Deep Learning for Plasma Tomography and Disruption Prediction

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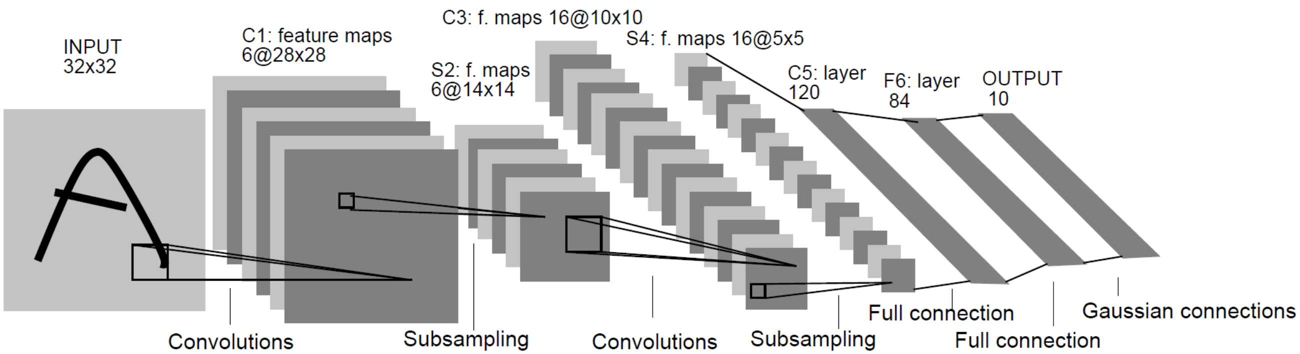
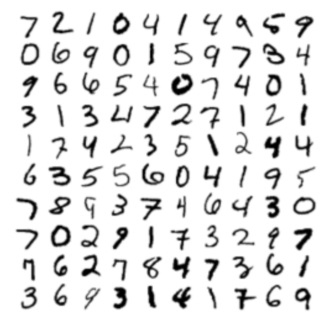
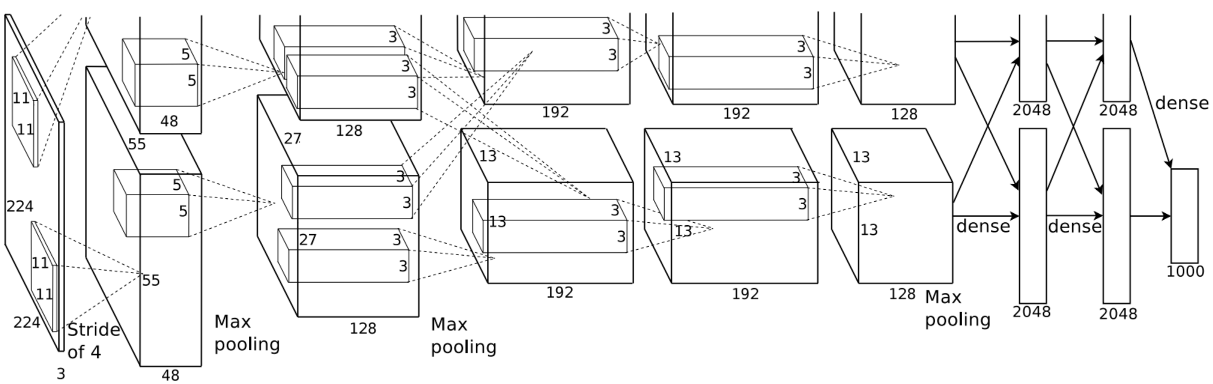
Deep Learning

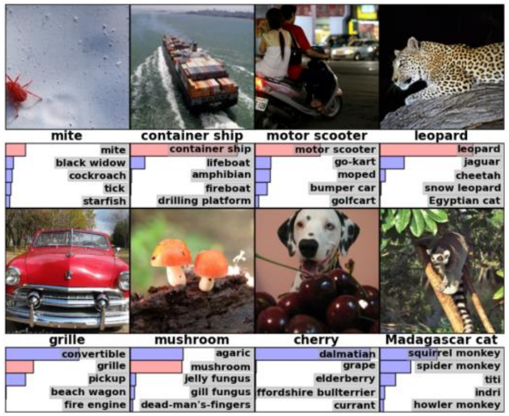
- Convolutional Neural Networks (CNNs)





Y. Lecun et al., *Gradient-based learning applied to document recognition*, 1998



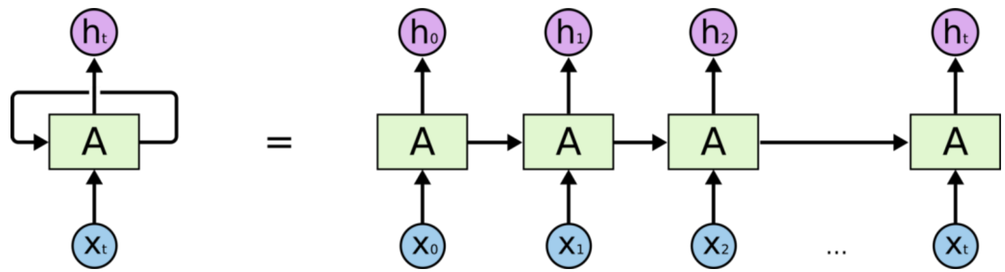


A. Krizhevsky et al., *ImageNet Classification with Deep Convolutional Neural Networks*, 2012

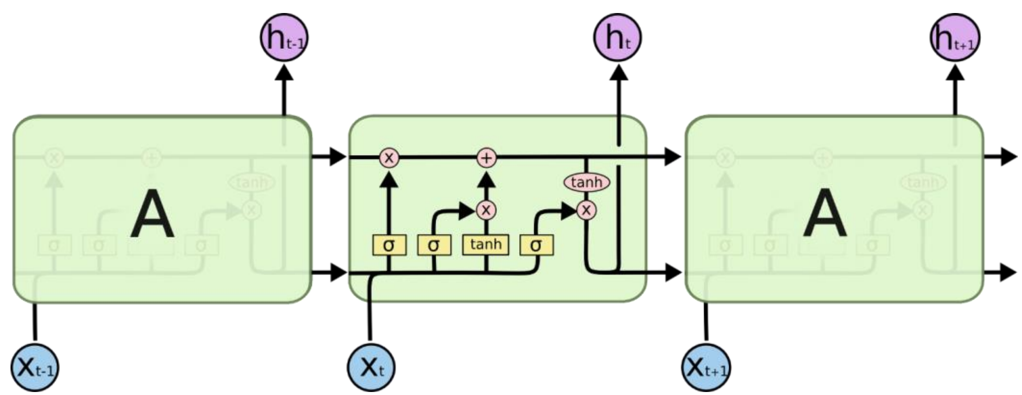
Deep Learning

- Recurrent Neural Networks (RNNs)
  - speech recognition
  - language modeling
  - machine translation
  - time series
  - …

