Real-time control for high bandwidth plasma dynamics with edge-ML and Beam Emission Spectroscopy at DIII-D

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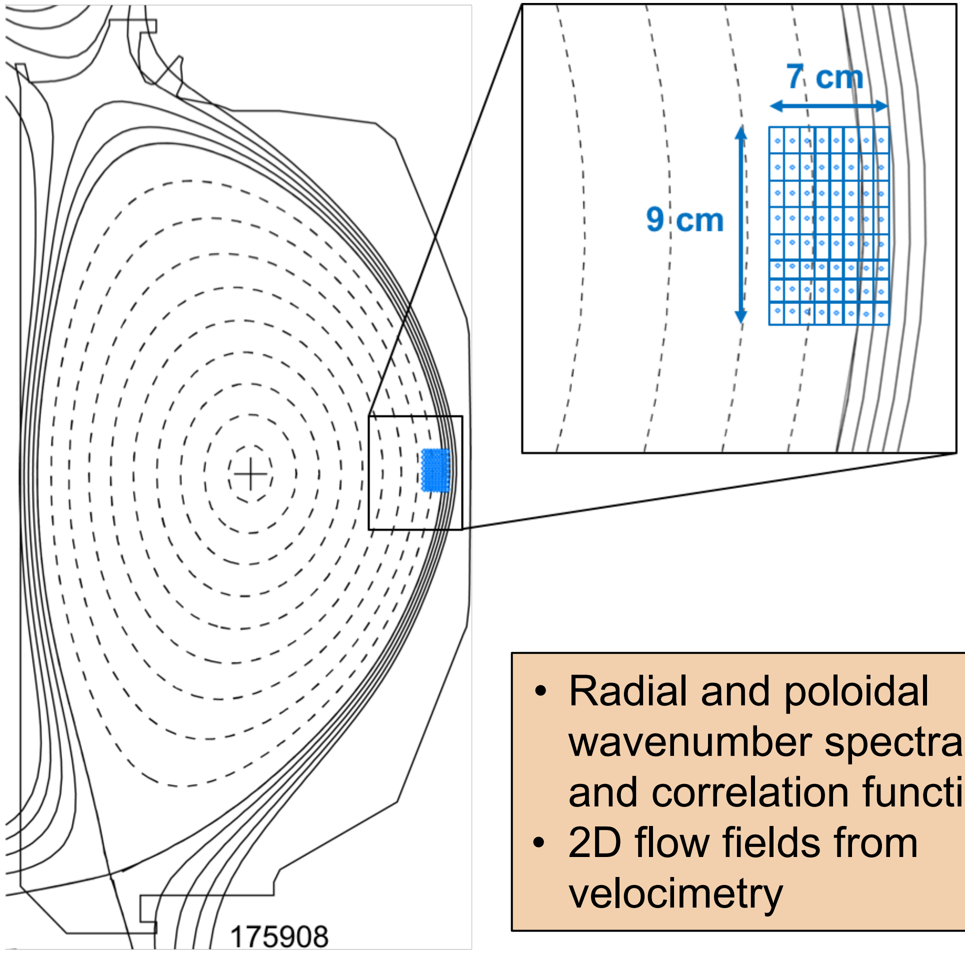
Real-time prediction and control for fusion plasma events

- Identify, predict, and control high bandwidth plasma dynamics in real-time
  - Extend RT control to fast plasma events and high bandwidth fluctuation diagnostics
  - Fluctuation diagnostics with high bandwidth data streams
  - High throughput edge ML on real-time platforms at the diagnostic sensor
- Events of interest
  - ELM onset events
  - Alfven eigenmodes (AE) and AE events
  - Confinement mode transitions and sustainment
  - Disruption prediction and avoidance

- This talk: Implementation of edge ML with the Beam Emission Spectroscopy system at DIII-D
  - 64 channels (8×8 2D configuration) digitized at 1 MHz

