Deep Neural Networks for Plasma Tomography with Applications to JET and COMPASS

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D. D. Carvalho[1], D. R. Ferreira[1], P. J. Carvalho[1], M. Imrisek[2], J. Mlynar[2], H. Fernandes[1] and JET Contributors*

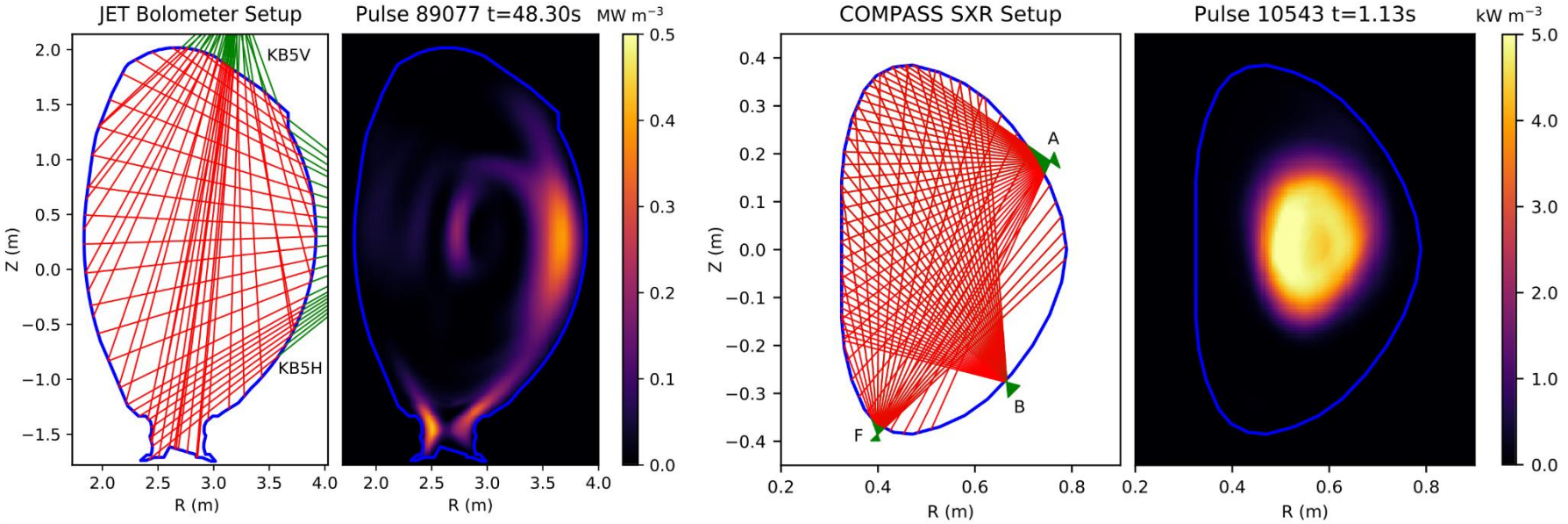
1. Instituto de Plasmas e Fusão Nuclear, IST University of Lisbon, Portugal
2. Institute of Plasma Physics AS CR, Prague, Czech Republic

* See the author list of "Overview of the JET preparation for Deuterium-Tritium Operation" by E. Joffrin et al. to be published in Nuclear Fusion Special issue: overview and summary reports from the 27th Fusion Energy Conference (Ahmedabad, India, 22-27 October 2018).

Plasma Tomography

Goal

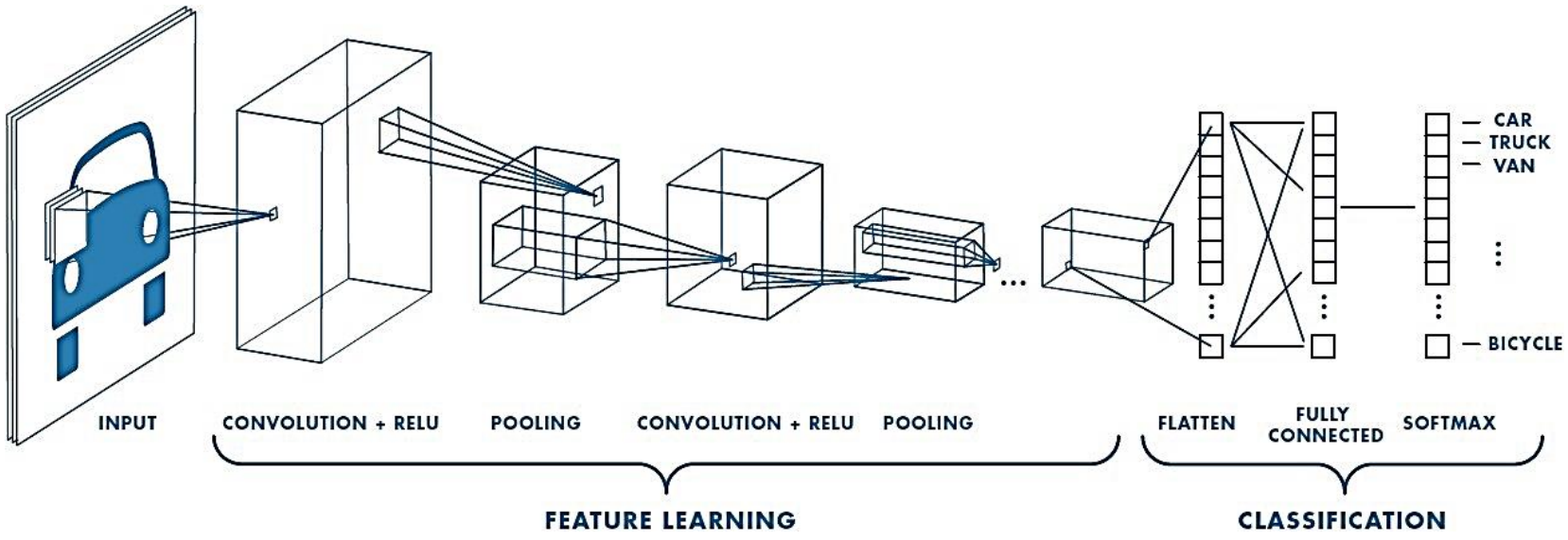
- Reconstruct plasma radiation profile based on line integrated measurements