Simple RNN



LSTM
(Long short-term memory)



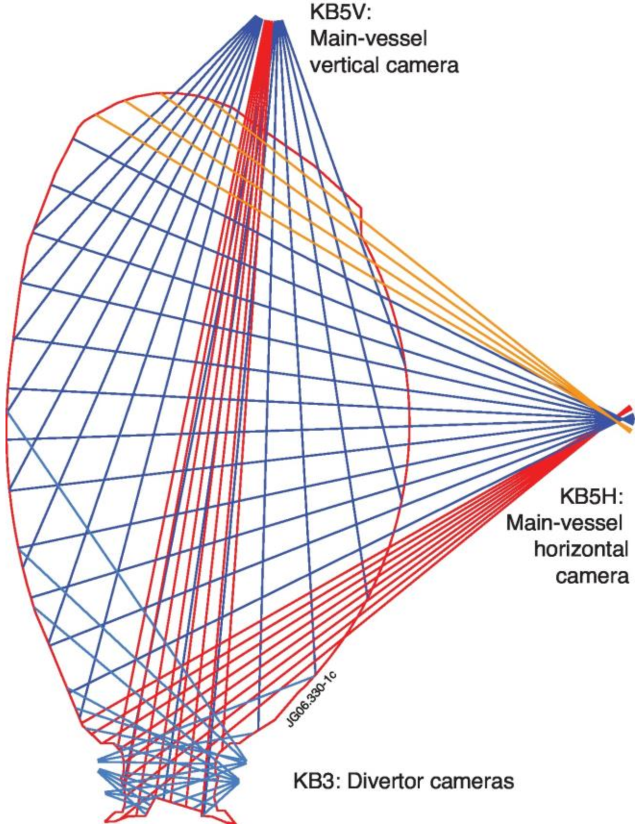
C. Olah, *Understanding LSTM Networks*, 2015

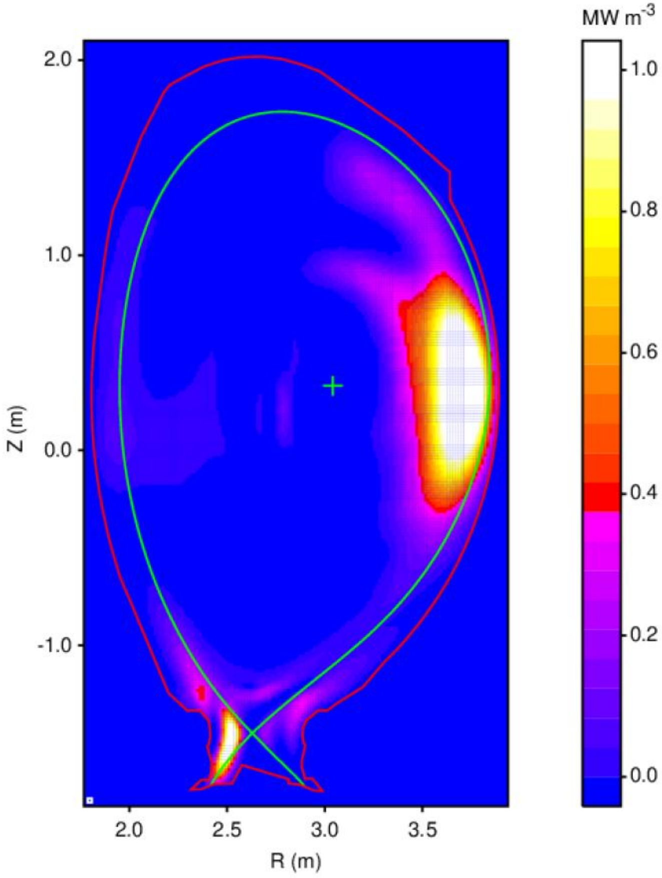
Deep Learning

- Convolutional Neural Networks (CNNs)
  - image processing
    - e.g. plasma tomography
- Recurrent Neural Networks (RNNs)
  - time series analysis
    - e.g. disruption prediction

Plasma Tomography

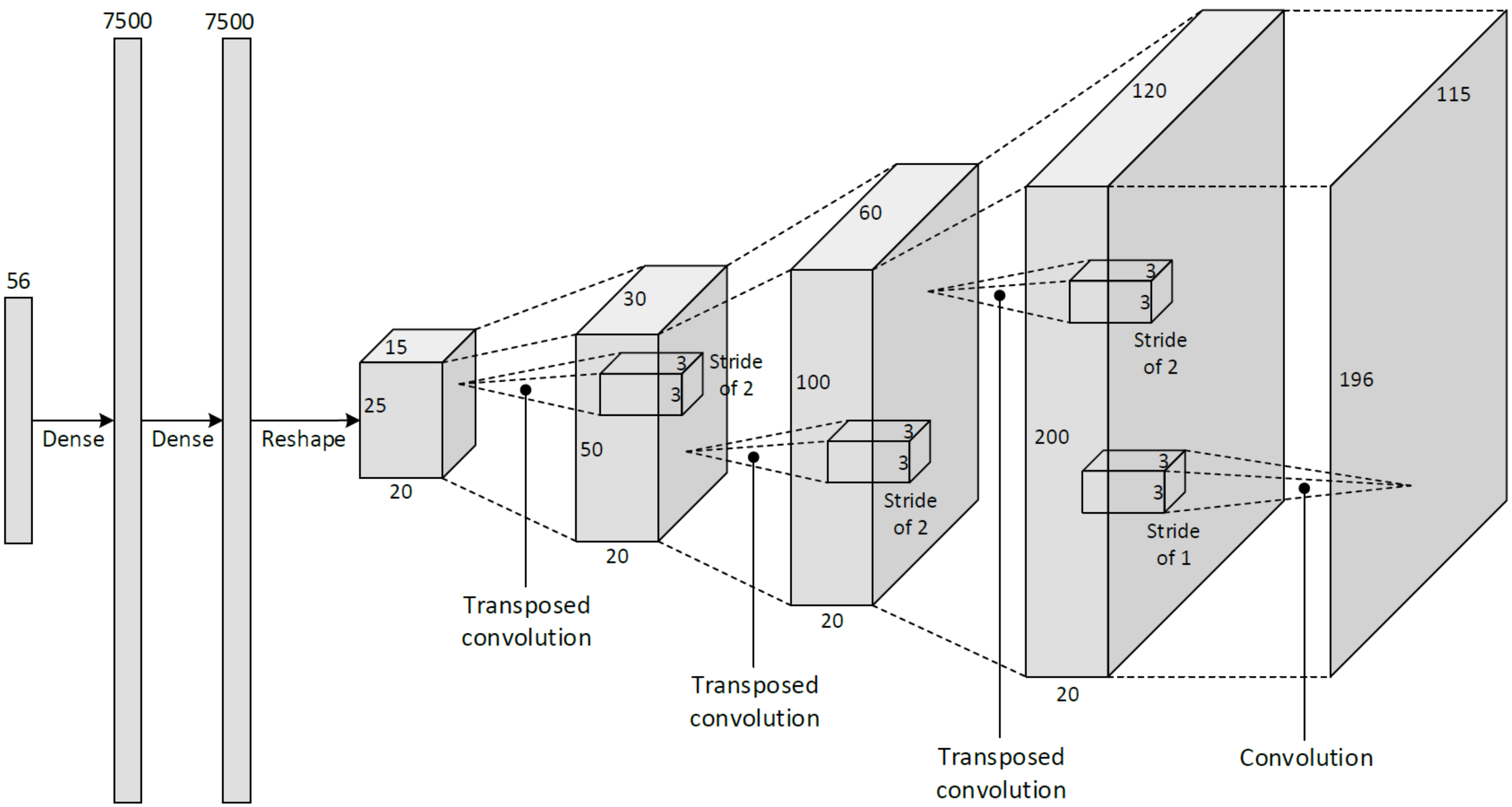
- Reconstruction of the 2D plasma radiation profile





