Towards AI-based surrogate models for pulse design

Pre-pulse prediction on the TJ-II stellarator

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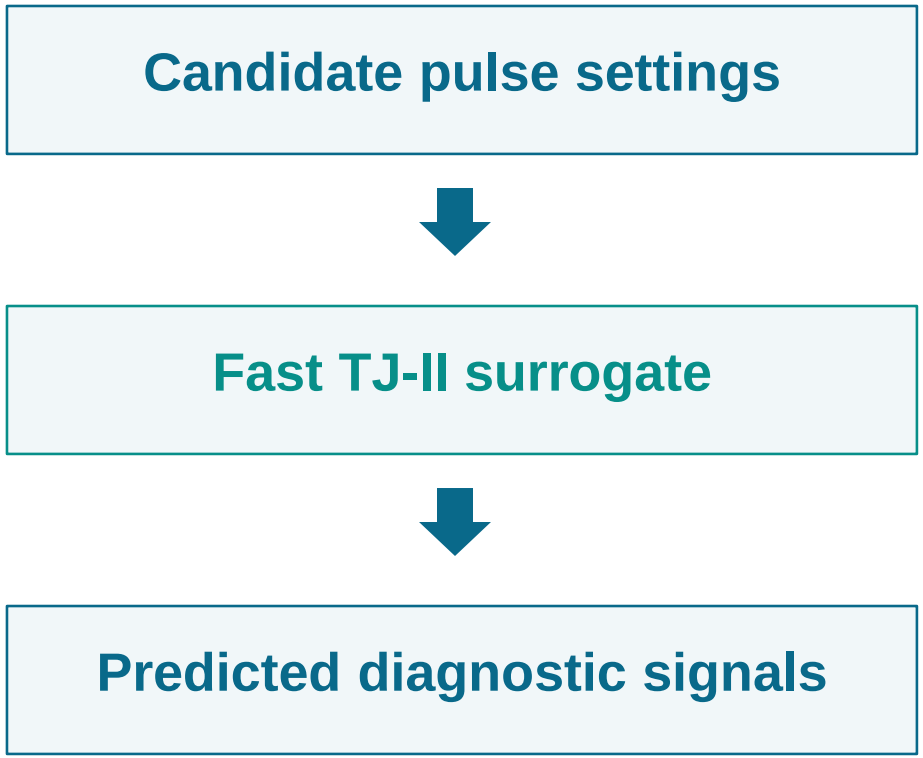
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Motivation

Fusion faces challenges in plasma physics, control, engineering and materials.

Machine time is limited and experiments are expensive

We cannot test every idea or every combination of operating parameters.



Purpose: screen candidate scenarios before requesting machine time.

Scope of the TJ-II surrogate

Physics-based/gyrokinetic modelling	Data-driven surrogate
Explain physical mechanisms. Go beyond the database info	Learns from past experiments
Can require substantial computing time	Gives fast predictions after training
Supports physical understanding and scenario analysis	Helps explore candidate pulse settings

Current scope

Create a prototype, able to predict the plasma evolution (three target signals)

Use

Support operation as flight simulator
Training student

Starting research and its evolution

Earlier work* (2014): estimate a missing diagnostic

We used other measurements from the same experiment to estimate a missing signal. For example, we trained a regression model using bolometer signals, soft X-rays and currents to estimate electron density and create a synthetic signal for control

Now: predict before the experiment starts

Those measurements do not exist yet. We use operating inputs and previous pulses.

Inputs

ECH1, ECH2
HYDROGEN, DEUTERIUM, HELIUM, OHI
WALL STATE, MAGNETIC CONFIGURATION

→ **TJ-II surrogate** →

Predicted signals

ACTON275
BOL5
Densidad2

Pulse history

We studied how much history to include and selected five previous discharges.

Model training on Turgalium

We train the models using data from thousands of past discharges to predict the target signals

**Rattá et al., "Simulation and real-time replacement of missing plasma signals for disruption prediction: an implementation with APODIS." Plasma Physics and Controlled Fusion 56 (2014), 114004.*

TJ-II database: curation and data split

≈5,000

TJ-II discharges*

→ **Data curation** →

≈3,000

Retained discharges

Curated dataset



Chronological split · approximate proportions

*Ganzábal, A. González, et al. "A comprehensive database of TJ-II signals and diagnostics for statistically based models." *Fusion Engineering and Design* 224 (2026): 115613.

