

Exploring data-driven models for spatiotemporally local classification of Alfvén eigenmodes

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Alfvén eigenmodes (AEs) are an important and complex class of plasma dynamics commonly observed in tokamaks and other plasma devices. In this work, we manually labeled a small database of 26 discharges from the DIII-D tokamak in order to train simple neural-network-based models for classifying AEs. The models provide spatiotemporally local identification of four types of Alfvén eigenmodes by using an array of 40 electron cyclotron emission (ECE) signals as inputs. Despite the minimal dataset, this strategy performs well at spatiotemporally localized classification of Alfvén eigenmodes, indicating future opportunities for more sophisticated models and incorporation into real-time control strategies. The trained model is then used to generate spatiotemporally-resolved labels for each of the forty ECE measurements on a much larger database of 1,112 DIII-D discharges. This large set of precision labels can be used in future studies for advanced deep predictors and new physical insights.

Keywords: Machine learning, Alfvén eigenmodes, energetic particles, tokamak

I. INTRODUCTION

Future steady-state operation of nuclear fusion devices necessitates active real-time control of a number of complex plasma processes, including edge-localized modes^{1–3}, disruptions^{4,5}, and Alfvén eigenmodes (AEs)⁶. Some of these dynamics are highly nonlinear, and can occur on fast time scales and small spatial scales where many analytic assumptions break down. The reality of fast time scales requires that many real-time plasma control schemes are limited to simple models such as those based on 1D transport⁷, linearization or local-expansions^{8–16}, heuristics (based on prior experimental knowledge)^{17,18}, the biorthogonal decomposition^{19–24}, and so forth. Despite the challenges posed by multi-scale dynamics and nonlinearity, many of these models have been successfully employed for real-time control in operational scenarios. However, future progress in controlled fusion hinges on models that have the potential to overcome the many barriers associated with predicting the dynamics of complex plasmas.

Fortunately, there has already been remarkable success in data-driven models for disruption identification and real-time control in tokamaks^{4,5,25–29}, including high-performance models that are not limited to a specific device³⁰. Neural network models can be trained offline and then used to predict plasma activity online. There has also been recent deep learning work for automated identification of AEs in diagnostic

data^{31–33}. Our prior work³⁴, briefly reviewed in Sec. I C, substantially advanced these Alfvén eigenmode studies by utilizing a large database of high-resolution spatiotemporal data for AE prediction. In addition to real-time control applications, machine learning studies open the possibility for new physical understanding of this unique class of plasma modes in terrestrial plasma experiments or even space-based probes³⁵.

Heuristic models for AEs have also seen some successes. For instance, Hu et al.¹⁸ controlled Alfvén eigenmodes by computing a measure of the strength of AEs “by the mean value of the coherent power spectral density from Fourier analysis of temperature measurements from ten pairs of ECE channels with a bandpass between the geodesic acoustic and TAE frequencies ... averaged over the period of $t = 400 - 700$ ms.” Despite this coarse-grained metric and lack of distinction between AE modes, it worked reasonably well for a linear feedback controller with neutral beam injection used as an actuator.

The purpose of this work is to use simple neural-network-based models to provide more sophisticated spatio-temporal predictions of AE activity. In this work, we meticulously label a database of 26 DIII-D tokamak discharges in order to train simple neural-network-based models for full spatio-temporal AE classification, improving on previous work that could not provide localized predictions in space and time. These models are then used to generate new labels for the much larger database³⁶ of 1,112 DIII-D discharges.

In the remainder of this section, we briefly describe AEs as well as the electron cyclotron emission (ECE) diagnostics

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AE Name	Acronym	Cause
Beta-induced	BAE ^{44–46}	Compressibility
Low-frequency modes	LFM ³⁶	Hot electrons, $q_{\min} \sim \text{rational}$
Reversed-shear	RSAE ^{47,48}	$q_{\min}$
Toroidal	TAE ^{49–52}	$m \& m+1$ coupling

Table I. Description of the AE activity considered in this work, adapted from Heidbrink⁵³. The poloidal wave number is denoted by m and the minimum value of the safety factor is denoted $q_{\min}$. Other AEs are omitted because they were not common enough for adequate training using the database described in Sec. II.

that we use to develop the data-driven models for locating and identifying AE modes. These models are introduced in Section II and their performances are discussed in Section III.