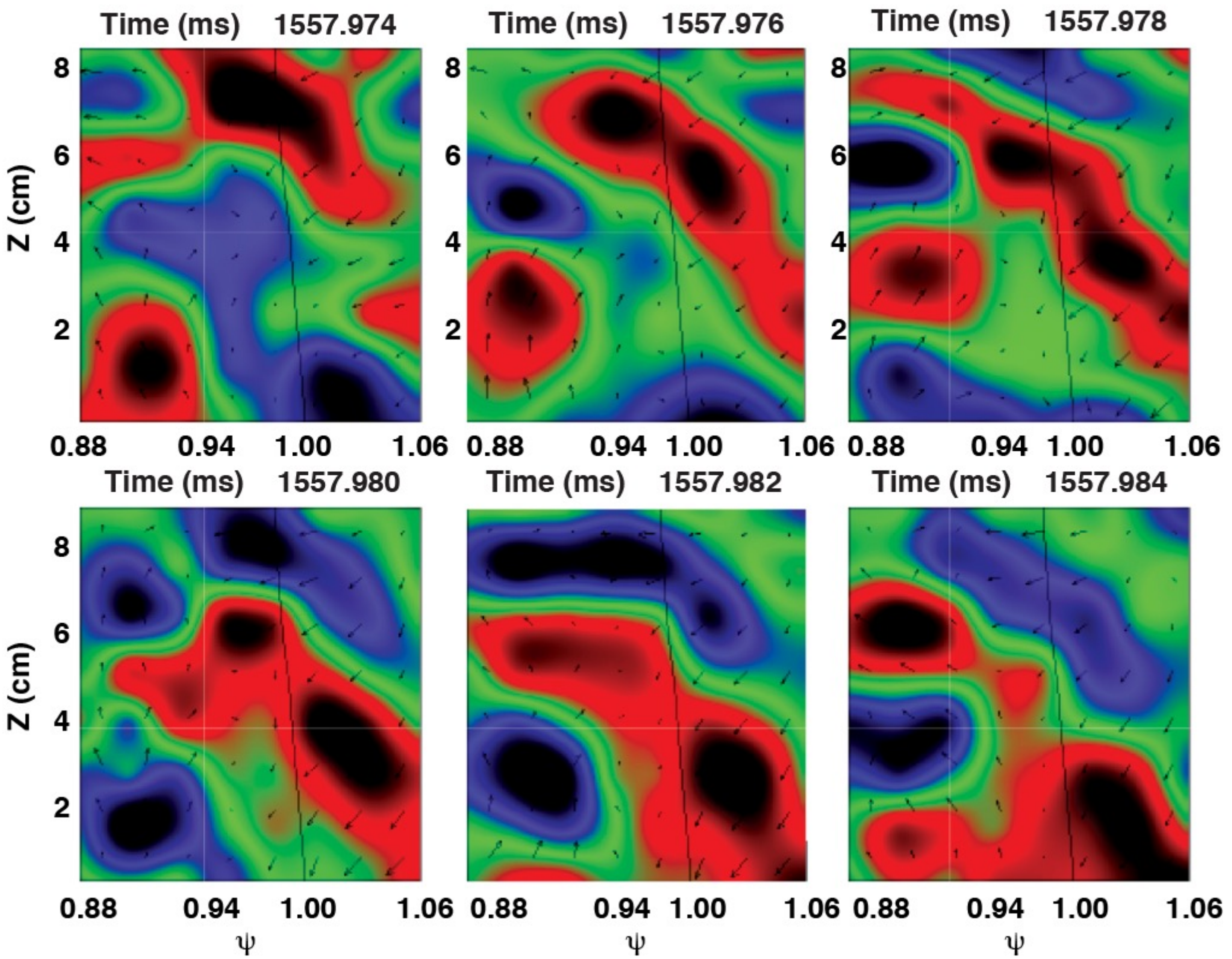
2D BES captures ion-scale turbulence and instabilities at μs-scale time resolution

