Full-pulse tomographic reconstruction with deep neural networks

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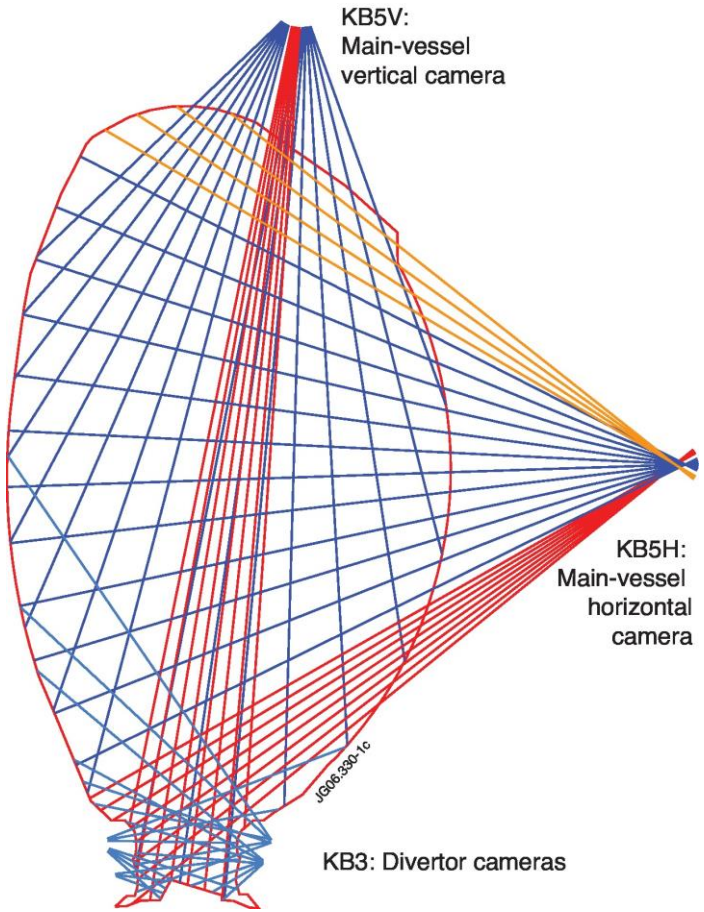
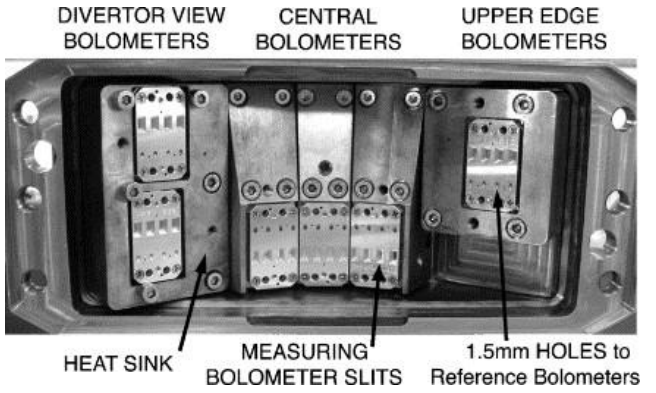
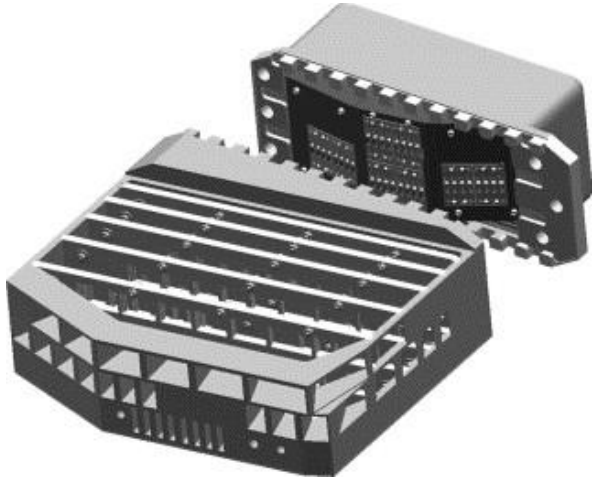
The KB5 diagnostic at JET

- 2 cameras with 24 bolometers each + 8 reserve channels (total 56)



