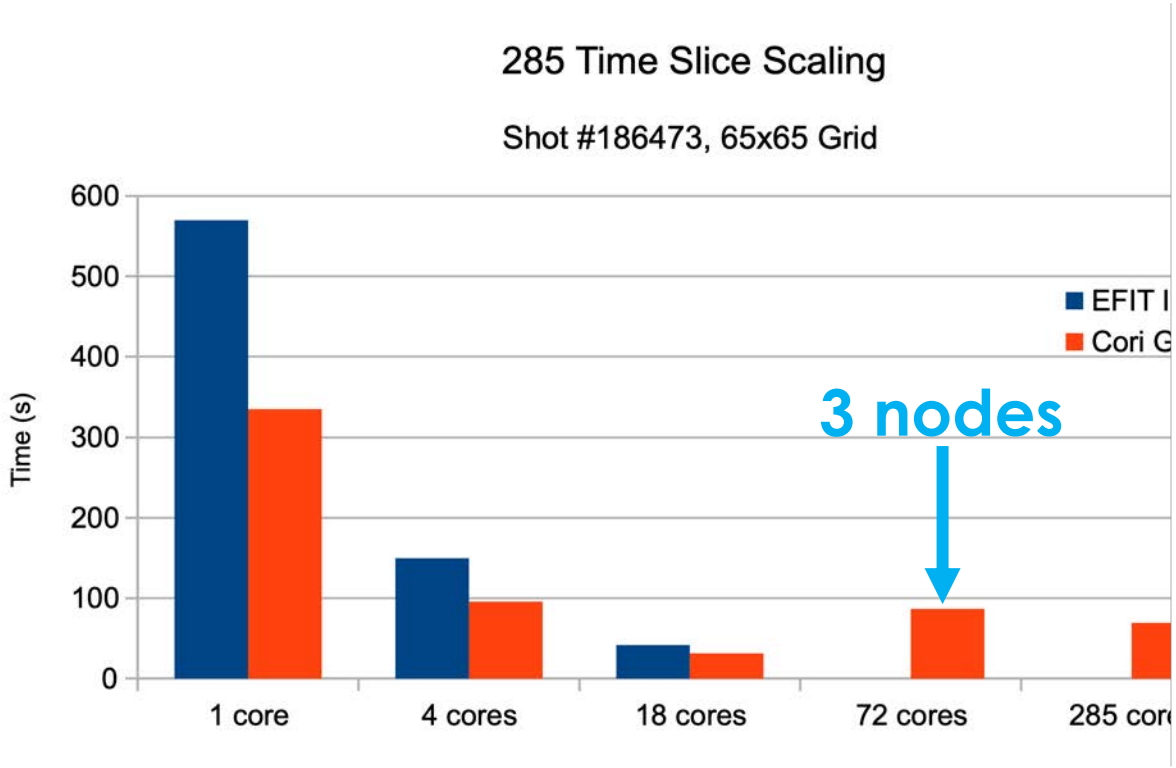


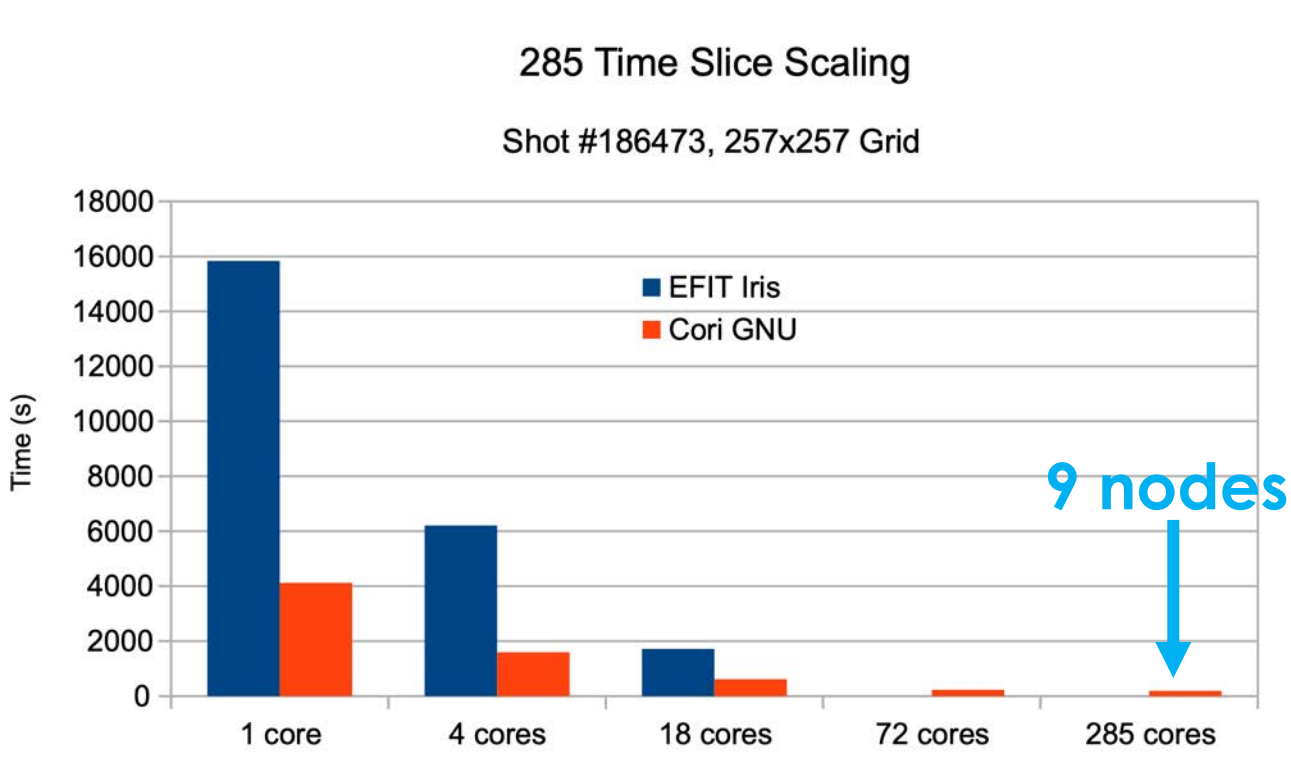
DIII-D Negative Triangularity, 285 Time Slices on 257 × 257 Grid



Processor Scaling Is Limited by Data Transfer and I/O