2D BES at DIII-D

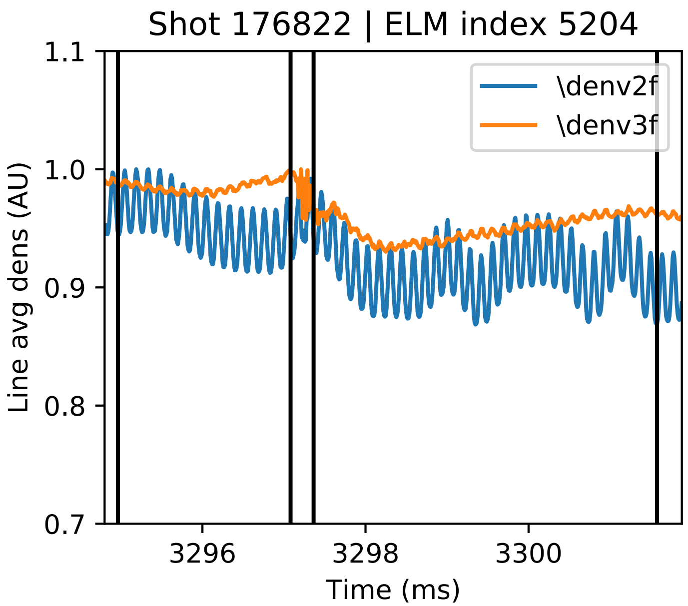


- Radial and poloidal wavenumber spectra and correlation functions
- 2D flow fields from velocimetry