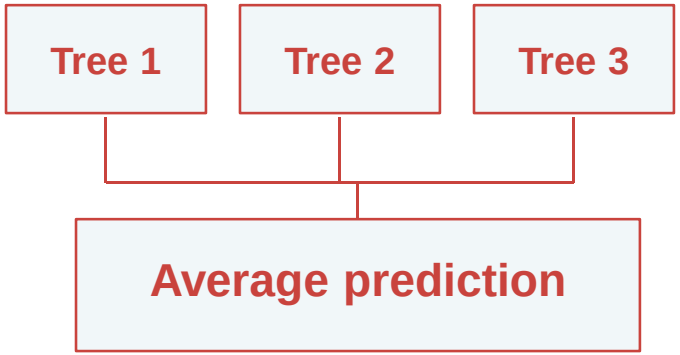
The 3 AI models

We did not know in advance which configurations were the best ones

We tested several ML models and selected the three with the higher results

ExtraTrees

Ensemble



Uses many decision trees and averages their predictions

LSTM

Recurrent sequence model



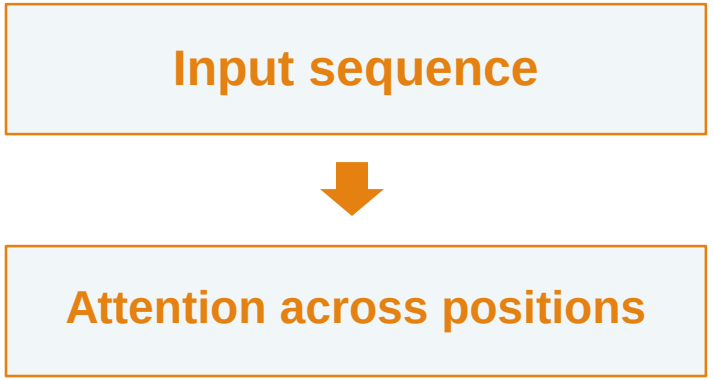
Memory carried along the sequence

Reads the inputs in time order and remembers information from earlier steps

Suitable for time series

Transformer

Sequence model with attention



Learns which parts of the input sequence to focus on when making a prediction

Target signals and seeds

These are the target signals, relevant in TJ-II

Target signal	ExtraTrees	LSTM	Transformer
ACTON275 · light emitted by carbon ions	5 seeds	5 seeds	5 seeds
BOL5 · bolometer chord	5 seeds	5 seeds	5 seeds
Densidad2_ · line density	5 seeds	5 seeds	5 seeds

Training

Training of the ML models has some randomness, so the same method can give different results each time

Five-seed mean

Each seed gives us a different run with different initialization parameters

Avoid randomness

We average them to get the final estimation

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Retrospective 90% error envelope

We wanted to provide an error envelope.

1 Central curve

Seed 1 **Seed 2** **Seed 3** **Seed 4** **Seed 5**

The estimation is the average of the five predictions at each time

The measured signal does not change this mean.

2 Envelope half-width

Compare the mean of the estimations with the measurements

We find a value that covers 90 percent of those errors

b = 90th percentile of absolute errors

One fixed b per signal and method, at all times.