A. Alfvén eigenmodes

Alfvén eigenmodes make up a diverse class of complex dynamics that pose many challenges for simple machine learning models, generalization to new datasets, and analytic methods. They are typically observed in tokamaks and other fusion-relevant plasma devices, although they can also occur in space plasmas³⁷. Some AEs are extremely well-studied, while others are recently discovered and yet to be fully understood. Although their causes and effects vary widely, some AEs can lead to confinement loss and damage to plasma-facing components in present and future devices. Previous examples include ablating carbon and ruining the transmission of optical components³⁸ and lost fast ions drilling a hole in TFTR that actually vented the machine³⁹. The database used in this work (described in Section II) distinguishes between several types of AE activity: Low-frequency modes (LFMs, these “Christmas light” patterns have been formerly characterized as BAAE modes³⁶), Beta-induced Alfvén eigenmodes (BAE), Reversed-Shear Alfvén eigenmodes (RSAE), and Toroidal Alfvén eigenmodes (TAE)^{36,40}. The AE modes are further described in Table I, where references to the relevant theoretical and experimental manuscripts can also be found.

Although AEs are relatively rare events, models for AE classification can be trained because AEs appear on many high-resolution plasma diagnostics and significant troves of past data are often available on tokamaks such as DIII-D. For future real-time control applications, there are a wide range of experimental actuators that can be used to control different AEs^{6,41–43}.

B. Electron cyclotron emission

Electron cyclotron emission (ECE) provides direct local measurements of the electron temperature for thermal plasmas⁵⁴, and as such, can provide spatiotemporally-localized information about AE activity. The DIII-D ECE diagnostic data is obtained at 500 kHz, in a single toroidal cross-section,

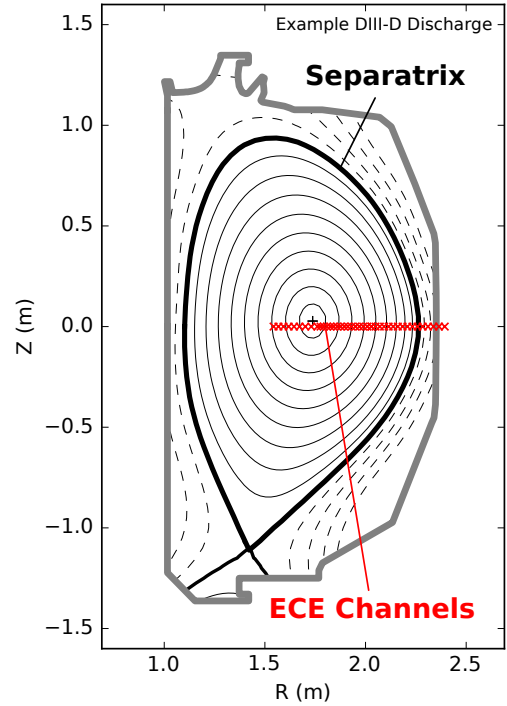


Figure 1. Illustration of the 40 radial ECE measurement locations alongside the closed (solid) and open (dashed) flux surfaces for an example DIII-D discharge. The effective position of the ECE channels can vary significantly in each discharge, and measurements outside the last closed flux surface are not local or accurate.

at 40 different channels corresponding to varying radial locations, as shown in Fig. 1. Each ECE channel spans an approximately 1 – 2 cm radial extent, which is small compared to the radial scale of AEs. Most of the time, an AE mode can be seen across several channels.

Properly capturing the spatial correlations is difficult because the effective position of the ECE channels changes with the magnetic equilibrium, and therefore can vary substantially during startup operation. The first few ECE channels regularly view data that is outside the last closed flux surface and this data is considered untrustworthy. Despite this spatial variability and data corruption, our prior work³⁴ used the full, raw, unprocessed ECE data, i.e. only the ECE channel indices corresponding to the relative major radial positions of the measurements. This has the advantage that the magnetic field evolution is not required. In the present work, we use the time-resolved magnetic field equilibrium data from EFIT⁵⁵ to map the ECE channels to the normalized plasma radius ρ , the square root of the toroidal flux normalized by the value at the last-closed flux surface.