Plasma Tomography

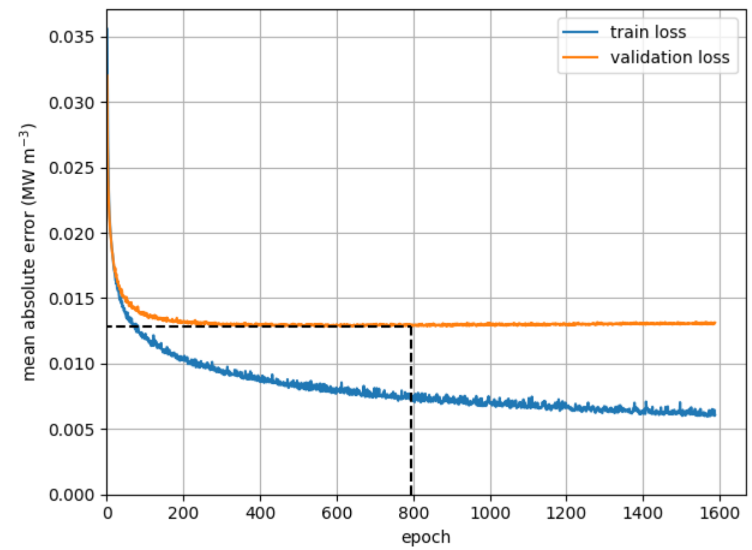
- “Deconvolutional” neural network



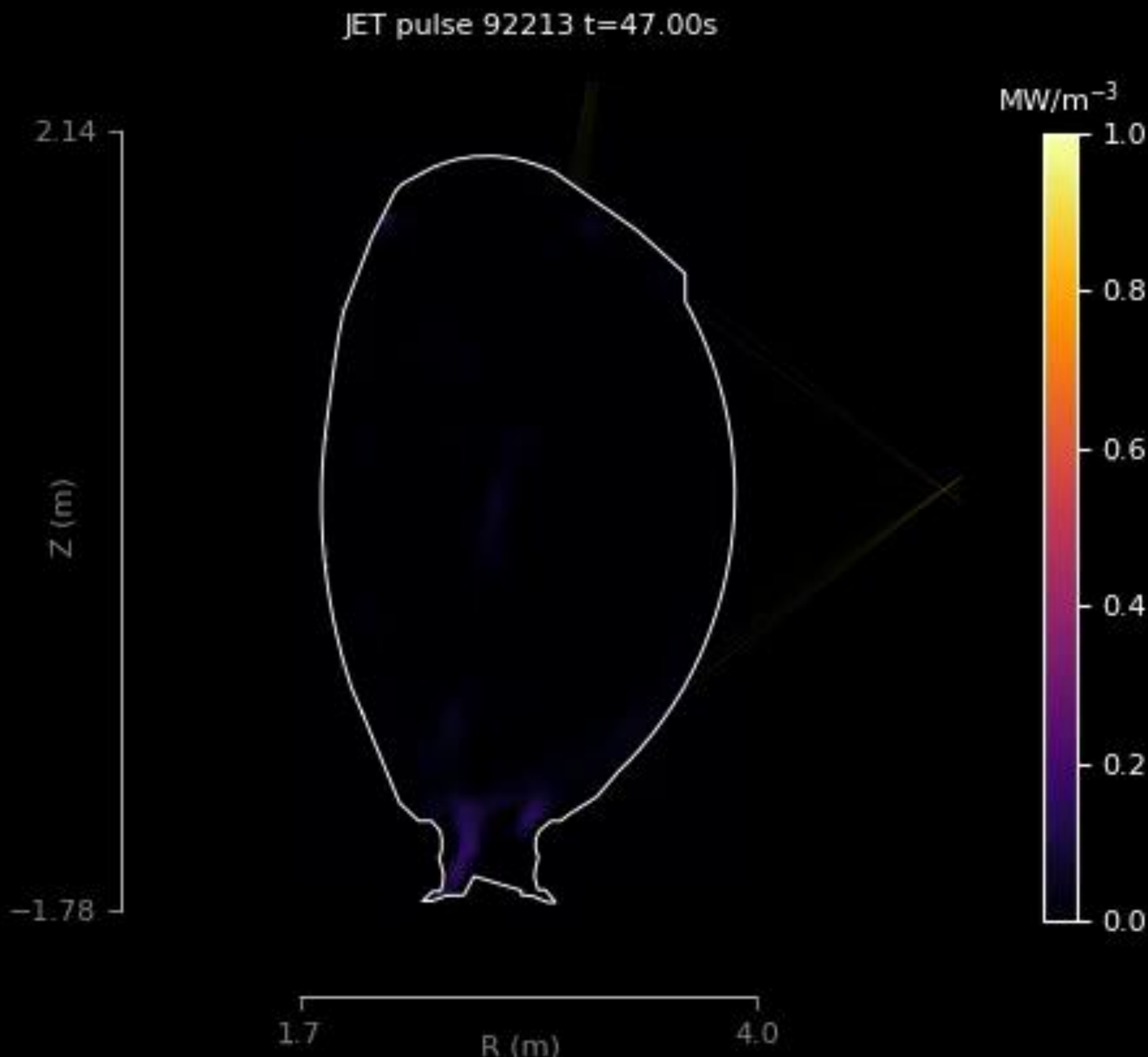
D. R. Ferreira et al., *Full-pulse Tomographic Reconstruction with Deep Neural Networks,* 2018