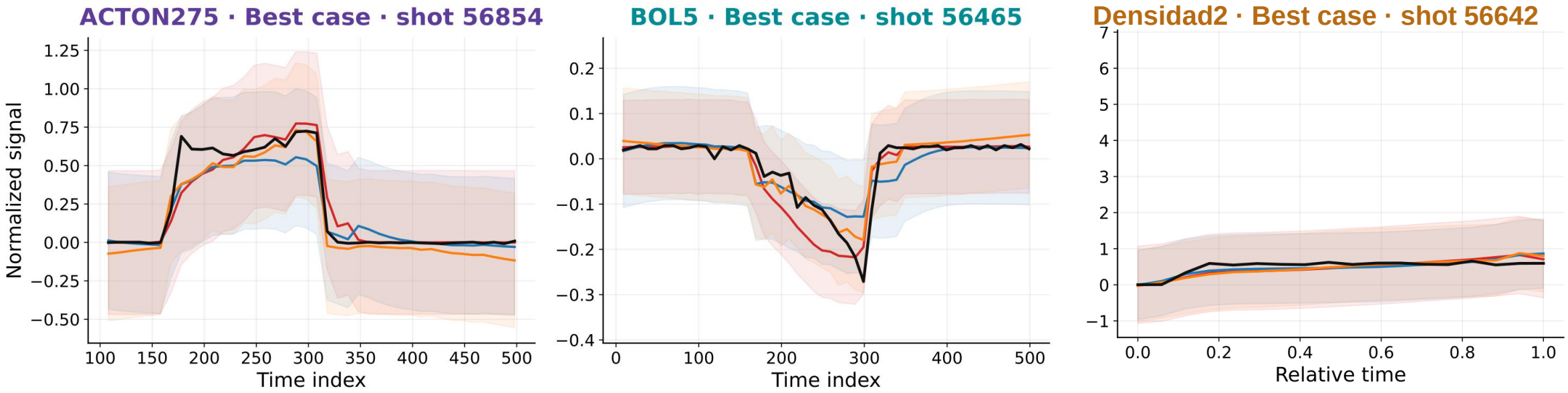
Error envelope = mean prediction ± b

ACTON275 · ExtraTrees: b = 0.467 in the stored signal scale

Retrospective error summary. Pointwise uncertainty and future coverage are not established.

Waveform examples with close agreement

Measured ExtraTrees LSTM Transformer retrospective 90% error envelope



Pulse shape

The models reproduce much of the observed evolution.

Different diagnostics

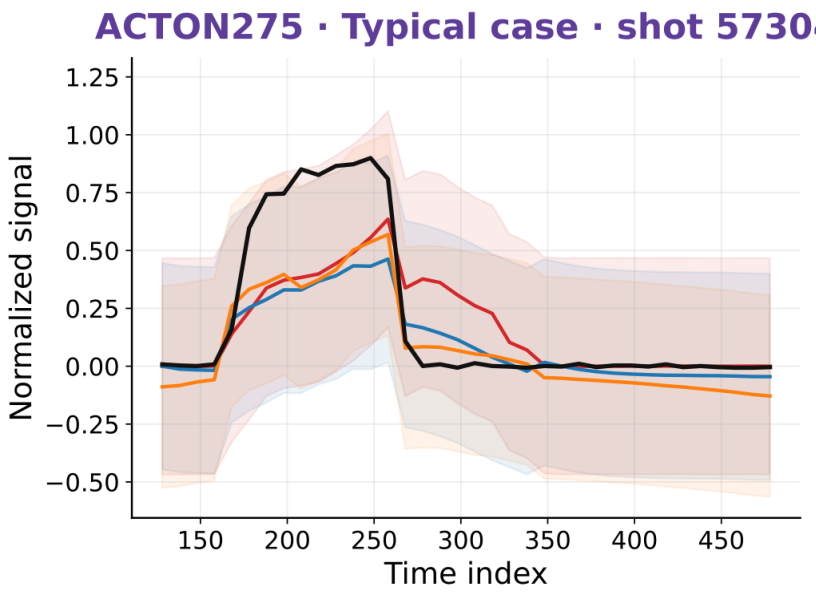
Agreement varies with the quantity being predicted.