Problem

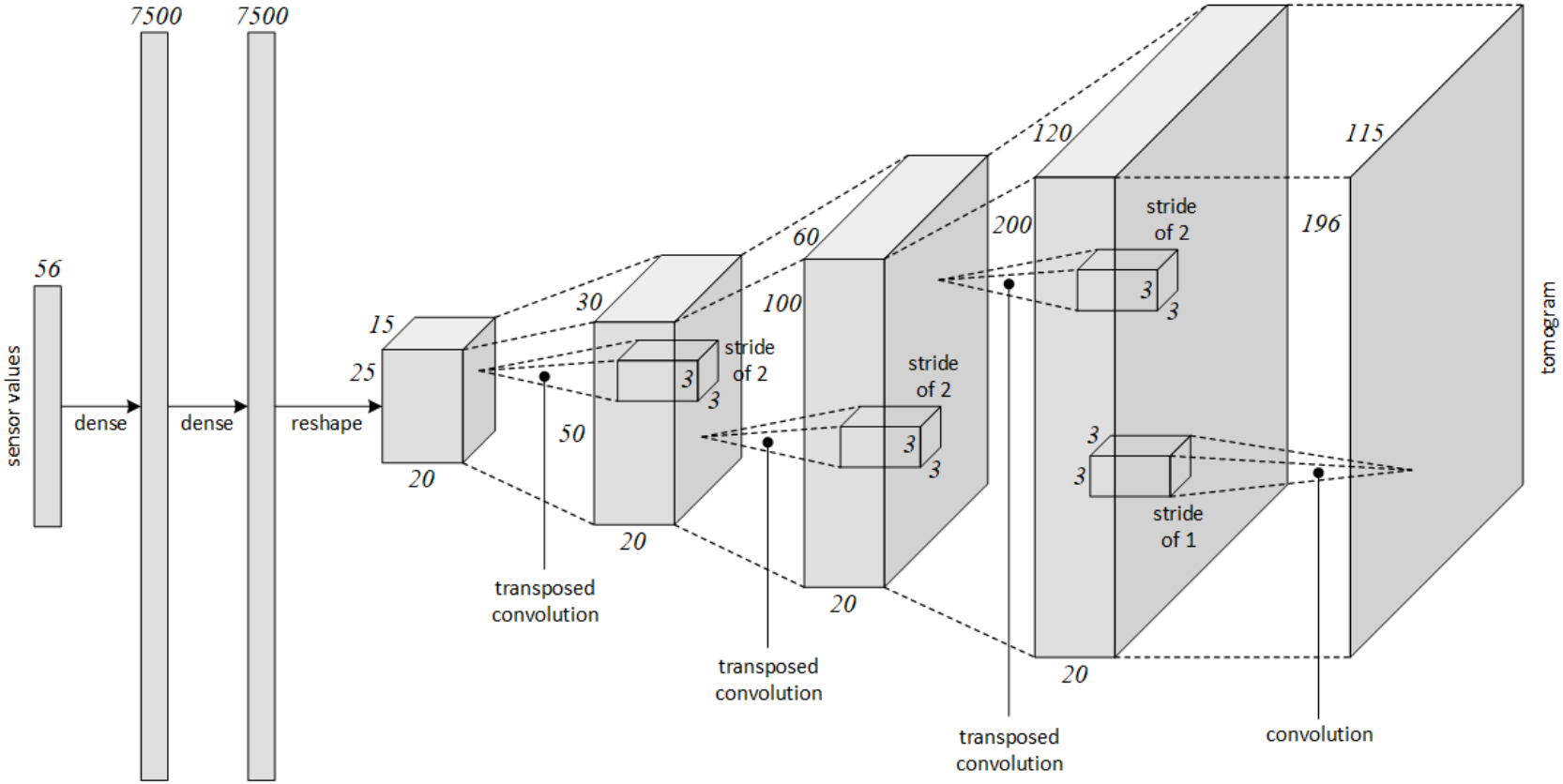
- Current algorithms take too much time to produce a reconstruction (from a few seconds to several minutes)