C. Summary of results from prior work

Despite the simplifications that we described in the previous subsection, high classification performance was obtained in our initial work³⁴. Table II illustrates the primary conclu-

Table II. Summary of the highest performance model from Jalalvand et al.³⁴, a 2-layer RCN with 8K-500 nodes per layer, on a validation set. A threshold of 0.2 has been applied to binarize the model output. There are 540 labeled AEs in this validation dataset.

AE	TP	FP	TN	FN	TPR	FPR
BAE	75	46,982	470,368	17	0.82	0.09
LFM	8	4,102	587,088	3	0.73	0.01
RSAE	167	48,319	417,211	13	0.93	0.10
TAE	248	76,133	330,057	9	0.97	0.19

sions of the prior work using a reservoir computing network (RCN)³⁴. RCNs are recurrent neural networks, and therefore are capable of processing temporal information while providing a simple weights initialization and training procedure^{56,57}. This work used a very large but imprecise database that contains labels for a single time slice per AE activity to indicate the approximate occurrence of AEs in the time domain. These labels are specific to the overall discharge but not specific to each ECE channel, so spatially-localized prediction of the modes was not possible. Moreover, since only a single time slice label indicates roughly where each AE occurs, significant interpolation and windowing is required to train a proper machine learning method. Otherwise, the learning architecture is attempting to learn from a dataset with very few true positives and a very large number of false negatives. Therefore, only somewhat temporally-localized predictions were possible – predictions of AE activity by the RCN were considered true positives if they were within 500 ms of the corresponding ground-truth time slice.

Furthermore, Table II illustrates the highly imbalanced nature of the data. Even after interpolation and windowing of the original labels, only about 0.02% of the training or validation sets are labeled as an AE. This fact is why true-positive-ratio (TPR) and false-positive-ratio (FPR) are the primary metrics reported in that work. Reporting the “accuracy” of the model would be profoundly misleading; a model that *never* predicts AE activity would report accuracy above 99%. Despite the many shortcomings of the data, the strong performance with RCNs was encouraging for continued machine learning work.

II. SPATIOTEMPORALLY-LOCALIZED AE CLASSIFICATION

The previous work identified that the primary avenue for further improvements was to provide improved database labels that are unique to each ECE channel, facilitating spatiotemporally-localized machine learning predictors. For instance, it was found that other machine learning classifiers (MLPs, GRUs, RNNs, CNNs, etc.) that were trained with the original, large database struggle to find performance $\gtrsim 70\%$ TPR, and very quickly overfit to the data. This poor training performance persists despite the different learning architectures, and despite large variations in the network hyperparameters. This behavior is characteristic of database labels that are of insufficient quality for training accurate machine learning models. This is an expected finding – the database labels are

not unique to each ECE channel so the model is inevitably being trained on many false positives and many false negatives, providing an upper bound on the performance achievable with any machine learning model. This finding further motivated a second, much smaller database consisting of higher-precision, spatiotemporally-localized AE labels.

A. High precision database labels

ECE-channel-specific labels were produced by selecting 26 very active DIII-D discharges, manually examining all $26 \times 40 = 1040$ ECE channel spectrograms, and providing specific time and frequency windows for the labels (a box is drawn on the spectrogram where the mode appears). This manual examination becomes significantly easier by first using standard image processing techniques⁵⁸ to enhance the spectrograms by highlighting the AE activity⁵⁹. Each spectrogram is shape 3709×256 in time $\times$ frequency space. The denoising process is as follows: the spectrogram values are (1) converted to the log of the values, (2) normalized to $[0, 1]$, (3) thresholded off if below the 90% quantile, (4) Gaussian-filtered with temporal standard deviations (31, 3), (5) mean-filtered along the frequency dimension, (6) morphologically-filtered, and finally (7) mean-filtered along the frequency dimension again. Across the vast majority of ECE spectrograms obtained from a wide range of DIII-D discharges, this image filtering sequence was empirically found to perform well at highlighting the AE activity while denoising the remainder of the image, as in Fig. 5.

Although this is a very small subset of the original database, each spectrogram provides 3709 time slice input vectors, each of dimension 256, meaning a total of ~ 4 million input vectors for training models. The raw signals, spectrograms, denoised spectrograms (denoised as described in the previous paragraph), labels, and predictions are illustrated for three active ECE channels during DIII-D discharge 178637 in Fig. 2. The model was not trained on this discharge. The denoising process strongly highlights the AE activity and improved both the manual and model-based labeling; models trained with the denoised spectrograms universally outperformed models with the raw spectrograms.