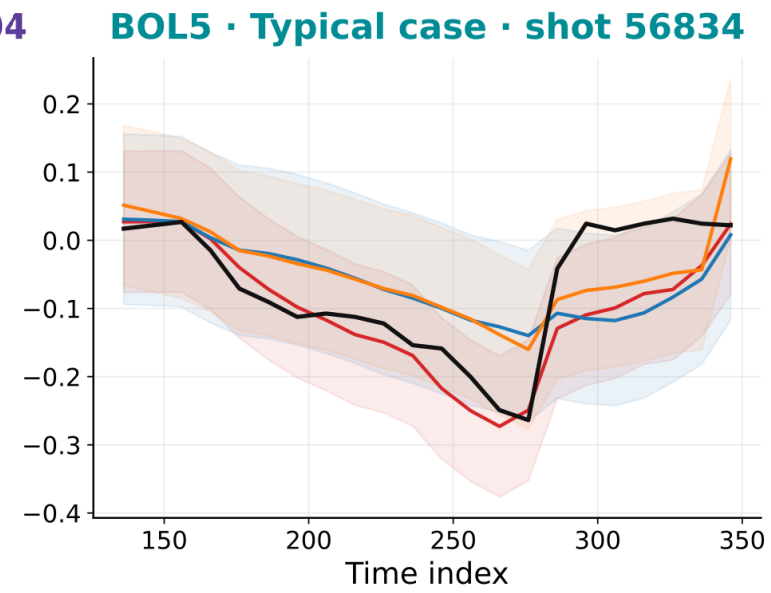
Selected examples

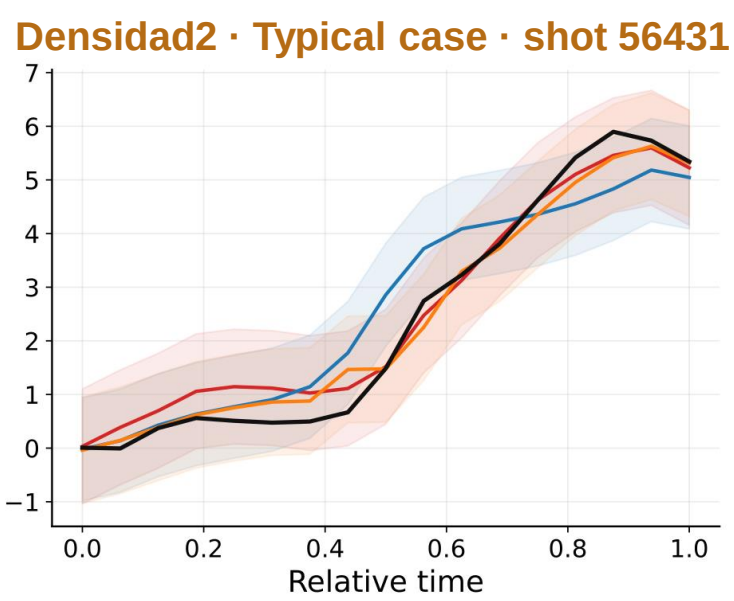
Examples of close agreement across the three diagnostics.

Typical cases expose amplitude and timing errors

Measured **ExtraTrees** **LSTM** **Transformer** retrospective 90% error envelope







ACTON275

The main peak is too low and the decay is slow

BOL5

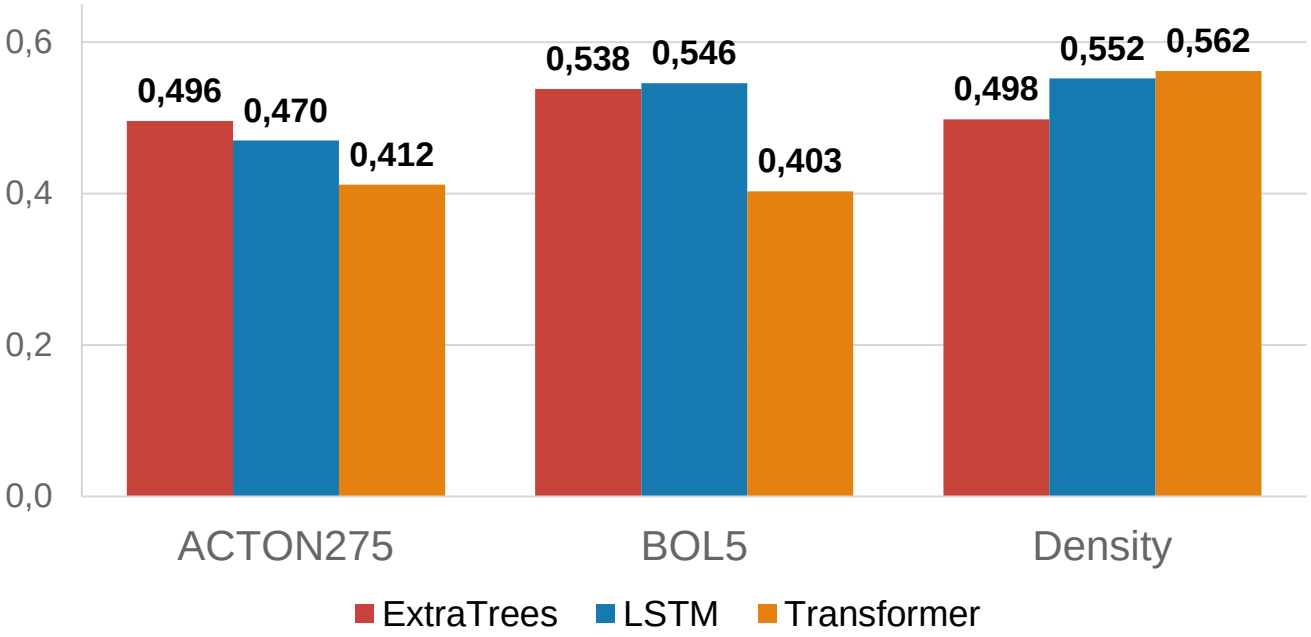
The dip and its recovery are imperfect

Density

The rise is reproduced; but timing and amplitude differ

General performance. 2 metrics

R^2: higher is better



Mean Absolute Error (MAE): lower is better

Method	ACTON275	BOL5	Density
ExtraTrees	**0.184**	**0.047**	0.454
LSTM	0.203	0.058	0.390
Transformer	0.216	0.062	**0.385**

Five-seed mean; all time points pooled.
Longer pulses contribute more points.