Convolutional Neural Networks

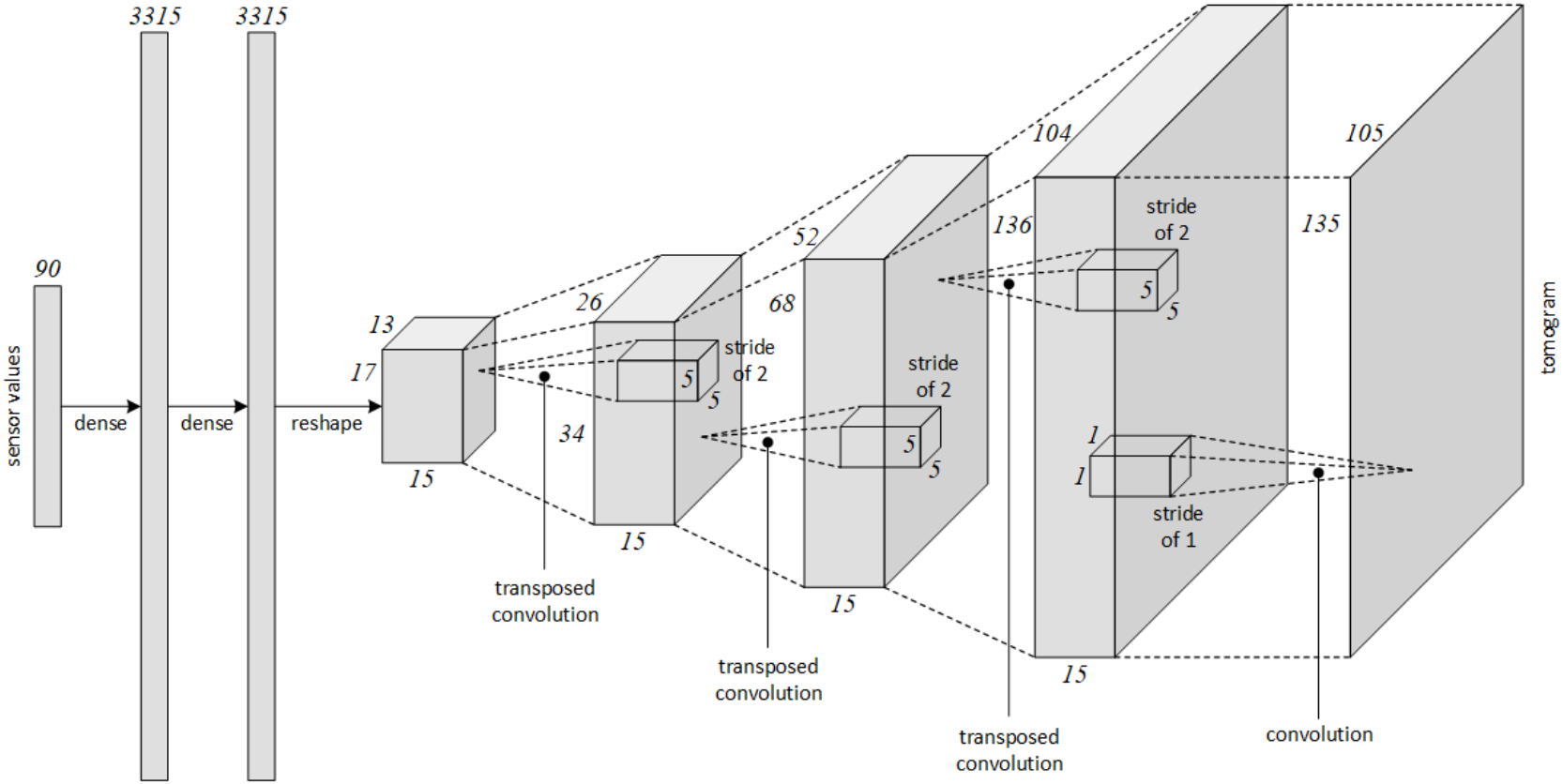


Source : Shyamal Patel*, Introduction to Deep Learning: What Are Convolutional Neural Networks?*

Deconvolutional Neural Network (JET)



Deconvolutional Neural Network (COMPASS)



Datasets

JET

- Gathered 28000 samples from several campaigns since installation of ITER-like wall in 2011 [1]
- Tomograms computed using TOMO5 algorithm [2]