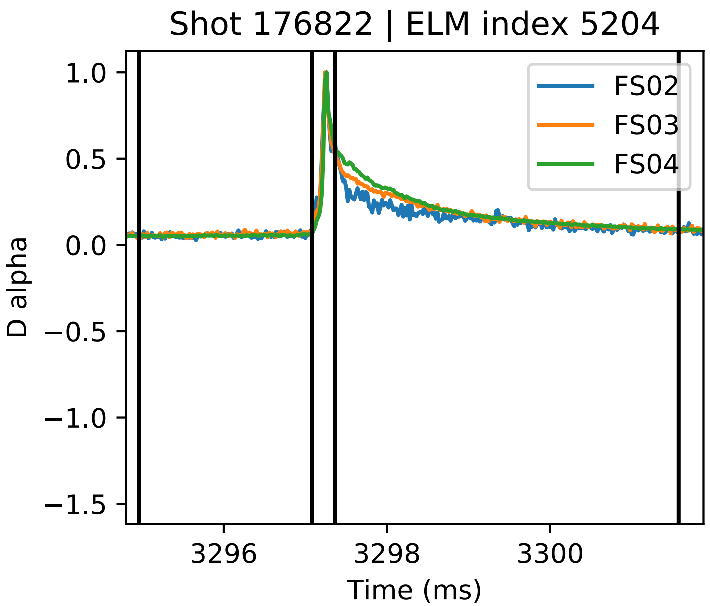
Turbulence imaging and velocimetry



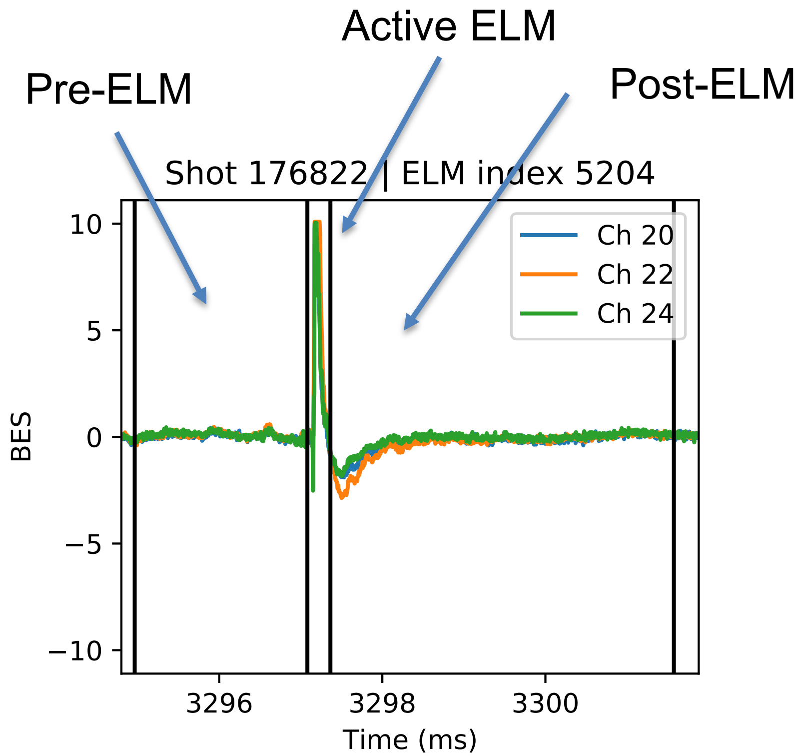
Created database of >400 ELM events with high bandwidth, 2D BES from a variety of DIII-D shots



Interferometer
line-integrated, low channel count, high bandwidth



Visible filterscopes
field-of-view integrated, low channel count, low bandwidth



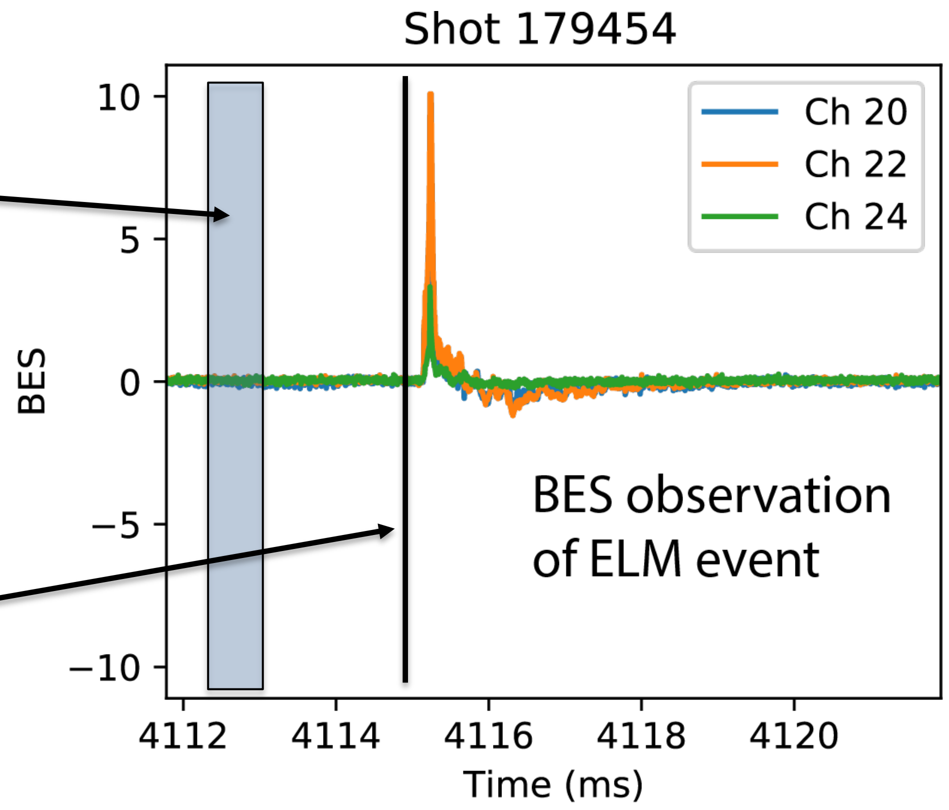
2D beam emission spect.
cross-beam localized, high channel count, high bandwidth