Plasma Tomography

- Dataset
  - JET ILW pulses 80128–92504
  - ~28k sample reconstructions
  - 80% training, 10% validation, 10% test
- Training
  - loss function: mean absolute error
  - min. validation loss: 0.0128 MW m^{-3}
- Test set
  - loss: 0.0147 MW m^{-3}
  - SSIM: 0.936
  - PSNR: 35.4 dB



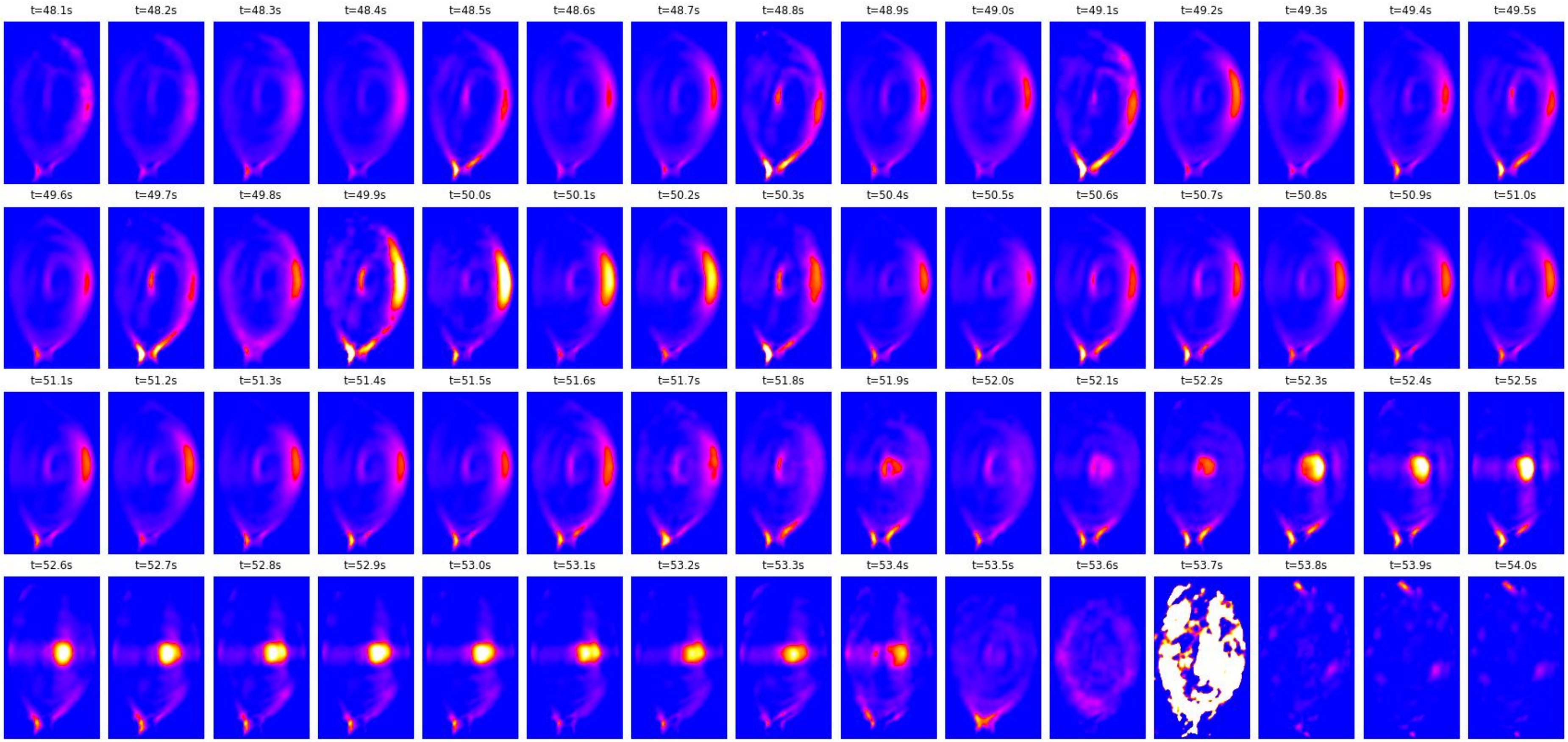
Keras TensorFlow NVIDIA



D. D. Carvalho et al., *Deep Neural Networks for Plasma Tomography with Applications to JET and COMPASS,* ECPD 2019

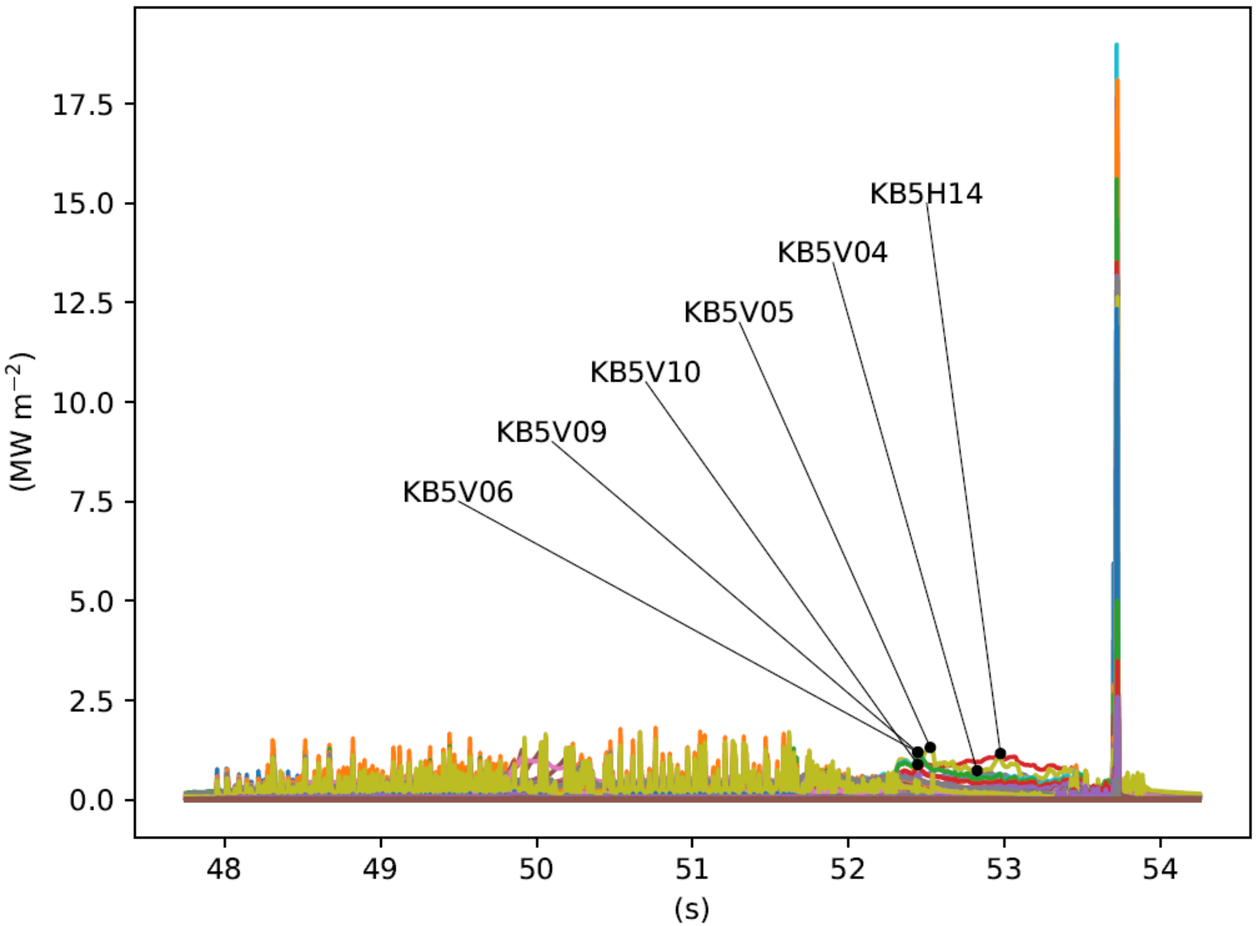
Plasma Tomography

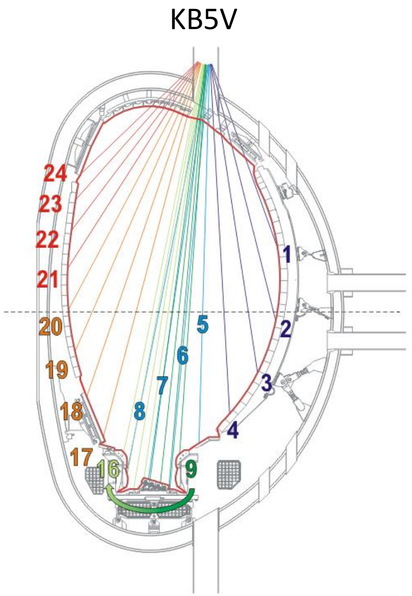
- Full-pulse reconstruction (92213)

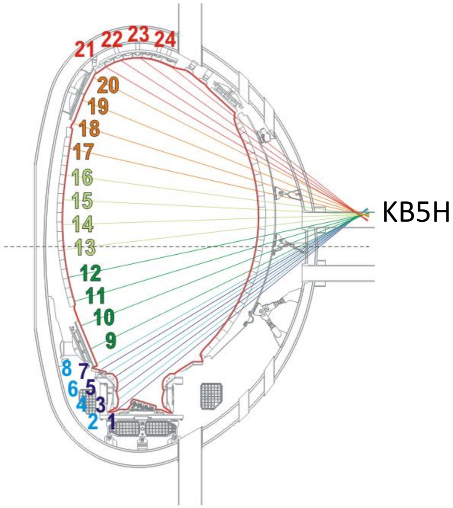


Disruption Prediction

- Bolometer signals (92213)