COMPASS

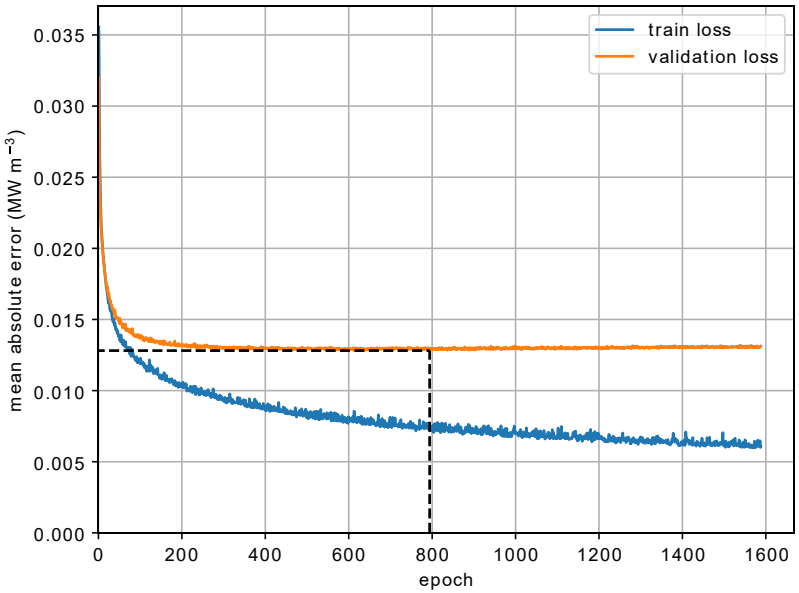
- Gathered 5800 samples from an interval of > 1000 shots
- Tomograms computed using Minimum Fisher regularization algorithm [3]

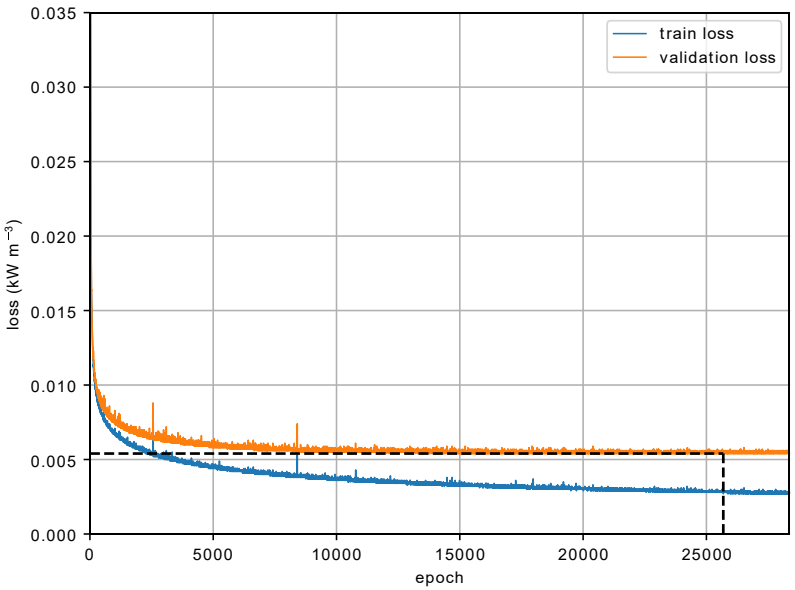
Divided into training/validation/test sets according to 80%/10%/10%

[1] G. F. Matthews et al., *JET ITER-like wall – overview and experimental programme*, Physica Scripta 2011 (2011)
[2] L. Ingesson et al., *Soft X ray tomography during ELMs and impurity injection in JET*, *Nuclear fusion* **38** (1998)
[3] M. Imríšek et al., *Optimization of soft X-ray tomography on the COMPASS tokamak*, Nukleonika 61 (2016)

Neural Network Training

- Neural network implementation in Keras [1]
- Training performed on a NVIDIA Titan X GPU using batched accelerated gradient descent (Adam [2]) with a learning rate of 10^{-4}
- Minimum error validation loss : *JET* = $0.0128\ MWm^{-3}$, *COMPASS* = $0.0054\ kWm^{-3}$





[1] F. Chollet et al., Keras, https://keras.io (2015)

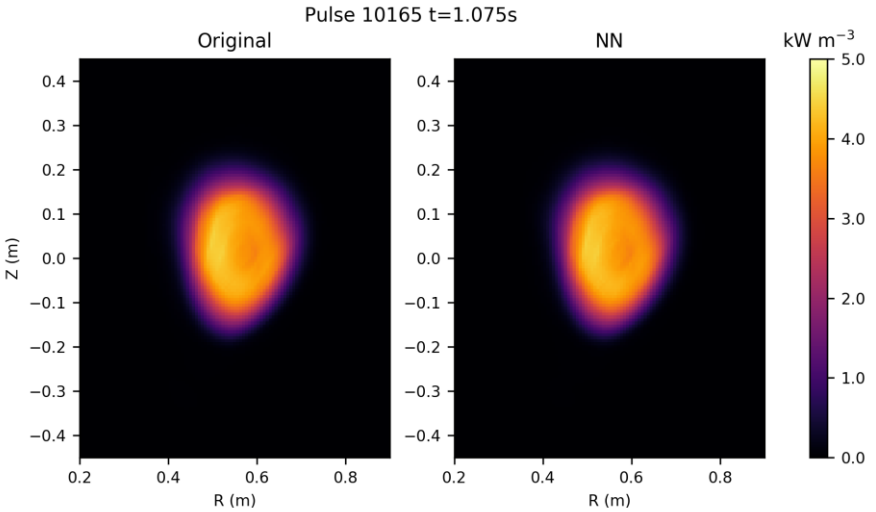
[2] D. P. Kingma and J. Ba, *Adam: A method for stochastic optimization*, *arXiv preprint arXiv:1412.6980* (2014)