Labeled dataset with > 400 ELM events drawn from a variety of DIII-D shots

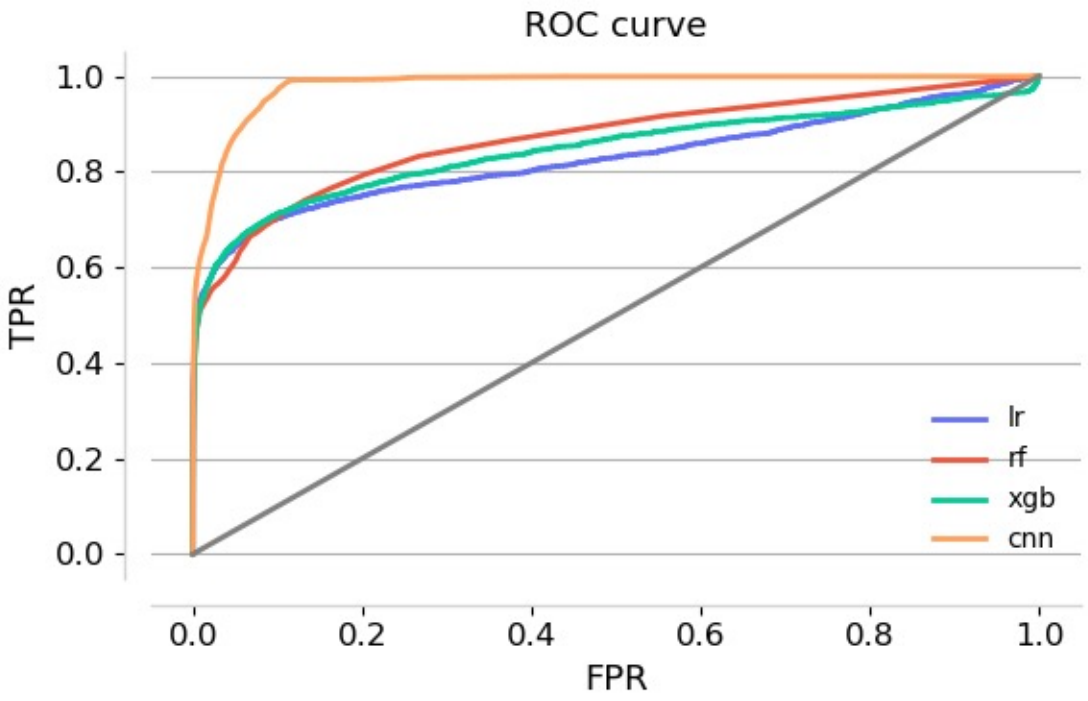
Goal: Predict ELM onset with real-time BES data stream (64 channels at 1 MHz)