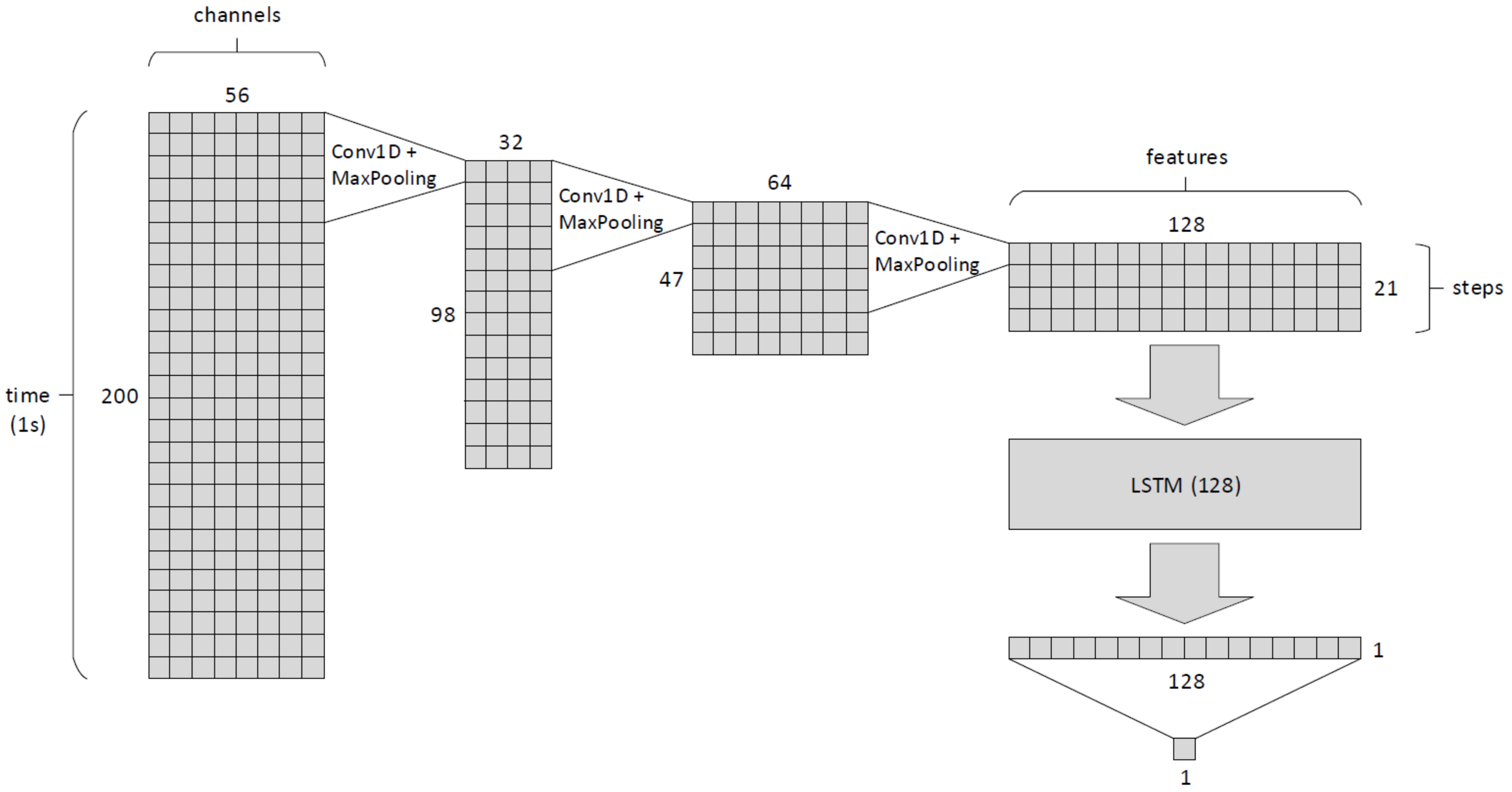






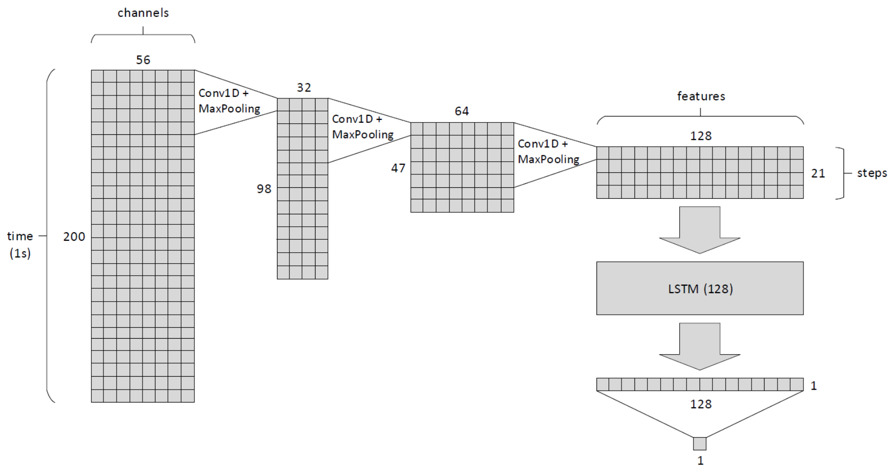
Disruption Prediction

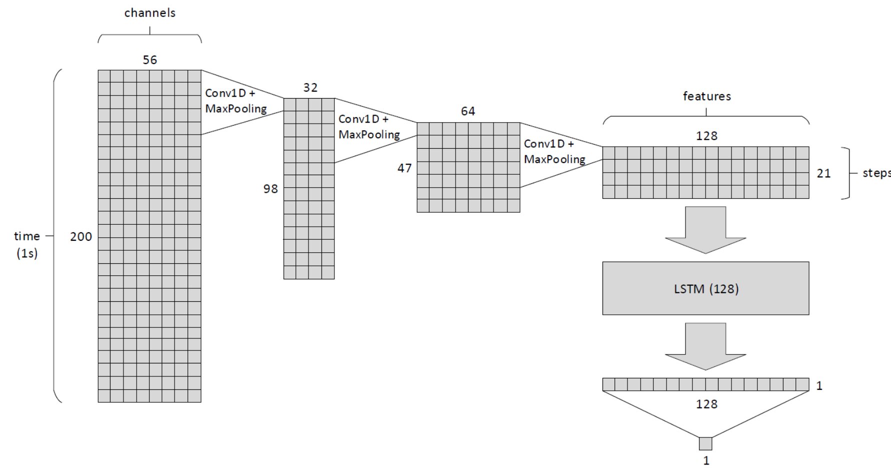
- Recurrent Neural Network



Disruption Prediction

- Two variants



