Detection of plasma confinement states in the TCV tokamak

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Introduction

- Tokamak plasmas can be described as being in three confinement states: Low (L), Dithering (D) and High (H) modes.
- Accessing and maintaining the plasma regime in H mode is a key aspect to optimise the energy confinement that large scale fusion reactors such as ITER and DEMO are foreseen to operate.
- Importance of early detection of confinement degradation, typically found in high density limit scenarios, which can potentially lead to a disruption, the highest concern for next-step fusion devices based on the tokamak principle.
- Need to inform the control system when the H-L transition occurs, since it can destabilize the plasma and cause disruptions.

Real time signals measured by TCV diagnostics

- Signal processing:
  - Resampling (50 kHz \rightarrow 10 kHz)
  - PD channel selection
  - FIR chords averaging
  - IP > 20 kA

- Signal validation

Validation of signals from expert knowledge using the DIS tool

- The validation and construction of the database is done using the DIS tool interface which allows domain experts to easily label each time step of a discharge as being in L, D or H mode.
- Labelling is a time consuming process which requires many iterations and consensus across different experts, where disagreement (in particular for the D modes) is typical.
- Accurate ML models can automate this process and help in the production of large and consistent DBs across different existing Tokamaks.

Encoder-Decoder neural networks to detect plasma confinement states

- Two encoder-decoder networks proposed: a 1D UNet architecture (UTime) and a seq2seq model with attention.
  - The multi-scale convolutional structure of UTime allows to capture patterns at different scales present in the plasma.
  - UTime processes the whole signal at once (offline) with the ability to see at large context, it is a good candidate model to help with the time consuming labelling process.
  - Seq2seq overcomes two limitations of previous studies based on a CNN-LSTM architecture [1]: it can produce decisions over sequence of outputs and is not constrained to have same source/target resolutions.
  - It can run in RT, with a delay determined by the length of the encoder.
  - The decoder was extended with an attention layer to capture larger context of long input sequences.

Results in TCV

Evaluation metric: Cohen’s Kappa-statistic (κ) measures the agreement between two sets of categorical data (ground truth vs model predictions).

<table>
<thead>
<tr>
<th></th>
<th>L</th>
<th>H</th>
<th>D</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNN-LSTM (best)</td>
<td>0.99 ± 0.01</td>
<td>0.97 ± 0.01</td>
<td>0.99 ± 0.01</td>
<td>0.98 ± 0.01</td>
</tr>
<tr>
<td>CNN-LSTM</td>
<td>0.94 ± 0.04</td>
<td>0.94 ± 0.04</td>
<td>0.94 ± 0.04</td>
<td>0.94 ± 0.04</td>
</tr>
<tr>
<td>seq2seq</td>
<td>0.97 ± 0.01</td>
<td>0.96 ± 0.01</td>
<td>0.97 ± 0.01</td>
<td>0.96 ± 0.01</td>
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<tr>
<td>UTime</td>
<td>0.97 ± 0.01</td>
<td>0.96 ± 0.01</td>
<td>0.97 ± 0.01</td>
<td>0.96 ± 0.01</td>
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- Two models based on an encoder-decoder architecture were developed to detect plasma confinement states in TCV.
- The existing TCV database of plasma states was highly extended and refined based on a consensus of expert knowledge.
- Thanks to both, the new database and the models, results surpassed by ~10% previous ones based on an CNN-LSTM model.
- As next steps we will rely on TL to deliver extensive and consistent databases for other machines. We will also implement the seq2seq model in the real-time control system and predict the confinement degradation as a disruption precursor.