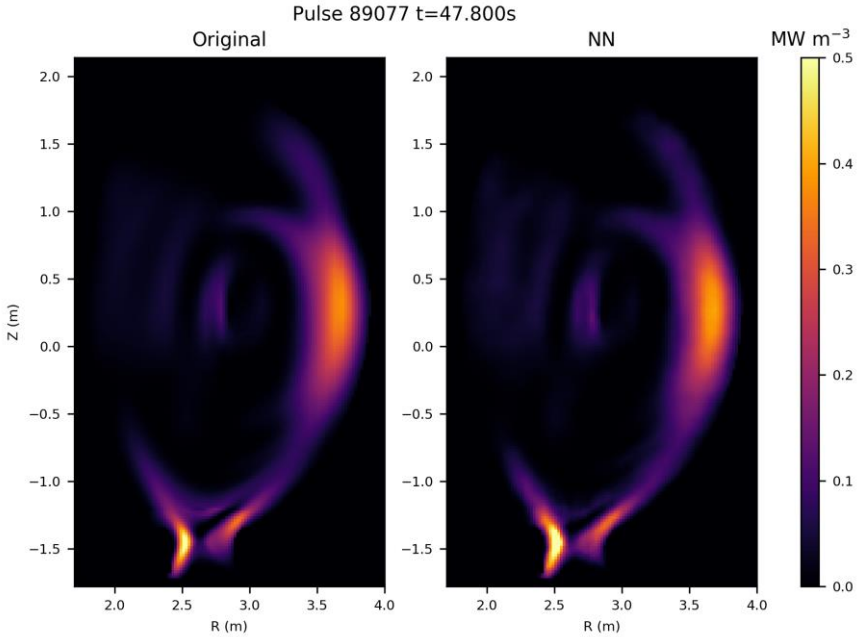
Neural Network Performance

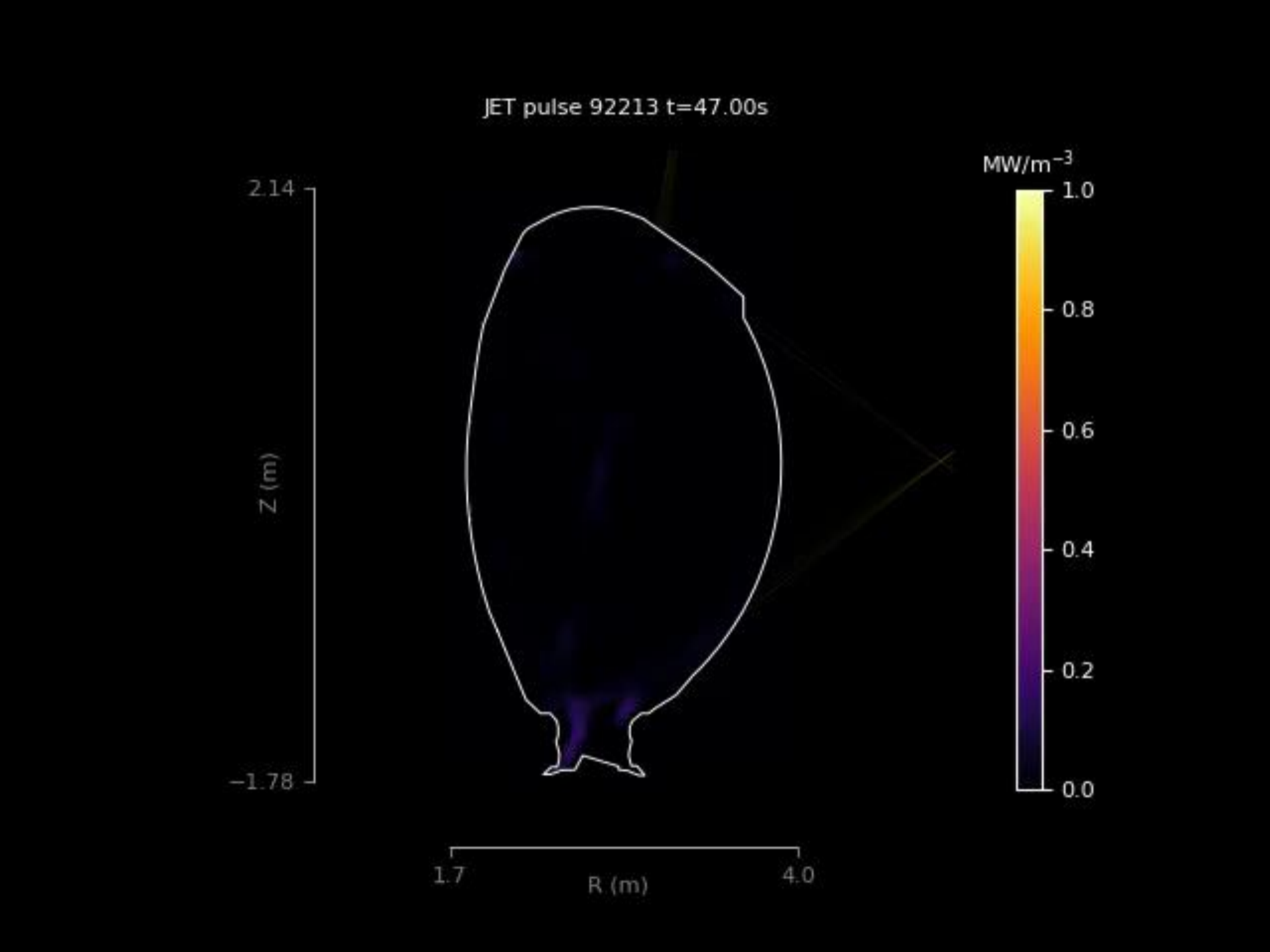
- Quality metrics on test set