Out of the 1040 ECE channel spectrograms, $\approx 2\%$ of the total time series contain an LFM, $\approx 3\%$ contain BAE, $\approx 8\%$ contain RSAE, and $\approx 7\%$ contain TAE. However, often the AEs are concurrent, so this is an underestimate of the inactive periods. The total number of “events” of each type are 143 LFM, 329 BAE, 415 RSAE, and 441 TAE (this can be reconciled with the previous percentages because BAE tends to appear on the ECE channels as short, isolated events). Overall, approximately 95% of the samples in this sub-database has no AE activity whatsoever. Although still quite imbalanced, this database is a substantial improvement over the original one where approximately 99% of the data contained no AE activity (or at least no AE labels).

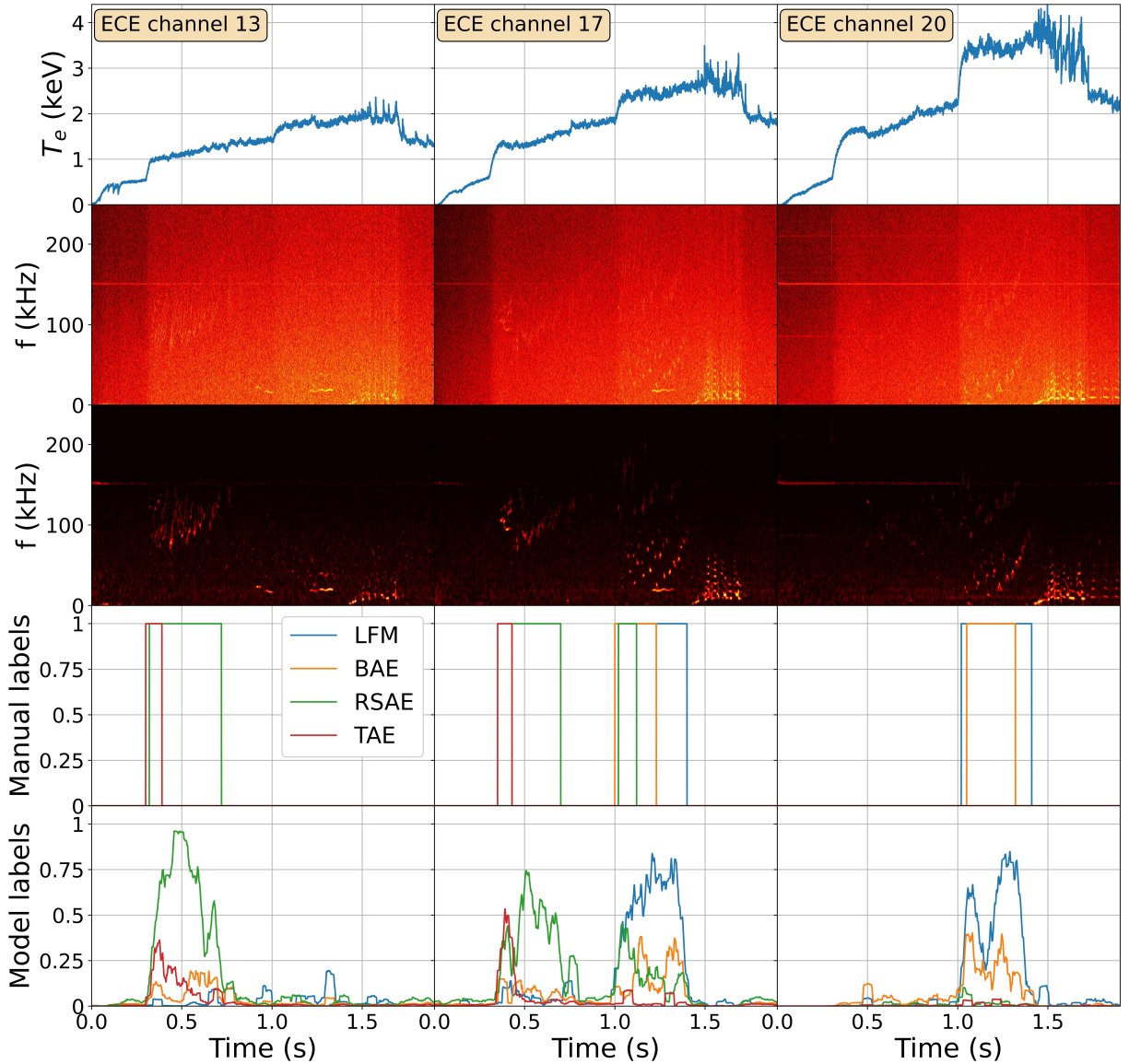


Figure 2. In order to facilitate more accurate NN predictions, a small dataset of 26 discharges was developed and contains high-precision labels unique for each ECE channel. From top to bottom this illustration shows three ECE channel time series for the DIII-D test discharge 178637, along with the corresponding spectrograms, the denoised spectrograms, the manual labels corresponding to each ECE channel, and the predictions using the baseline MLP. The model closely predicts the manual labels, albeit with weaker strength.

III. MODELS AND RESULTS

Evaluating model performance with this database is not straightforward. Often, the TPR and FPR are used for imbalanced datasets. However, we are primarily interested if the model can provide accurate, spatiotemporally localized predictions of the AEs. In other words, metrics should be evaluated not on individual spectrograms, but on the full, 40 channel ECE data. Each discharge’s ECE data forms an “image” in the space of normalized plasma radius and time (ρ, t).

One of the primary metrics in the field of image segmentation is the intersection-over-union (IOU)^{60–62}. For each AE type, this metric places a bounding box over the entire active

portion of the ground truth image, and another bounding box over all of the active image pixels that are predicted by the model to be above some threshold value λ . Then the IOU can be computed from these two bounding boxes, providing a similarity metric between the predictions and manual labels. IOU above 0.5 is typically considered strong performance in image identification.