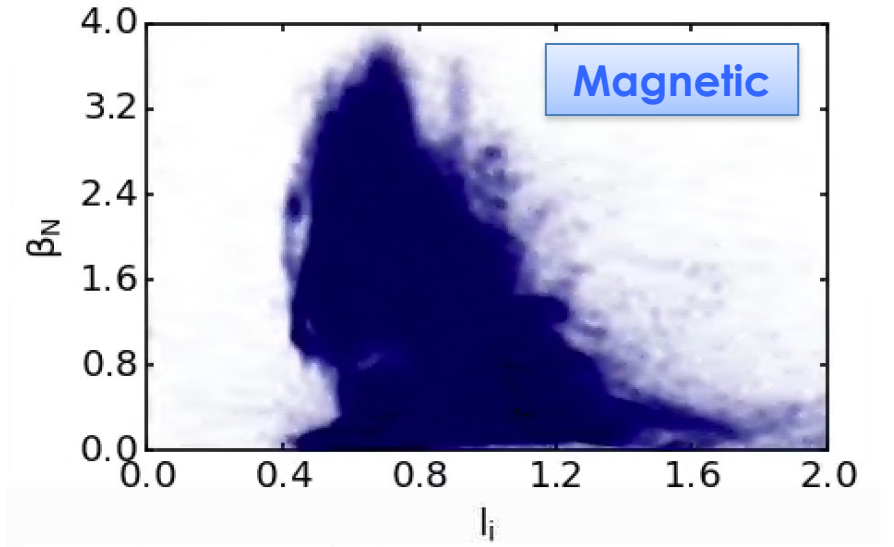
- Performance improves with the number of processors, until they are distributed across multiple nodes
- Data transfer bottleneck is hidden by additional compute requirements for the 257 × 257 grid case