A. Huber et al, Fusion Eng. Des. 82, 1327 (2007)

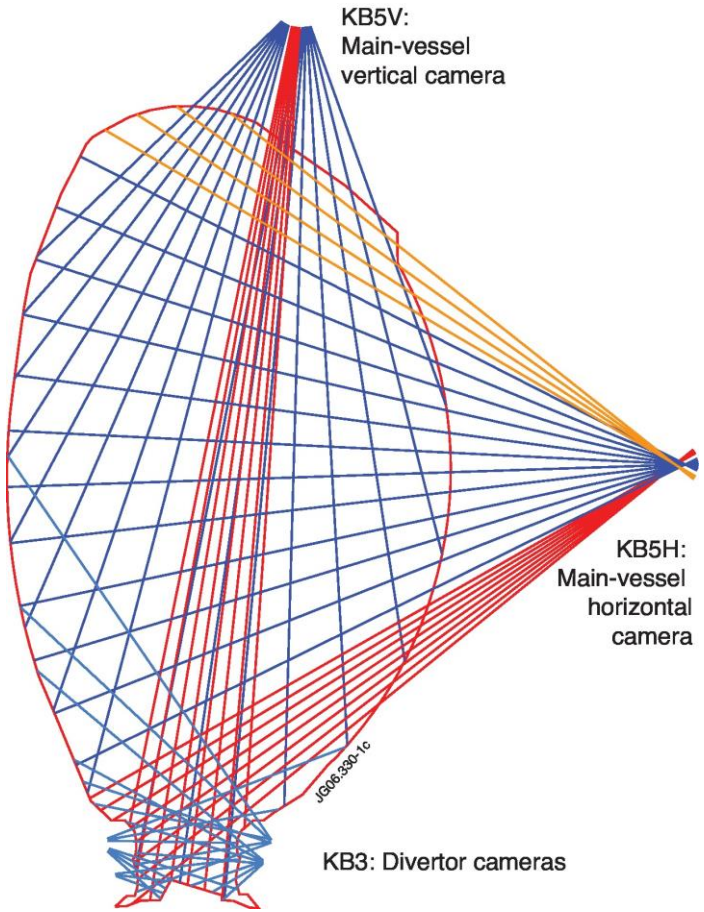




McCormick et al, Fusion Eng. Des. 74, 679 (2005)

Tomographic reconstruction

- iterative constrained optimization method



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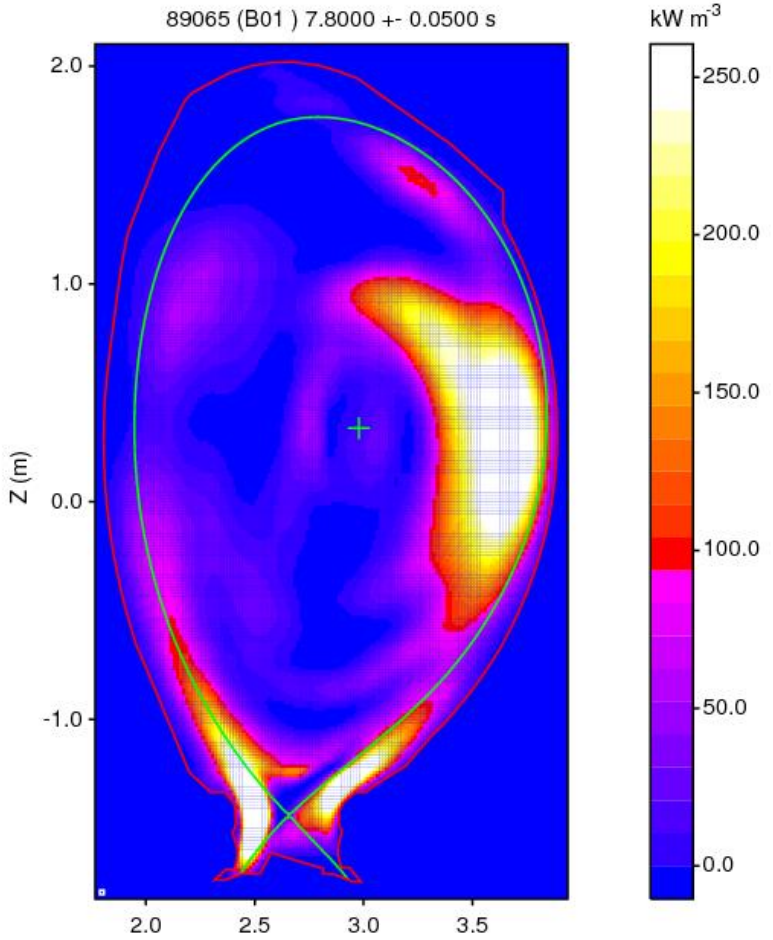