Rolling RT signal window
- 64 channels
- 1 MHz
- ~ 32-128 frames

Rolling active-ELM prediction on high-throughput RT compute



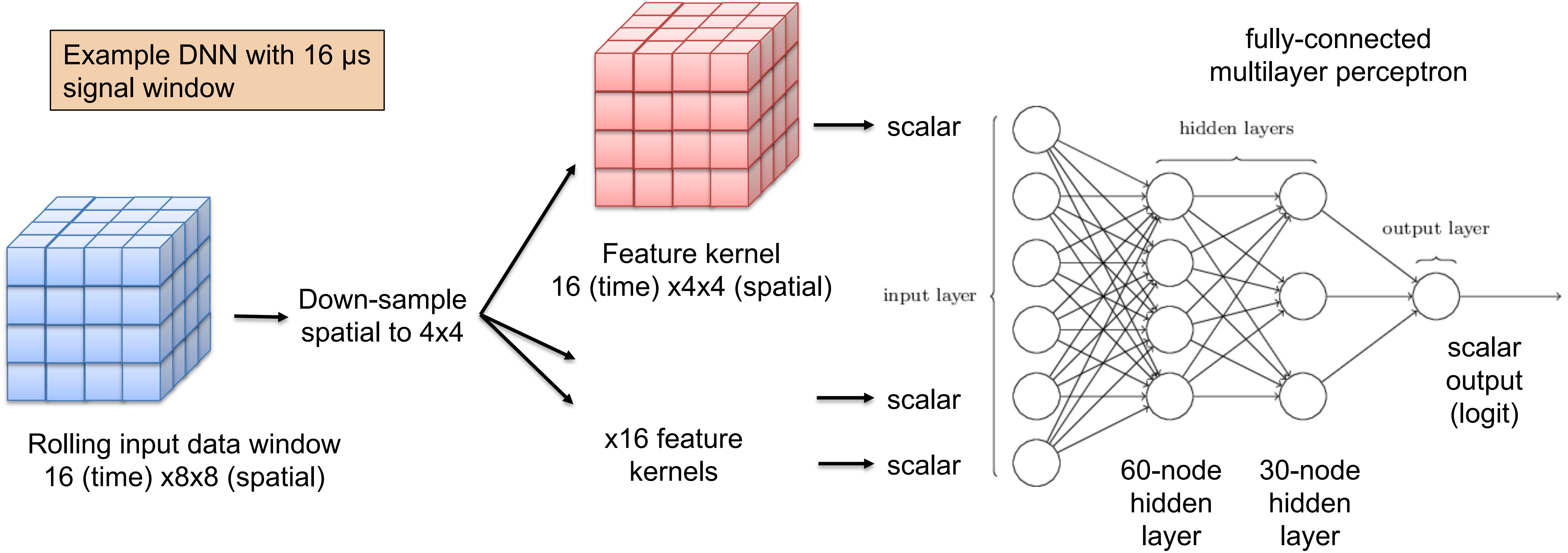
Deep neural nets outperform classical ML algorithms for ELM onset prediction