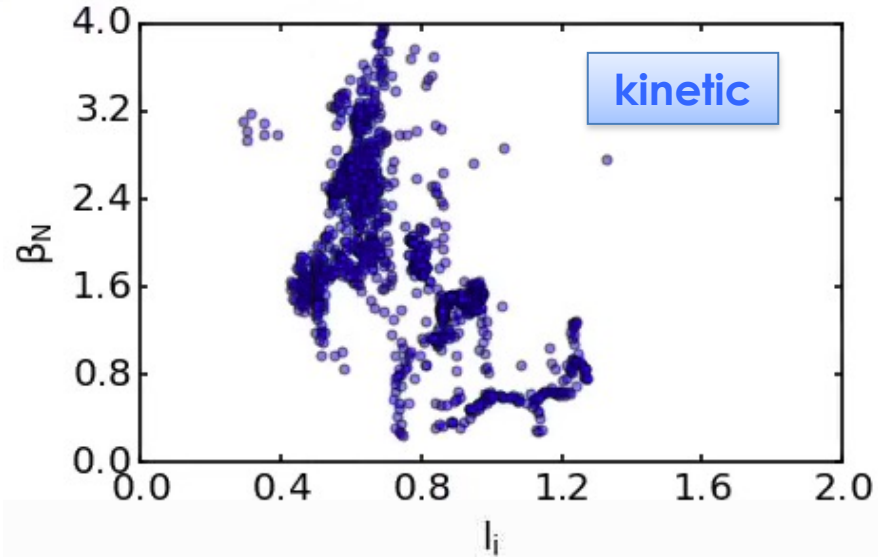




An *EFIT* Database Comprising of DIII-D Magnetic, MSE, and Kinetic Reconstruction Data Has Been Generated

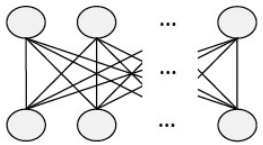
- **Leverage *OMFIT*/*OMAS* developments**
  - *OMAS* format: Very complete record of discharge and *EFIT* runs (complete provenance)
  - *OMAS* easily converts to IMAS
  - HDF5 used as core file storage: self-describing, highly-performant, works well with AI tools
  - *OMFIT*: Enable scripting of generating *EFIT* and export to *OMAS*
  - *Needed data extracted to meet EFIT-AI needs*
- **Contains 4 types of DIII-D *EFIT* runs**
  - Magnetics (438,986 equilibria)
  - Magnetics + MSE (299,991 equilibria)
  - Gathering existing Kinetic *EFIT*s (~1500 equilibria so far)
  - CAKE (Automated kinetic *EFIT*s)
- **Current plans for distribution**
  - Use NERSC as central database storage and considering publishing on Zenodo or similar service





NN-Based MOR Representations Are Being Trained and Tested with Encouraging Results

- **A parallel Python framework extracts data from the database to construct I/O**
  - Compatible with IMAS data format,
  - Designed to handle exceptions due to test, vacuum, and disruptive shots
  - Contains independent modules for separate tasks
  - Uses physically-informed feature normalization
- **Datasets**
  - Total good shots: 185 shots (of ~2.1K total)
  - Total samples (time slices) = 35,443
  - Train samples = 31,943 (90% of Total)
  - Test samples = 3,500 (10% of Total)
- **Implementation**
  - Python PyTorch
  - Adam optimizer
  - Argonne's Swing GPU node: NVIDIA A100 40GB GPU