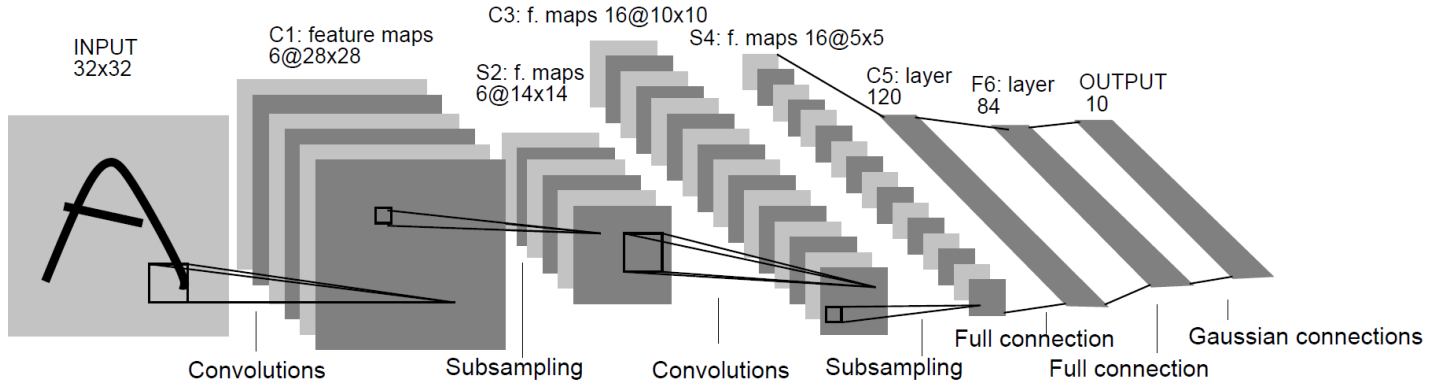
L.C. Ingesson et al., Nucl. Fusion 38, 1675 (1998)

Some facts

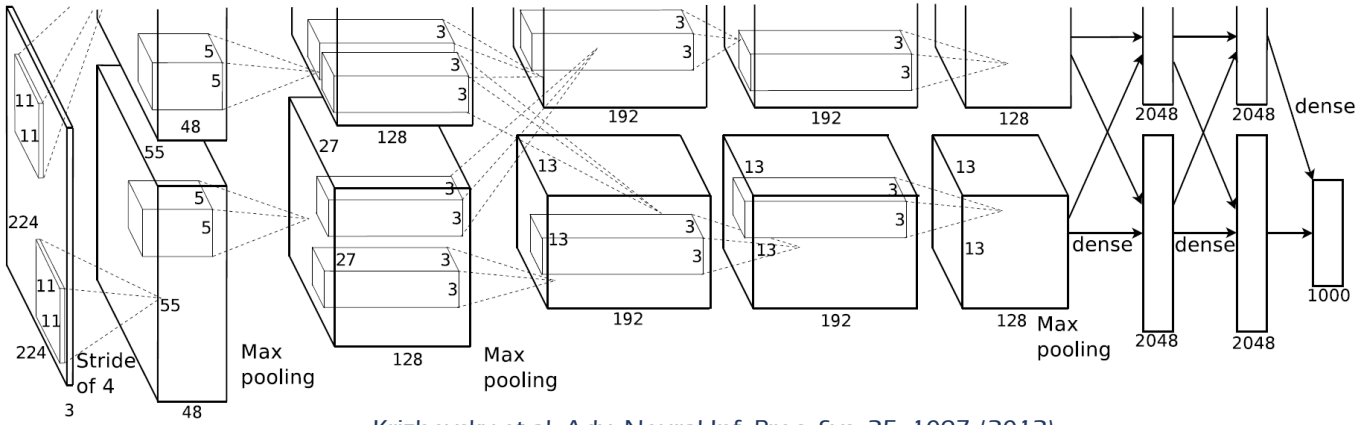
- KB5 sampling rate: 5 kHz
  - window average of 5 ms (25 samples)
  - 5 kHz / 25 = 200 Hz
- pulse duration: ~30 sec
  - 30 sec × 200 Hz = 6000 reconstructions/pulse
  - in practice, only a few (0-99)
- time per reconstruction
  - >1h on average
  - 6000 × 1h = 250 days