ACTON275

ExtraTrees leads both metrics

BOL5

R^2: LSTM MAE: ExtraTrees

Density

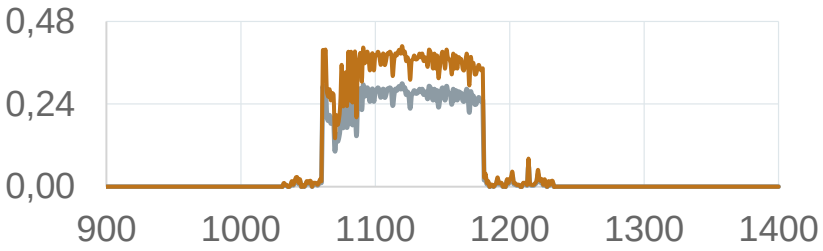
Transformer leads both metrics

TJ-II Pulse Simulator: working prototype

Retrospective target matching · shot 52774

ECH1

Reference Modified



Target RMSE

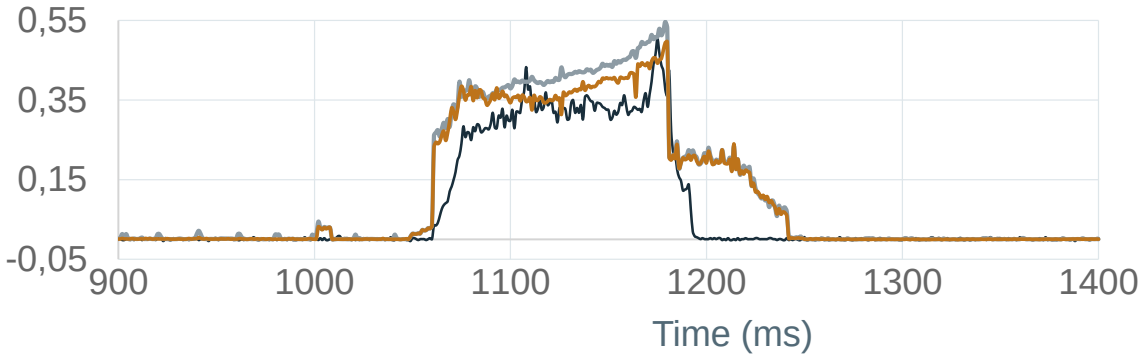
0.101993

12.41% lower

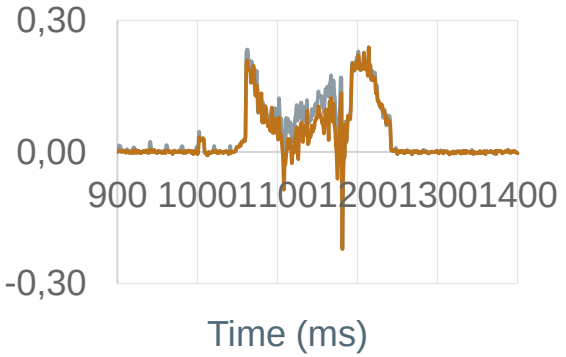
Simple change

ECH1 ×1.364

ACTON275 **Target**



Prediction − target



Two amplitude changes reduce target RMSE by 12.41%.

Retrospective fit, without experimental validation. Training domain and physical units unverified.

Next steps

Now	**Forward prediction**	We give the model the operating inputs, and it predicts how three plasma signals will change during the pulse
Next	**Shadow mode**	We will make a prediction before a real experiment. Then we will compare it with the measurements to see how well the model works
Then	**Assisted pulse design**	We could also turn the question around: if we want a particular plasma response, what combination of input values should we use?
Later	**Other fusion machines**	Finally, we would like to try the same approach on other machines, using their own experimental data to train and test the models

Conclusions

A TJ-II surrogate prototype was created

With further validation, it could help us plan experiments, support pulse design, train students and operators

I would like to thank our collaborators, the TJ-II Team, and CETA-CIEMAT for access to Turgalium

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