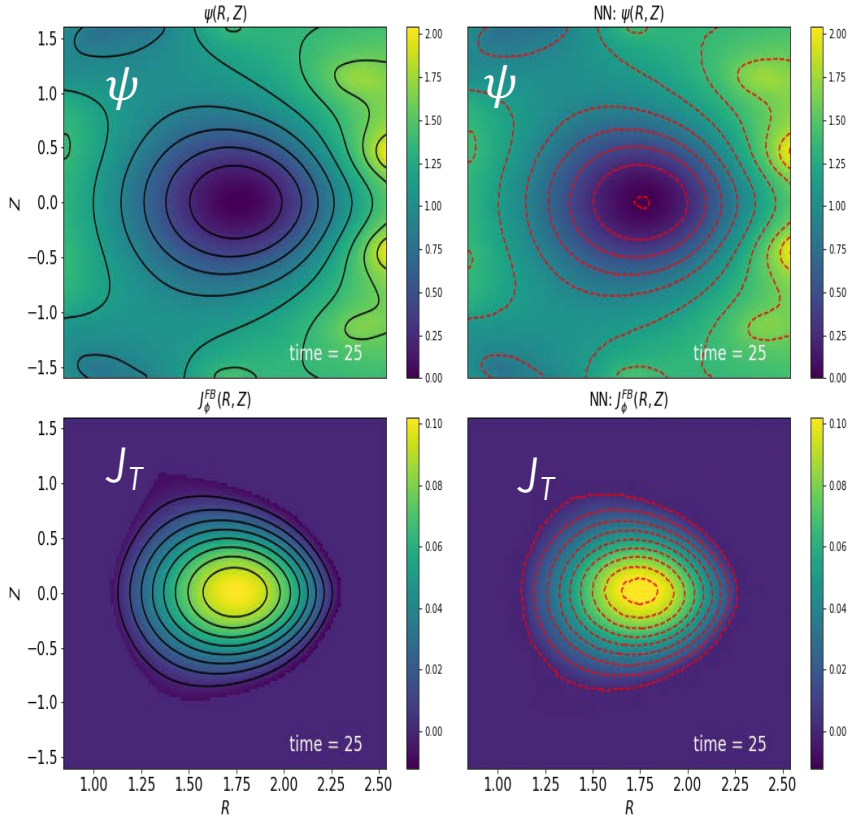


Feedforward neural nets:
- Three fully connected (FC) layers
- 500, 1000, 129*129 units at the layers
- LeakyRELU activation