A. MLP and other models

As a baseline, a multi-layer perceptron (MLP) with three layers, 512 nodes per layer, and interleaving 30% dropout layers was trained with the mean-squared error loss, directly on

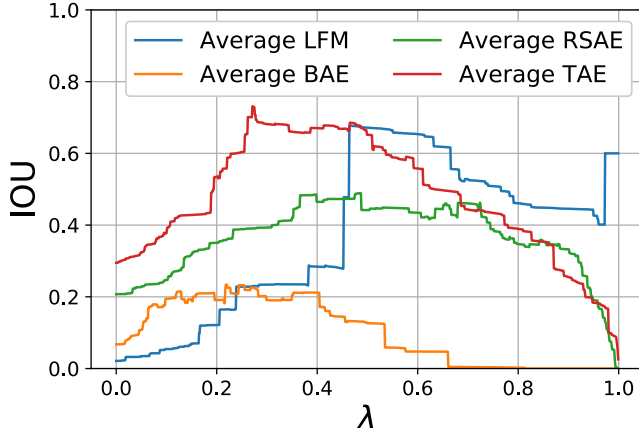


Figure 3. IOU values for each of the AE types as a function of the threshold λ . The IOU values were computed from the five test discharges.

the denoised spectrogram data from this new database. Each input is a single column from the denoised spectrogram, i.e. a feature vector of length equal to the number of frequency points in the spectrogram. Therefore, the inputs do not contain any temporal information beyond that which is encoded in the frequency information in the spectrogram. Such a memory-less approach tends to produce rather “spiky” predictions, so we smooth the outputs using a running average with a window of ~ 50 ms. In order to compare some of model predictions with the manual labels, the 26 discharges are split into 16 training discharges, 5 validation discharges, and 5 testing discharges in a way that provides enough LFM and BAE instances for training. Model performance was fairly insensitive to changes in the dropout rate, additional nodes per layer, and other network hyperparameters.

The performance of the model is evaluated by computing the IOU for each of the validation discharges and for each of the AE types as a function of the prediction threshold λ . The full IOU validation results are shown in Fig. 3 and indicate that at $\lambda \approx 0.4$, LFM, RSAE, and TAE IOUs are $\approx 40 - 80\%$ or higher, while the BAE IOU peaks at $\approx 20\%$. It is possible that the lower performance for BAE is because this mode tends to be more intermittent than other AEs. We plot each validation discharge image and the corresponding bounding box in Fig. 4 for a threshold of $\lambda = 0.4$. The visualization illustrates that the model accurately captures the spatiotemporal location of AE activity in all the testing discharges, with most of the degradation in IOU coming from small outliers. The model IOU can frequently be further improved by using a more aggressive output smoothing than the 50 ms running average employed here.