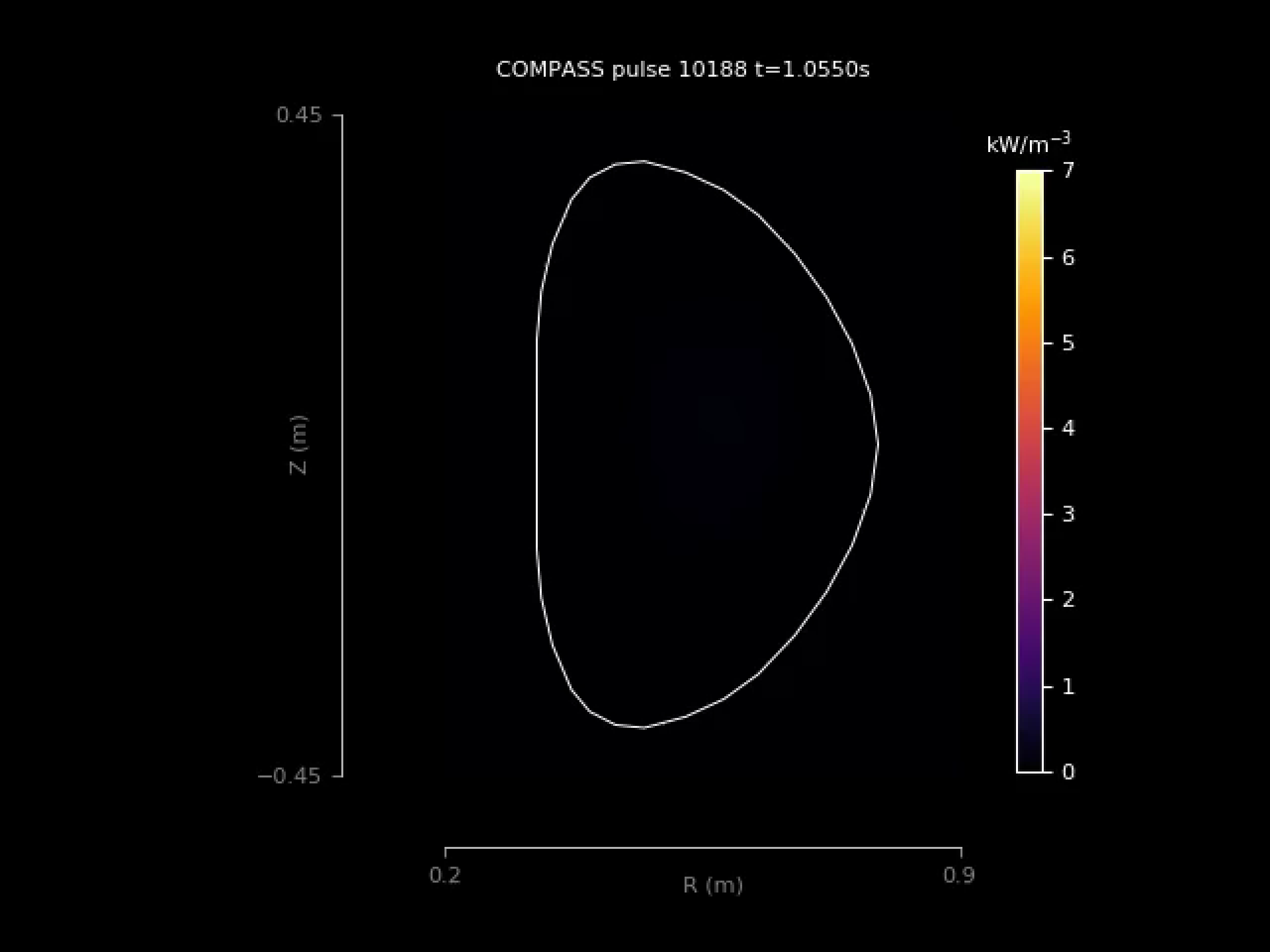
	SSIM		PSNR (dB)	
	Mean	Std dev	Mean	Std dev
JET	0.936	0.061	35.36	7.17
COMPASS	0.998	0.004	49.96	4.63