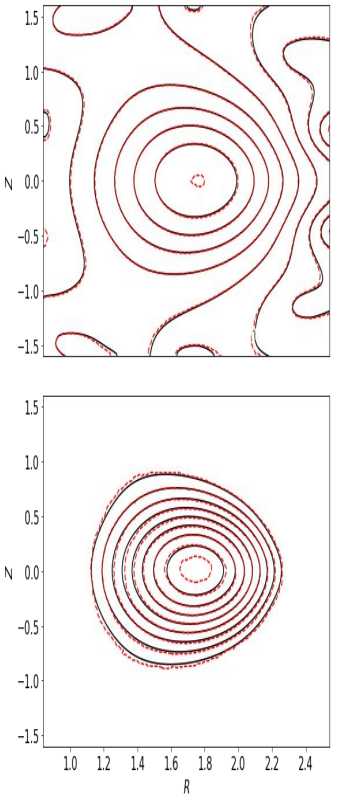
R^2 on test set	
ψ	0.99
J_T	0.90

True

Predicted

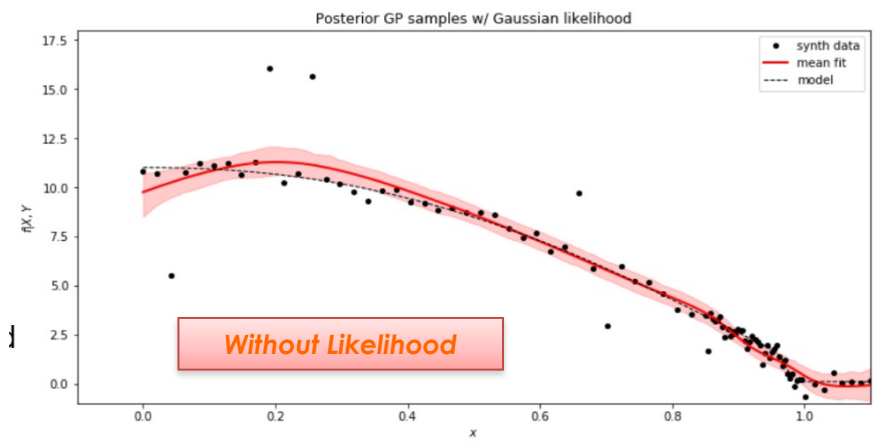


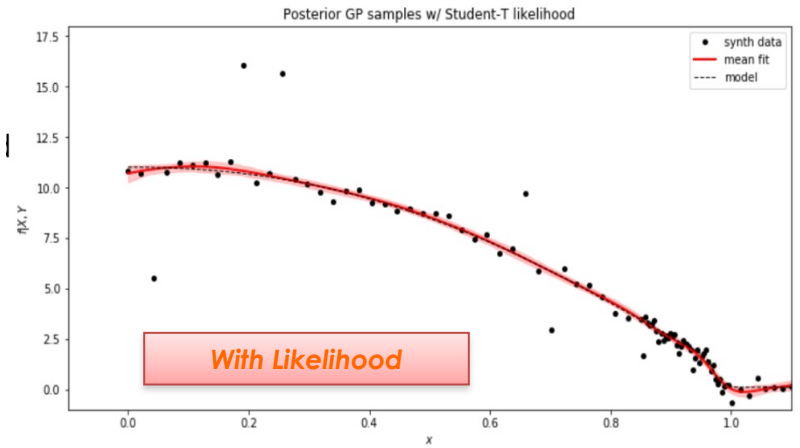
Contours overlaid

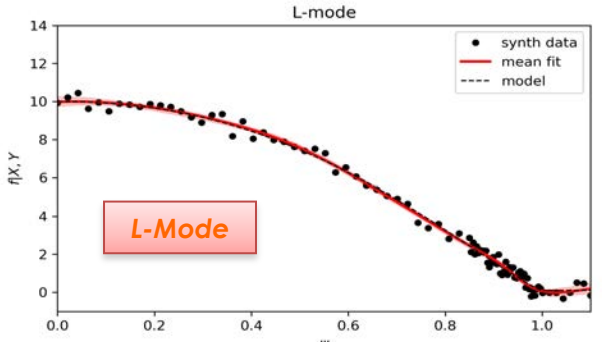


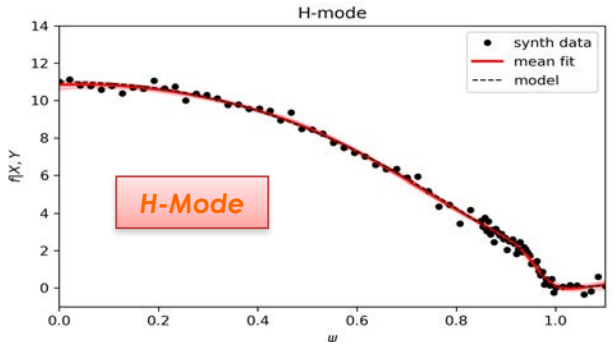
A Gaussian-Process Bayesian Framework Is Being Developed and Tested to Improve Processing of Experimental Input Data

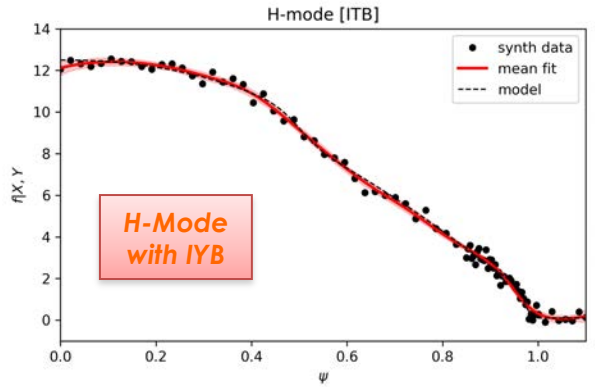
- **With proper settings Gaussian Process Regression (GPR) can produce**
  - smooth fit that avoids overfitting
  - error estimation
  - robustly handles outlying data
  - minimizes a priori assumptions
- **GPFlow change-point kernel can adapt its many hyperparameters to fit L-mode, H-mode, and H-mode with ITBs**
  - No a priori identification of regime is required and the same fitting settings are used for all fits
- **A non-gaussian likelihood with heavy tails is used to handle outliers**
  - Can reduce error and maintain a quality fit