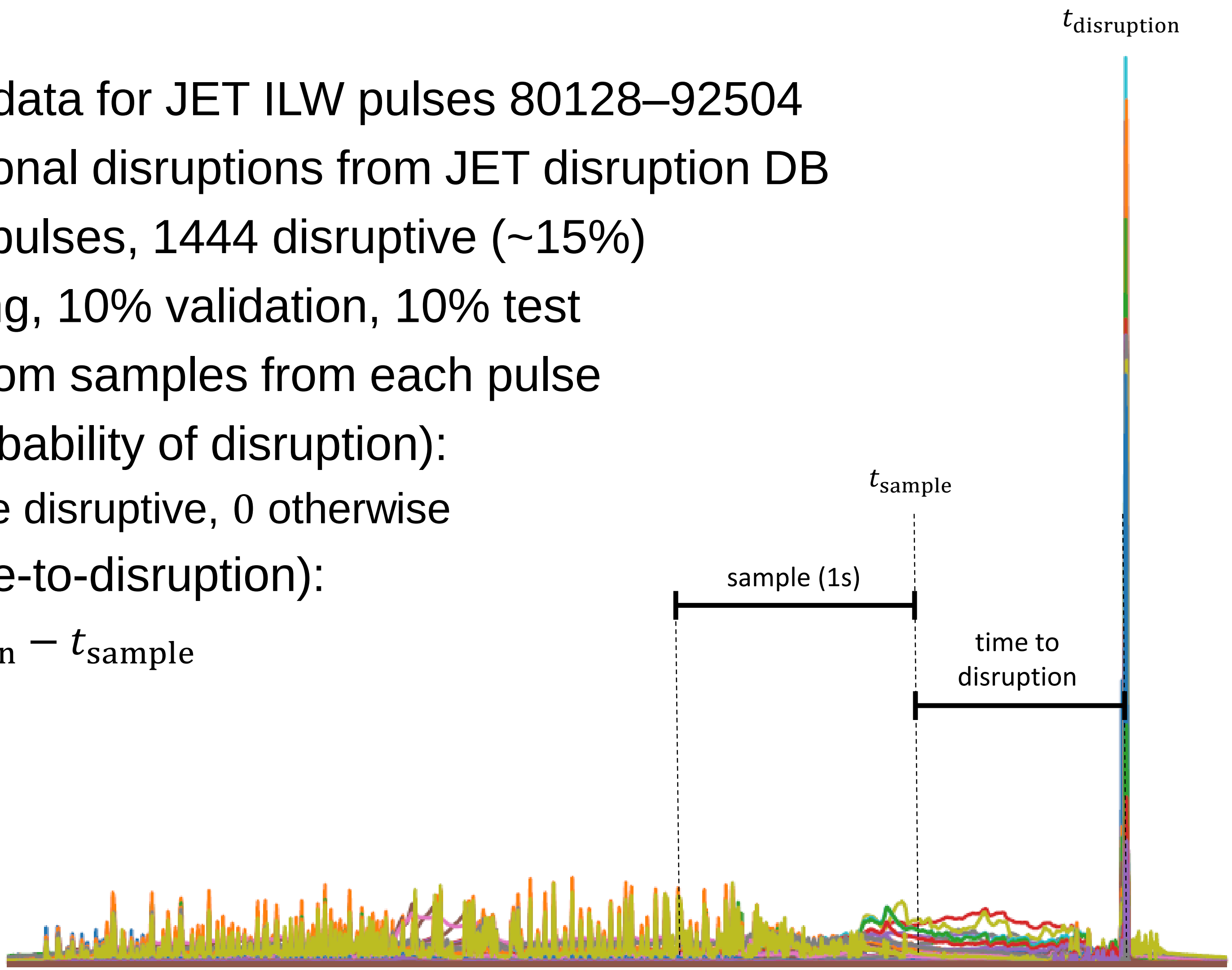


- probability of disruption (classification)
  - output: **sigmoid activation**
  - loss: **binary cross-entropy**
  - training: **disruptive** and **non-disruptive** pulses