The baseline MLP did not use spatial or temporal correlations in the data to train, and yet manages to accurately capture much of the spatiotemporal dependence of AEs in the data. The frequency content at a single time slice of the individual denoised spectrograms is apparently already very informative for AE classification. Temporal memory was also found to be fairly unimportant in our prior work. The lower

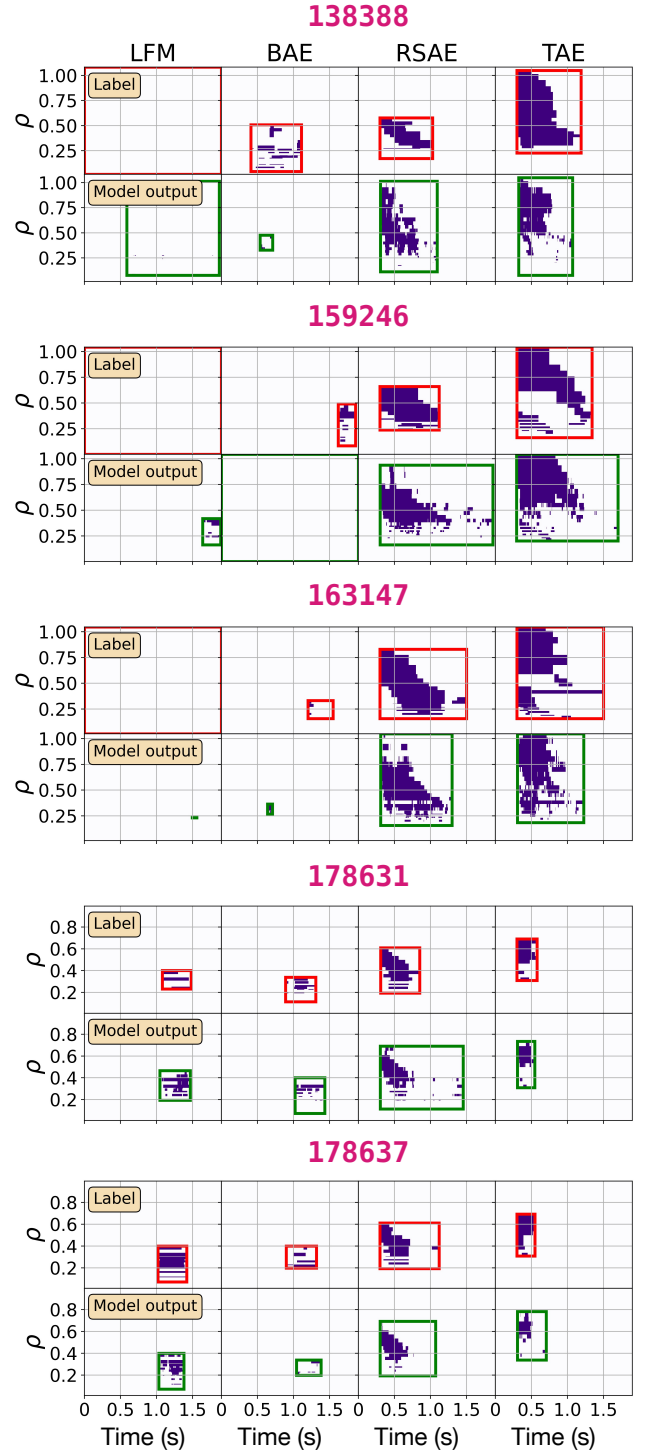


Figure 4. Summary of the IOU results for the 5 test discharges, at a threshold of $\lambda = 0.4$. Apart from some of the BAE, it is visually apparent that the model can accurately predict the spatiotemporal dependence of the modes; the primary degradation in the LFM, RSAE, and TAE IOU tend to be isolated outlier predictions, which could be removed by additional output smoothing. It is also worth noting that the manual labels are not perfect. It is possible that in some cases, the model is actually more accurate than the provided labels. For instance, on additional inspection discharge 159246 looks like it does exhibit some weak LFM activity at the location predicted by the model, and had been labeled as such in the original database containing 1,112 discharges (but not in the database of 26 discharges).

