

## Highlights

- We developed a KSTAR<sup>[1]</sup> data-driven forward model predicting future Mirnov-coil (MC) cross-power/phase spectrograms from recent MC history and operational control variables.
- Instead of predicting a task-specific plasma-state label, PanoMHD<sup>[2]</sup> predicts future diagnostic signals, enabling downstream readouts from the predicted MC spectrograms<sup>[3]</sup>.
- Here, L-H transition is used as a representative downstream readout.

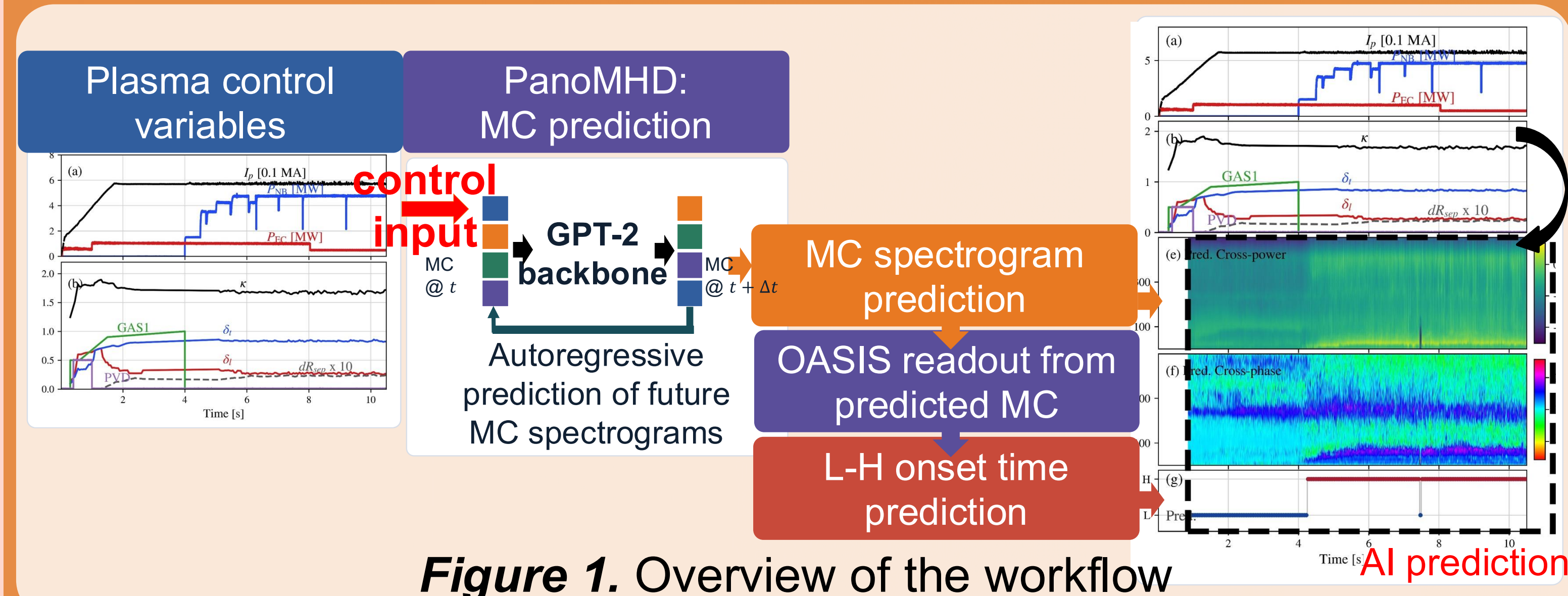


Figure 1. Overview of the workflow

## PanoMHD: Predicting MCs autoregressively from tokamak control

- PanoMHD performs GPT-like next-token prediction on MC-spectrogram tokens from recent MC history and operational controls.