- Computing one reconstruction takes *JET:* $2\ ms$ and for *COMPASS:* $1\ ms$
- Close to real time - usual acquisition frequencies $\sim kHz$
- Full pulse reconstructions
  (1000+ reconstructions)
  calculated in seconds



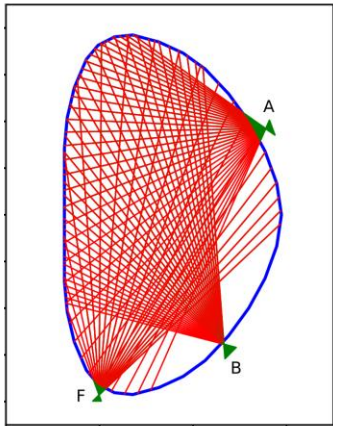



JET pulse 92213 t=47.00s
MW/m^{-3}
1.0
0.8
0.6
0.4
0.2
0.0
2.14
−1.78
Z (m)
1.7
4.0
R (m)

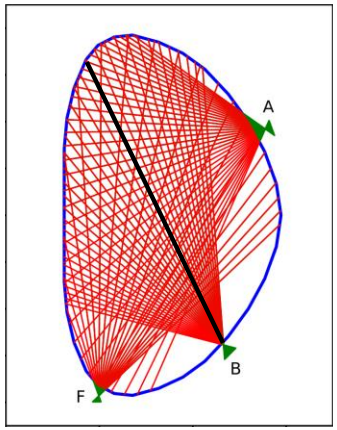

COMPASS pulse 10188 t=1.0550s
0.45
−0.45
Z (m)
0.2
0.9
R (m)
kW/m^{-3}
7
6
5
4
3
2
1
0

Performance with missing detectors (COMPASS)