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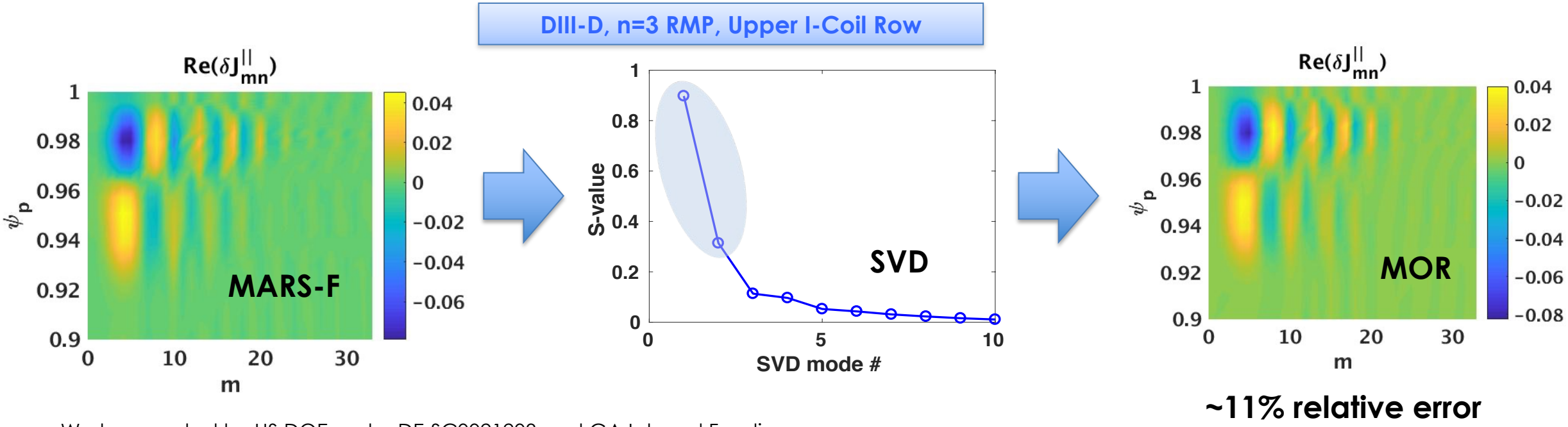
A 3D perturbed equilibrium database from MARS-F toroidal full MHD linear response modeling has been constructed