performance with BAE and LFM may be a symptom of the simplicity of this MLP. The MLP is only three layers, and the input data contains no temporal memory for the MLP to extract. There is no spatial memory either, because each ECE channel is processed individually. This is not very relevant for BAE and LFM, which tend to have smaller spatial extents than TAE or RSAE. LFM in particular exhibit a complex pattern in time, meaning one might expect that identifying these modes would be more sensitive to temporal memory. A simple way to incorporate some temporal information in these models is to enrich the input by including first and second temporal derivatives, calculated from an arbitrary window of size Δt around each input at time t . This triples the size of the input features, but we observe some minor improvements in performance. The addition of temporal information primarily increases the confidence of the model decisions, particularly for detecting LFM.

The MLP models were then compared with two other relatively simple machine-learning models, one based on ridge regression and another based on a two-layer RCN. The MLP outperforms ridge regression, which struggles to identify BAE or LFM, cannot distinguish between TAE and RSAE, and struggles to fully turn off when AE activity is not present. The RCN performs similarly to the MLP model. All four of the linear, RCN, MLP, and MLP + derivatives models were tested against a set of 20 randomly chosen discharges to visually compare model performances. A representative set of spectrograms from discharge 170669 are illustrated in Fig. 5, along with the outputs from the original RCN used in our prior work. The RCN and MLP models accurately predict AE activity quite well. The older RCN predicts the overall AE activity in the discharge well, but cannot distinguish activity in each ECE channel since it was trained on the original database labels that are not specific to ECE channel. Nonetheless, the older RCN performs well at predicting the timing and type of primary AE activity that occurs across the ECE channels.

Encouraged with the performance of this baseline MLP, we now use the model to predict labels for the large database consisting of another 1,112 DIII-D discharges. This larger database varies across a very wide range of parameter space despite the database having been compiled to focus on discharges with energetic particles. This sort of bootstrapping is critical for creating more useful datasets in the fusion community; recent work⁶³ provided similar labels for LH transitions in a DIII-D database. In this scenario, we denote a “true AE” in a specific ECE channel if the mode is predicted to occur with probability > 0.2 for more than 50 ms of the data. With this definition, the percent of spectrograms in the database with at least one occurrence of LFM, BAE, RSAE, or TAE is 3.9%, 1.0%, 22%, and 24% respectively. However, the percentage of time in the whole database where each AE is predicted to occur with probability > 0.2 is only 0.6%, 0.2%, 4.8%, 5.2%. In total, 8% of the data has at least one of type AE occurring. This estimate contains far more AE activity than was originally labeled in this database and it alone represents an interesting finding. It provides an estimate for the frequency of occurrence in AE modes across a broad parameter space of DIII-D operation. A representative example

is illustrated in Fig. 6 where weak AE activity was originally ignored but the model correctly predicts AEs. Future work could cluster the AE activity by various plasma parameters in order to assess AE occurrence frequencies and other AE properties in different dynamical regimes.

IV. CONCLUSION

A small set of 26 DIII-D discharges were manually labeled for AE activity and used to train machine learning models to generate spatiotemporally localized classification of AEs. Initial work with this small database shows that simple machine-learned models can already produce strong spatiotemporally-localized AE classification from denoised spectrograms of individual DIII-D ECE channel data. The baseline MLP model performs favorably compared with a ridge regression model, a RCN model, and a memory-aware MLP. The baseline MLP was subsequently used to generate spatiotemporally localized labels for a much larger database of 1,112 DIII-D discharges. These labels facilitate future work using more sophisticated deep learning models, as well as physical studies on the characteristics of AEs in different dynamical regimes. Additional future work includes prediction and control algorithms for AEs and combining datasets from different diagnostics such as ECE, magnetics, and beam-emission spectroscopy.