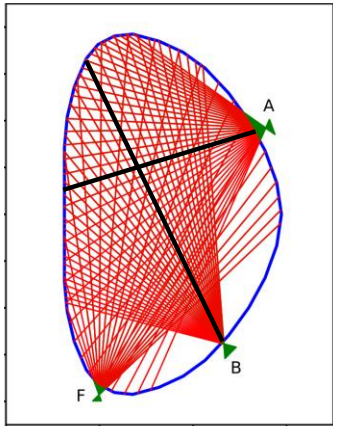
All detectors available



1 Missing Detector



2 Missing Detectors



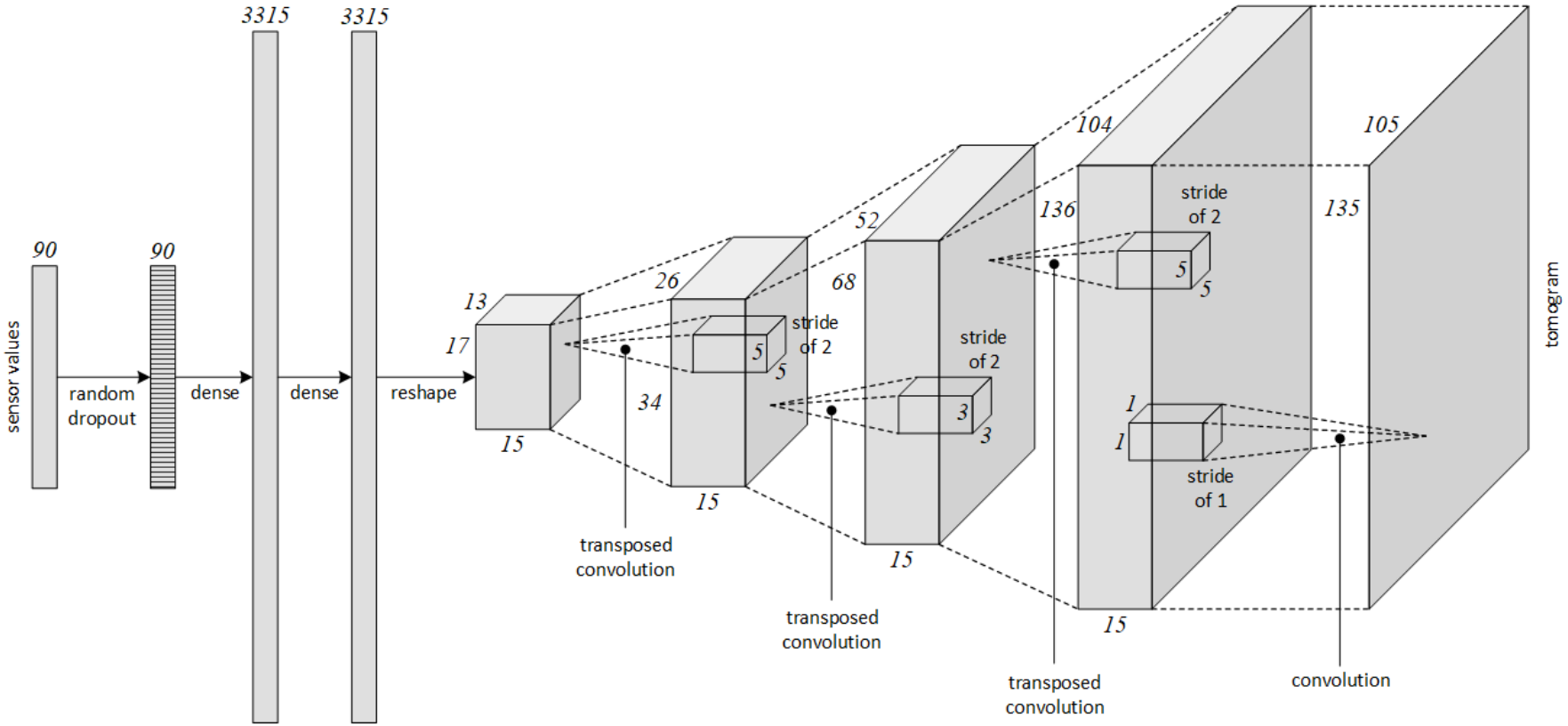
Dropout (%)	SSIM		
0	0.998	0.987	0.983

Dropout (%)	PSNR (dB)		
0	49.96	41.77	37.99

Similar behavior observed for JET neural network

Note : Quality metrics presented are calculated for the same test as before, and represent the average values over all possible combinations of missing detectors

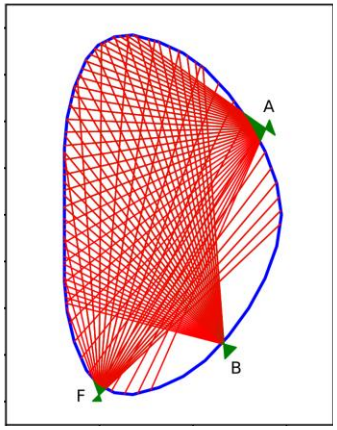
Modify architecture – include dropout layer



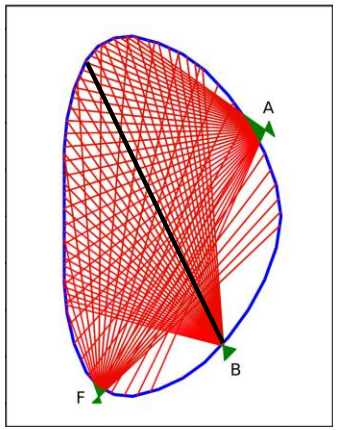
- Dropout layer is only active during training
- Trained 3 different neural networks using different dropout values – 1% , 5% and 10 %

Performance with dropout layer (COMPASS)

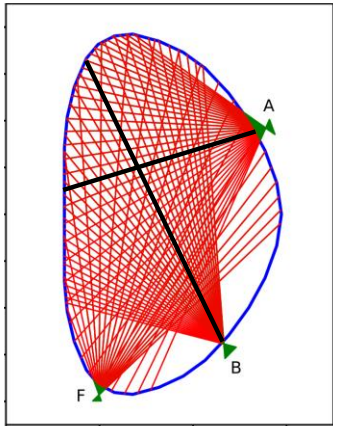
All detectors available



1 Missing Detector



2 Missing Detectors



Dropout (%)	SSIM		
0	0.998	0.987	0.983
1	**0.999**	**0.996**	**0.998**
5	0.992	0.994	0.997
10	0.992	0.988	0.992

Dropout (%)	PSNR (dB)		
0	49.96	41.77	37.99
1	**50.23**	**48.79**	**48.97**
5	39.23	38.76	39.19
10	33.44	33.03	33.30

Note : Quality metrics presented are calculated for the same tet as before, and represent the average values over all possible combinations of shutdown detectors

Additional Materials

Code

- JET: https://github.com/diogoff/plasma-tomography
- COMPASS: https://github.com/diogodcarvalho/PlasmaTomoML

Related work

- D. R. Ferreira et al., *Full Pulse Tomographic Reconstructions with Deep Neural Networks*

  https://arxiv.org/abs/1802.02242
- J. Mlynar et al., *Current Research into Applications of Tomography for Fusion Diagnostics*

  https://link.springer.com/article/10.1007/s10894-018-0178-x