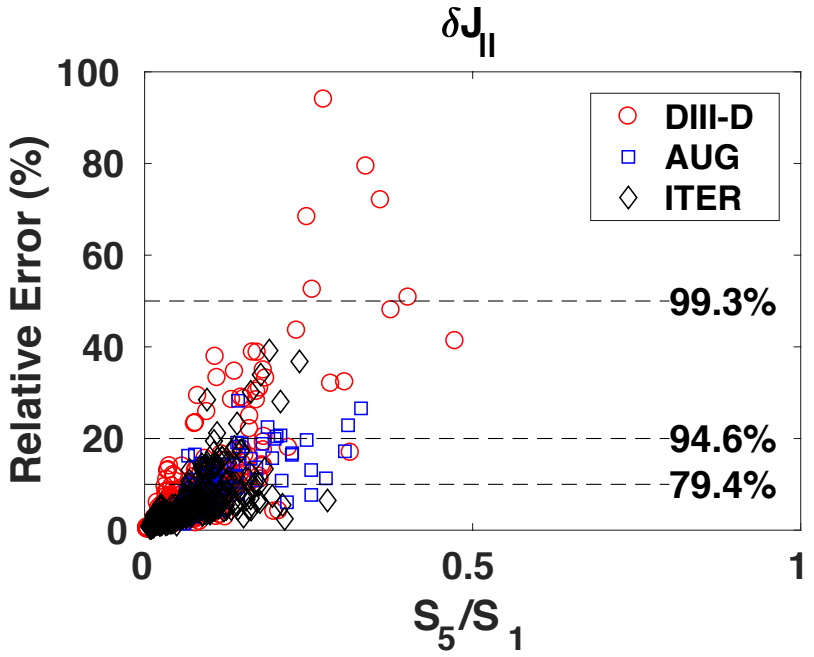
- **3D perturbed equilibrium due to externally applied 3D magnetic-field perturbation**
  - 4 devices DIII-D, MAST, AUG, and ITER with 1000+ data points
  - *n* = 1-4 fields with various rows of RMP coils
- **Each data point consists of** (δB, δJ, δp, ξ) **with volumetric distribution**
  - 15+ TB of total data
- **SVD-based MOR is efficient and provide reasonable accuracy in representing 3D perturbed equilibria**
  - ~10% relative error achievable with two SVD eigenstates

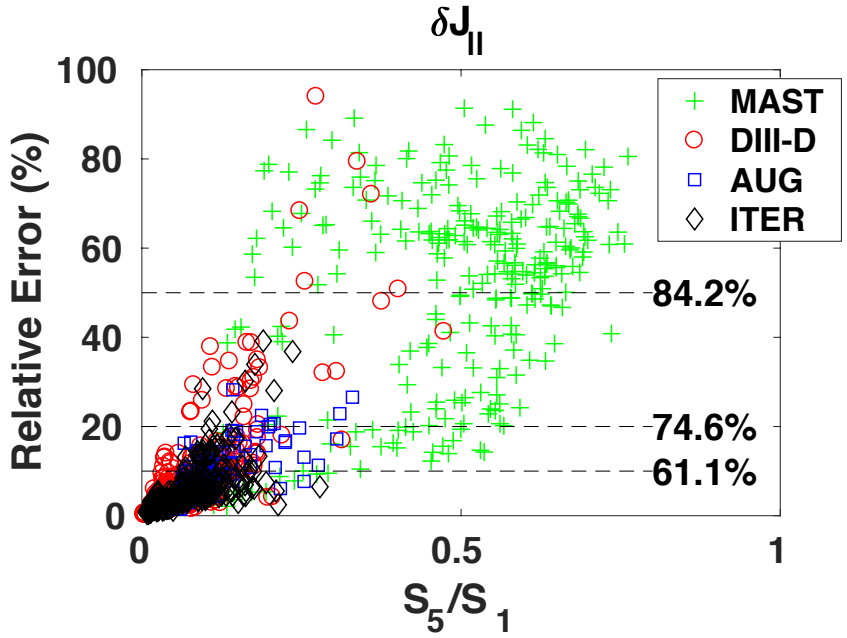


~11% relative error

Work supported by US DOE under DE-SC0021203 and GA Internal Funding

SVD Enables MOR of Perturbed Parallel Current with < 20% relative error for ~95% data points in conventional aspect ratio tokamaks





- **Include 5 SVD eigenstates for full database**
- **Relative error (RE) generally decreases with ratio of fifth to first singular values:** S_5/S_1
- **SVD performs less well for low aspect ratio device (MAST)**
  - With MAST data ~75% data with RE<20%
  - Without MAST data ~95% data with RE<20%

Work supported by US DOE under DE-SC0021203 and GA Internal Funding

Significant Progress Made in Developing a Portable AI/ML Enhanced *EFIT-AI* Equilibrium Reconstruction

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  - Performance tests look promising achieving ~ 7x speed-up with aggressive optimizations and more cores
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