Logistic regression
Random forest
XGBoost (gradient boosted RF)
CNN

Feature model with dense kernels gives best performance for ELM onset prediction

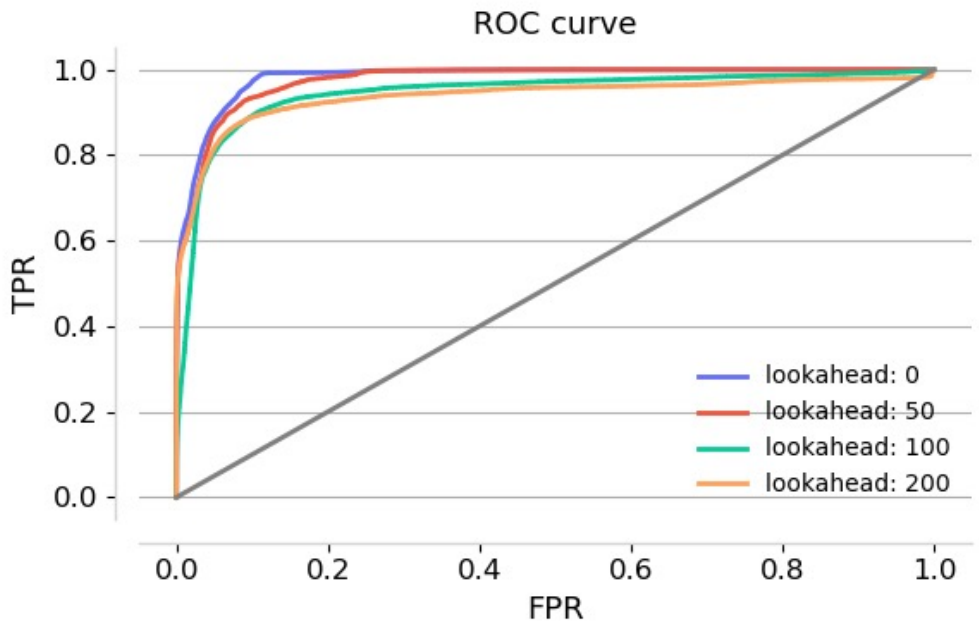
Example DNN with 16 μs signal window



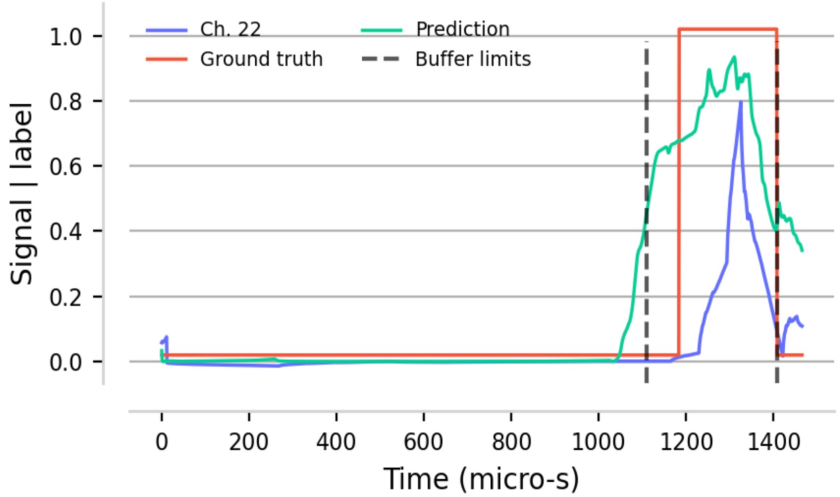
Feature space:
x16 scalars from inner product between signal window and feature kernels