- A 457M-parameter GPT-2-backbone<sup>[5][6]</sup> (36 layers, 16 heads, 1024 embeddings) is trained on KSTAR plasma-token sequences:  $p_{\theta}(\hat{\mathbf{z}}_t | \mathbf{z}_{t-L:t-1}, \mathbf{c}_{t-L+2:t}^{pre})$

- Autoregressive rollout: ( $L=10$  context length,  $\Delta t = 50$  ms)

$$\hat{\mathbf{z}}_t \sim p_{\theta}(\mathbf{z}_t | \mathbf{z}_{t-L:t-1}, \mathbf{c}_{t-L+2:t}^{pre}),$$

$$\hat{\mathbf{z}}_{t+1} \sim p_{\theta}(\mathbf{z}_{t+1} | \mathbf{z}_{t-L+1:t-1}, \hat{\mathbf{z}}_t, \mathbf{c}_{t-L+3:t+1}^{pre}),$$

- Predicted tokens are decoded into future MC spectrograms.

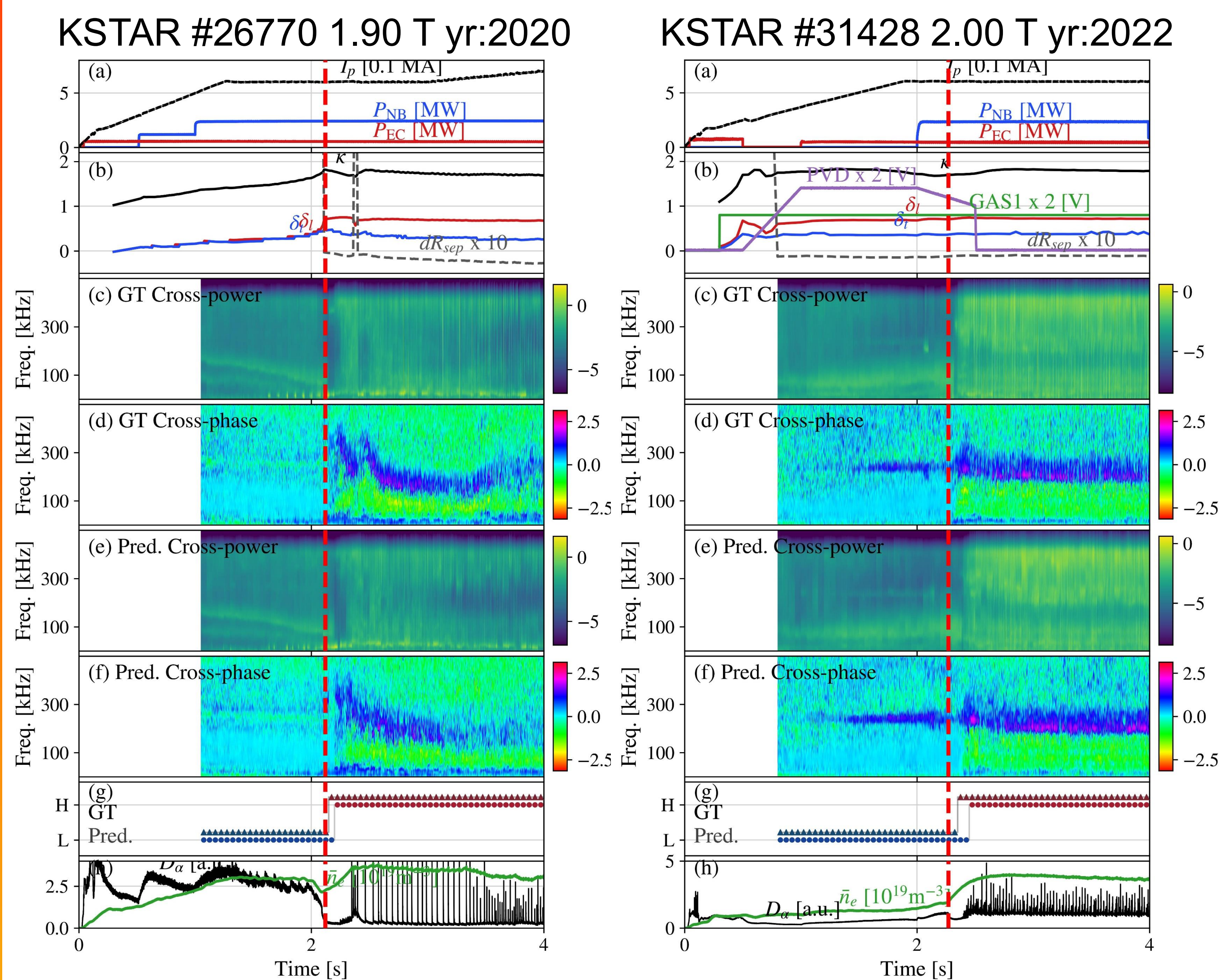
## Downstream evaluator: Optimal Autoencoder-based State Identification System OASIS<sup>[7]</sup>