- time-to-disruption (regression)
  - output: **no activation**
  - loss: **mean absolute error**
  - training: **disruptive** pulses only

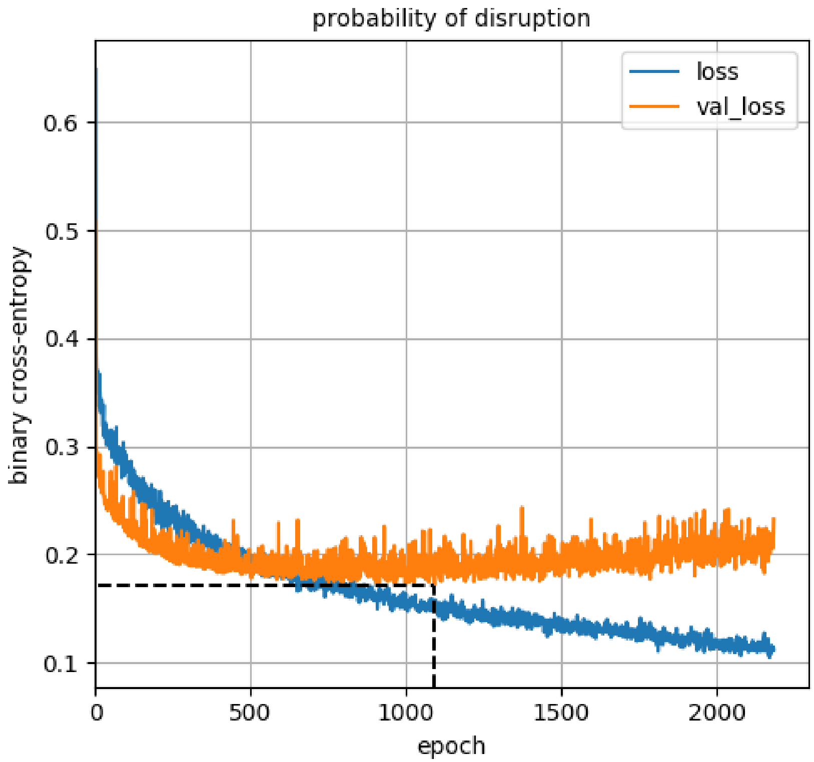
Disruption Prediction

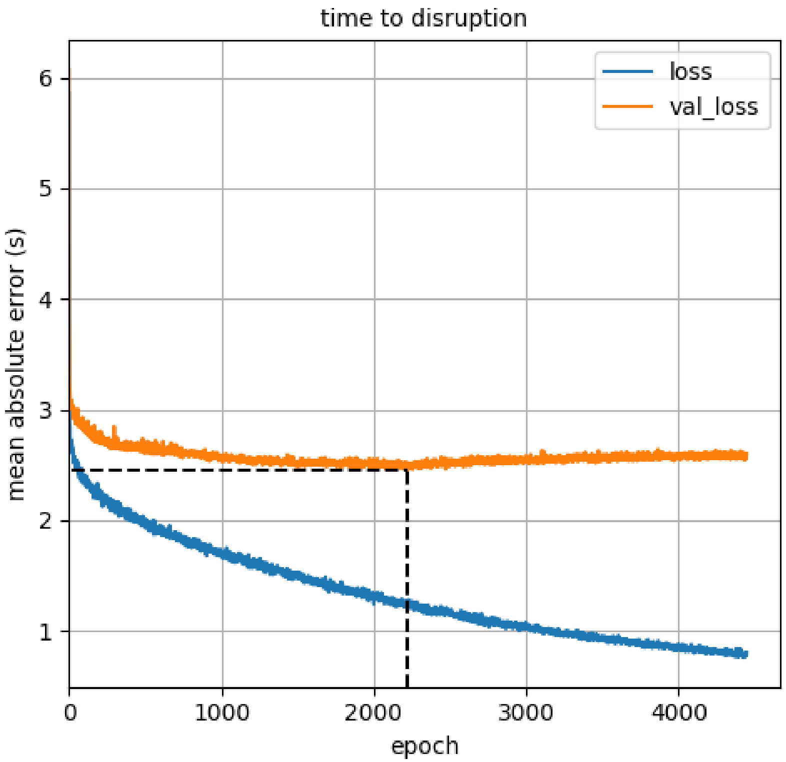
- Dataset
  - bolometer data for JET ILW pulses 80128–92504
  - non-intentional disruptions from JET disruption DB
  - total 9323 pulses, 1444 disruptive (~15%)
  - 80% training, 10% validation, 10% test
  - input: random samples from each pulse
  - output (probability of disruption):
    - 1 if pulse disruptive, 0 otherwise
  - output (time-to-disruption):
    - $t_{\text{disruption}} - t_{\text{sample}}$



Disruption Prediction

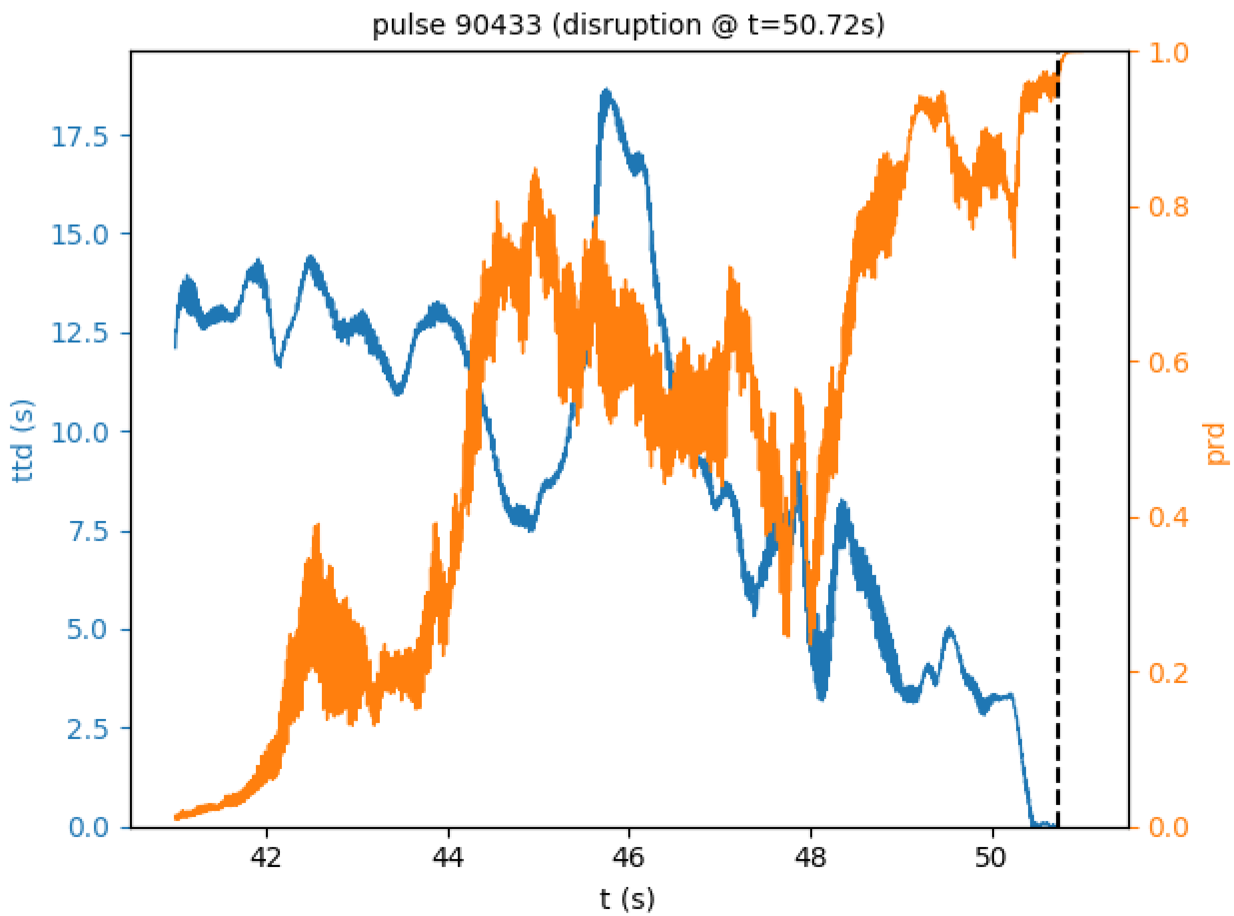
- Training
  - min. validation loss
    - probability of disruption: 0.172 (binary cross-entropy)
    - time-to-disruption: 2.45s (mean absolute error)