Deep neural nets can accurately predict ELM onset up to 200 μs in advance

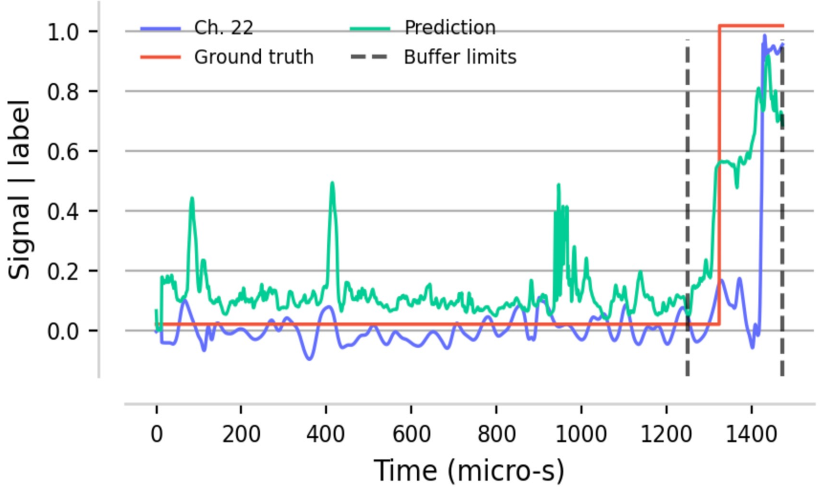
Models use 16 or 32 μs signal windows



See more details in talk later today by Lakshya Malhotra



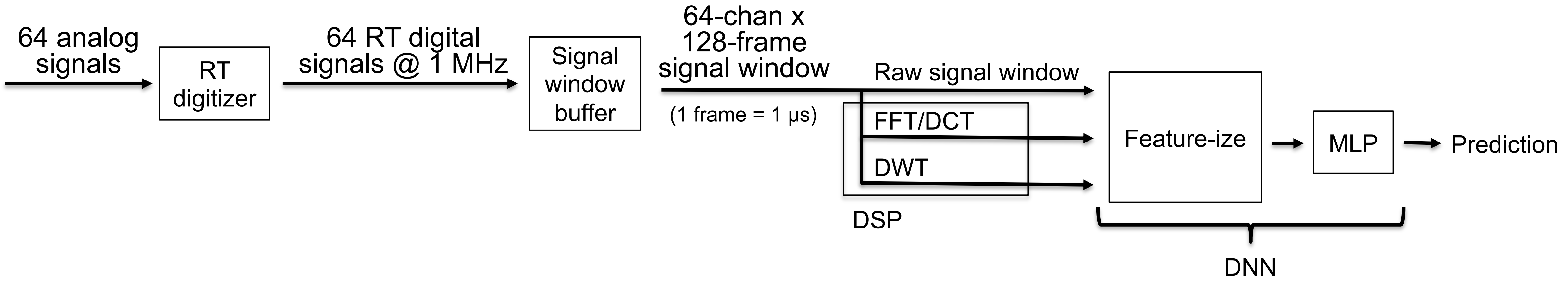
0 μs forecast



200 μs forecast

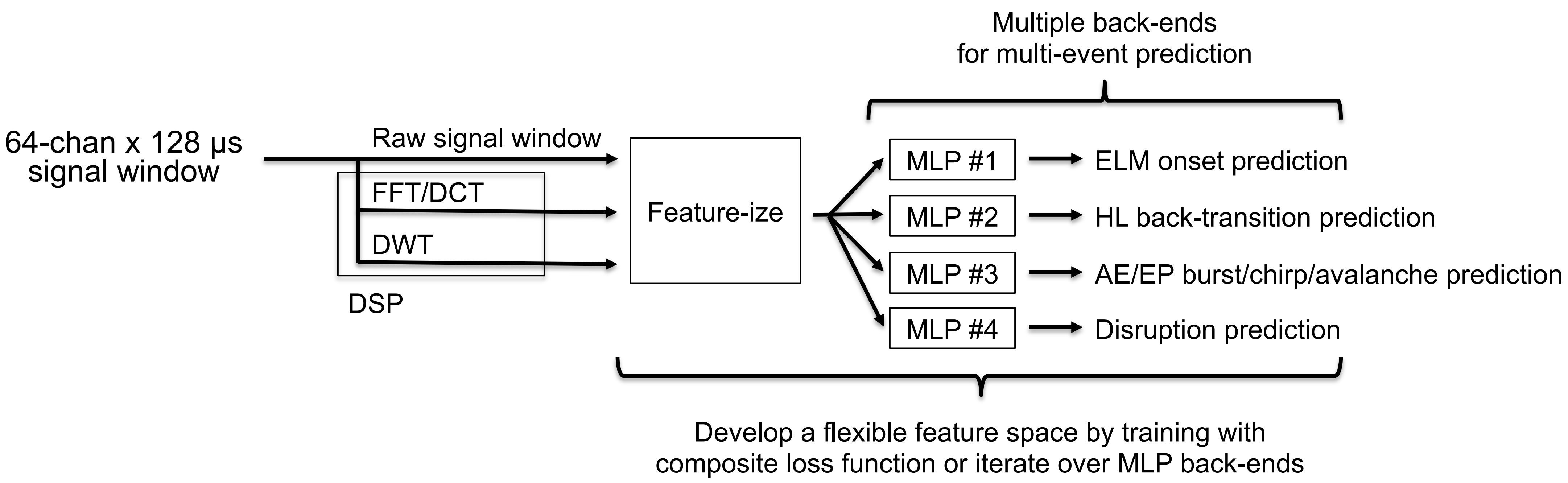
Strategies to extend the forecast horizon for ELM onset prediction

- Longer signal windows for low frequency dynamics
  - for example, 128 μs signal windows
- Signal transformation with high bandwidth DSP
- Expand training dataset with marginal cases from unseen data
  - Leverage large dataset of unlabeled ELMs
  - Improve coverage of high dimensional data space



DNN must be compatible with high-throughput RT compute platform like FPGA
- e.g., RNN may not be compatible

Flexible feature space can feed multiple back-ends for multi-event prediction



RT edge ML predictions can be implemented as new signals for feedback control within the RT plasma control system (PCS)

Summary

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