- Previously validated KSTAR MC-spectrogram-based L/H classifier.
- Applied to both measured and predicted MC to compare L/H mode.
- OASIS assesses whether predicted MC spectrograms retain L/H-onset features.

## Motivation

- Task-specific tokamak predictors require task-specific labels and are difficult to reuse across diagnostics or events.
- PanoMHD instead learns KSTAR Mirnov-coil diagnostic dynamics: future MC cross-power/phase spectrograms from recent MC history and scenario inputs.
  - Magnetic-centric** diagnostics approach
    - MCs: routinely available diagnostics
  - Designed for reusable **downstream readouts**
- This work shows **L-H transition as both a downstream readout and an evaluation of PanoMHD**: we test whether predicted MC retains enough relevant information to recover the **L-H onset timing**.

## Held-out KSTAR L/H transition replays



## Methodology

### Dataset: KSTAR

- 978 shots (train:val:test = 8:1:1)
- Campaigns: 2020—2022
- KSTAR control variables:  $\mathbf{c}_t^{pre} \equiv \{B_t, I_p, \text{heatings, shapings}\}$

### Tokenized MC dynamics

- Challenge:** MC spectrograms are high-dimensional and evolve rapidly near transitions and MHD activity.
- Reformulation:** spectrogram regression  $\rightarrow$  discrete-token classification.
- A VQ-VAE<sup>[4]</sup> tokenizer maps each 50-ms MC spectrogram chunk into  $d$  discrete code indices.
- Impact:** 258x compression while preserving high-fidelity reconstruction<sup>\*</sup>

Name of data	Range
Toroidal magnetic field $B_t$	[1.40—3.50] T
Plasma current $I_p$	[0.18-1.00] MA
EC heating power (channels 2—5)	[0.00-0.904] MW
Resonant ( $r, z$ ) positions of EC channels 2—5	
NB1 heating power (beamlines A—C)	[0.00-2.02] MW
NB2 heating power (beamlines A—C)	[0.00—2.00] MW
Fuelling GAS1—3, PVD	[0.00—7.00] V
Minor radius	[0.34—0.55] m
Major radius	[1.64—2.14] m
Separatrix position ( $dR_{sep}$ )	
Diverted (1) / limited (0) configuration	
Elongation $\kappa$	[0.66—2.19]
Upper triangularity $\delta_u$	[-0.31—0.97]
Lower triangularity $\delta_l$	[-0.50—0.96]
Mirnov coil signal $m$	