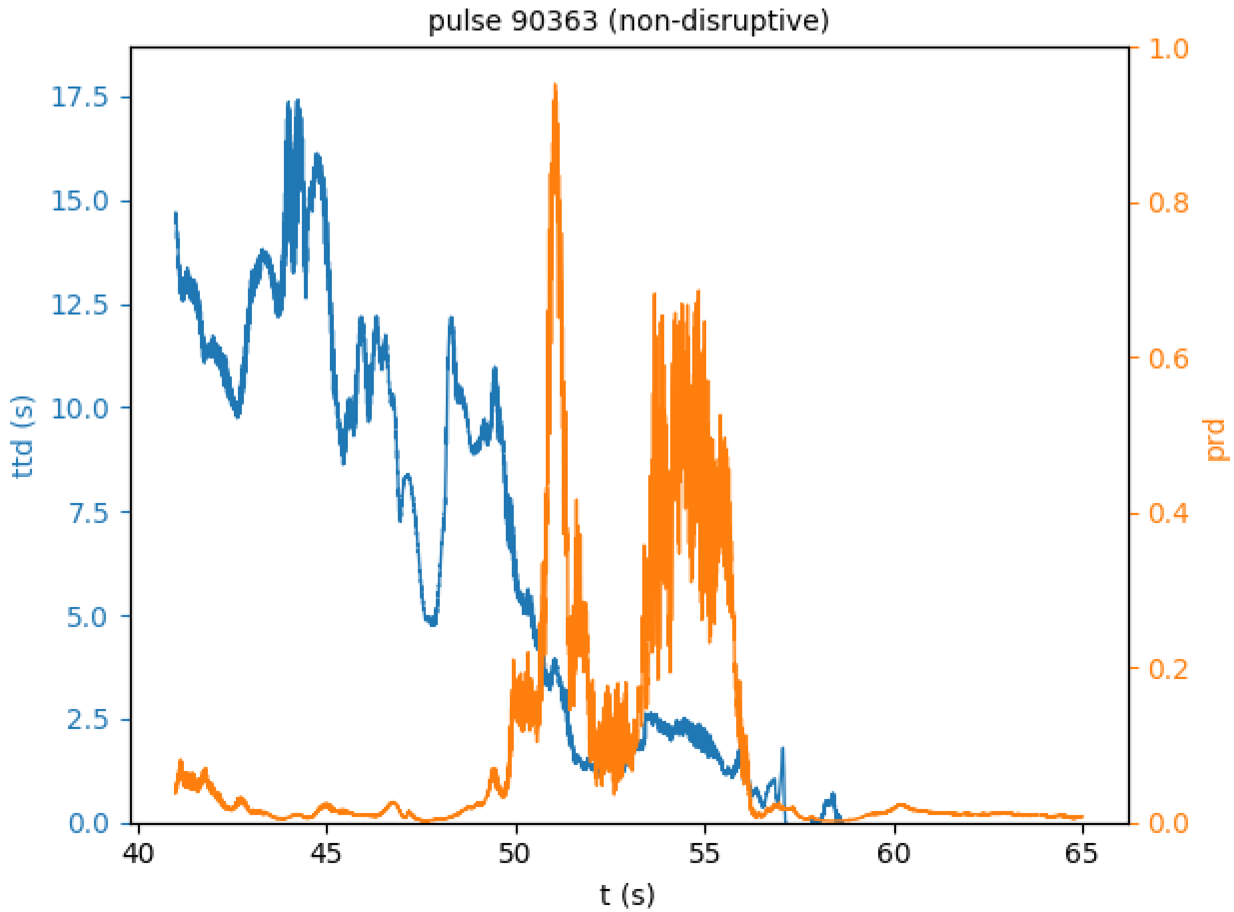
Disruption Prediction

- Full-pulse prediction (90433)



Disruption Prediction

- Full-pulse prediction (90363)



Disruption Prediction

- Alarm-triggering thresholds
  - example: $(prd \geq 0.85) \wedge (ttd \leq 1.5)$
    - TP: 11.7%
    - TN: 77.9%
    - FP: 5.3% (false alarms)
    - FN: 5.2% (missed alarms)
    - precision: TP/(TP+FP) = 69.0%
    - recall: TP/(TP+FN) = 69.4%
  - comparison: APODIS*
    - recall: 85.4%
    - FP: 2.5% (false alarms)

* Moreno et al., *Disruption prediction on JET during the ILW experimental campaigns*, 2016

Conclusion

- Several opportunities for deep learning
  - CNN → plasma tomography
  - RNN → disruption prediction
- From single to multiple diagnostics
  - magnetic equilibrium → CNN
  - plasma parameters → RNN
- From JET to other devices
  - CNN → JET and COMPASS (*)
  - RNN → JET and DIII-D (**)

(*) D. D. Carvalho et al., *Deep Neural Networks for Plasma Tomography with Applications to JET and COMPASS,* ECPD 2019
(**) J. Kates-Harbeck et al., *Predicting disruptive instabilities in controlled fusion plasmas through deep learning,* Nature, 2019