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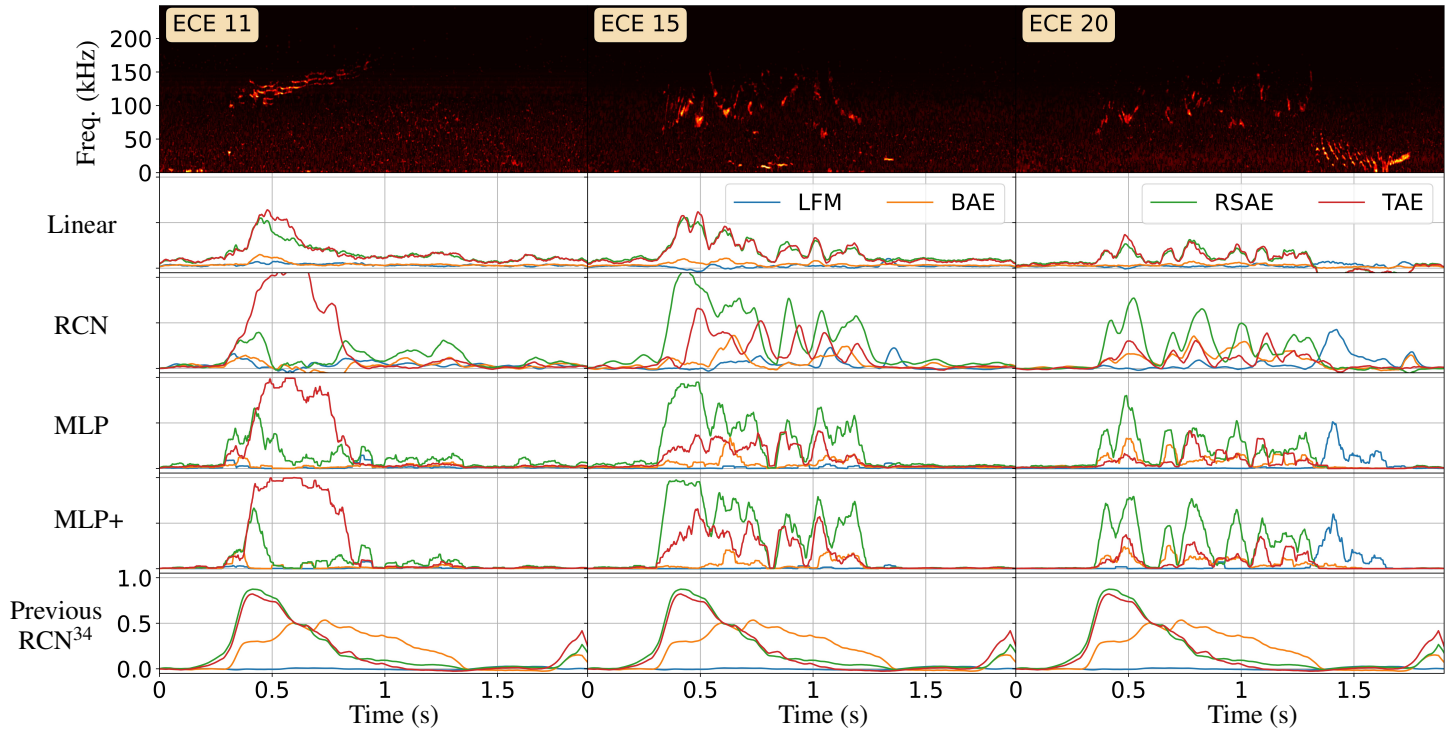


Figure 5. Illustration of the predictions for the linear, RCN, MLP, and MLP + derivatives models on the active ECE channels in discharge 170669, along with the RCN outputs from our prior work³⁴. The linear model struggles to accurately predict AEs, the new RCN and the MLPs predict AEs quite well, and the older RCN accurately predicts the “average” AE content of the discharge but cannot distinguish between ECE channels. Recall that the RCN from previous work was trained on a different set of labels that is not unique to each ECE channel; despite this setback, it predicts well the timing and type of primary AE activity that occurs over the majority of ECE channels.

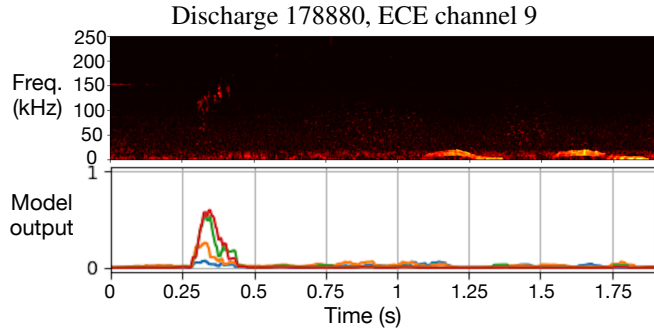


Figure 6. The model correctly identifies minor AE activity throughout the database, which is not usually labeled manually.

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