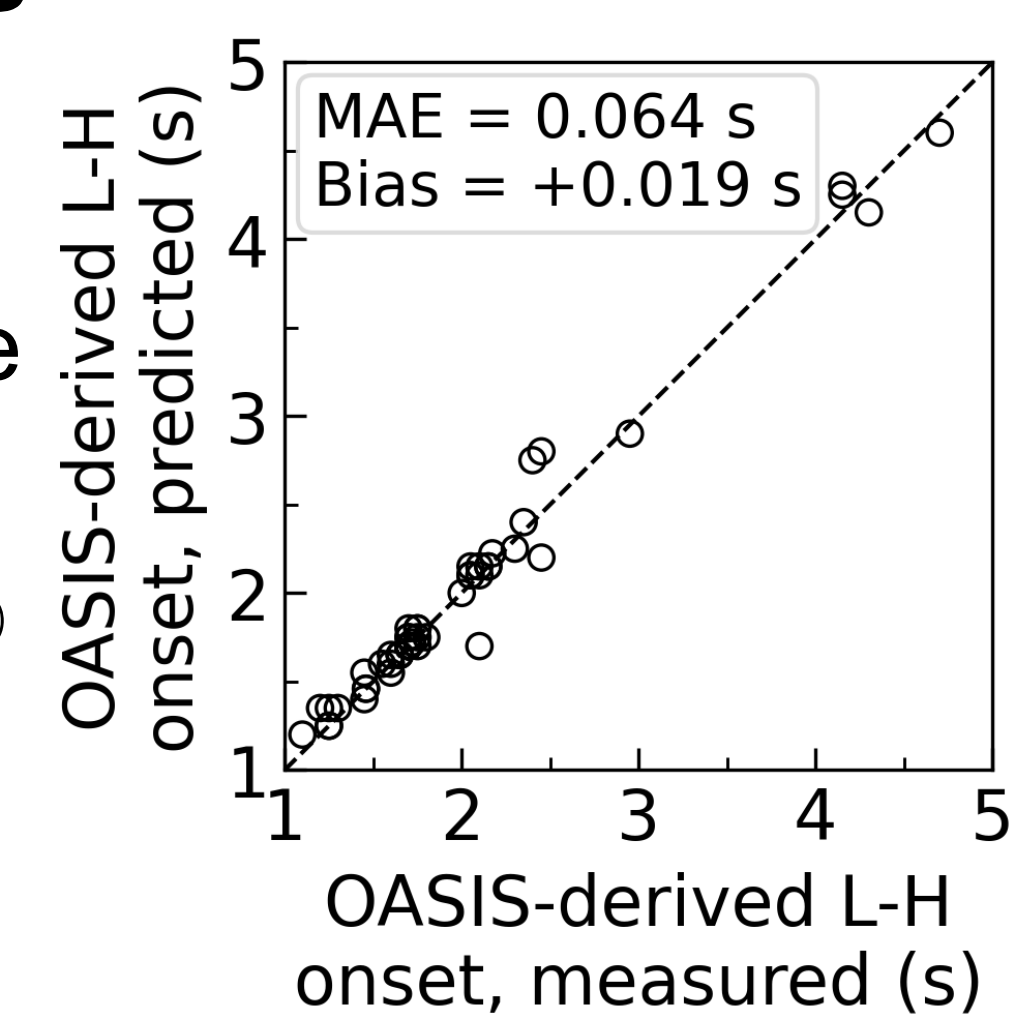
Table 1. Data used for PanoMHD

## OASIS-derived L-H onset agreement

- OASIS agreement:** OASIS is applied to measured MC spectrograms and PanoMHD-predicted MC spectrograms to obtain L/H mode sequences.

- Transition-time error:**  $\Delta t_{LH}^{OASIS} = t_{LH}^{OASIS(\hat{m})} - t_{LH}^{OASIS(m)}$

- Quantitative agreement:**  $\langle \Delta t_{LH}^{OASIS} \rangle = 0.019$  s, MAE\*\* = 0.064 s (~single step), accuracy 94.6%



## Scope and future work

- Present validation is retrospective on held-out KSTAR L-H transition shots; prospective validation in new discharges remains future work.
- This work evaluates L-H transition readout; other downstream tasks such as MHD-instability remain to be tested.

[1] G.S. Lee *et al.* 2000 *Nucl. Fusion* **40** 575.

[2] H. Noh *et al.* 2026 *arXiv preprint*.

[3] J.S. Kim *et al.* 1999 *Plasma Phys. Control. Fusion* **41** 1399.

[4] A. Van Den Oord, & O. Vinyals 2017 *NeurIPS*, **30**.

[5] A. Radford *et al.* 2019 *OpenAI blog*, **1(8)**, 9.

[6] A. Vaswani *et al.* 2017 *NeurIPS*, **30**.

[7] H. Noh. *et al.* 2025 *EPS*.

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\*Reconstruction PSNR [dB]: cross-power 31.6, cross-phase 24.1 \*\*MAE: Mean Absolute Error  $\sum |y - \hat{y}|$