Deep neural networks

- traditional CNNs (convolutional neural networks)



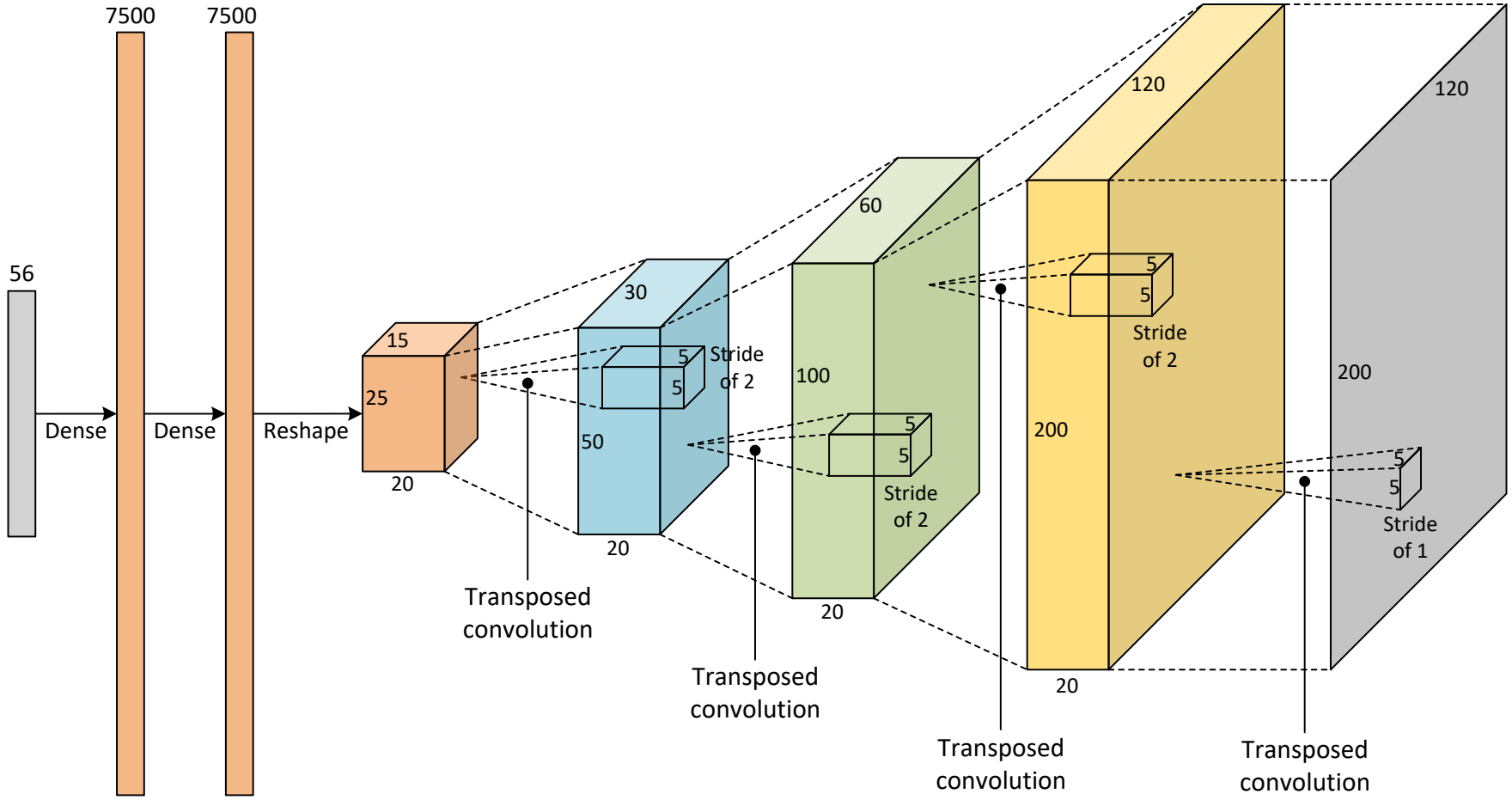
LeCun et al, Proc. of the IEEE 86, 2278 (1998)



Krizhevsky et al, Adv. Neural Inf. Proc. Sys. 25, 1097 (2012)

Deep neural networks

- inverse of a CNN ~ "deconvolutional" neural network

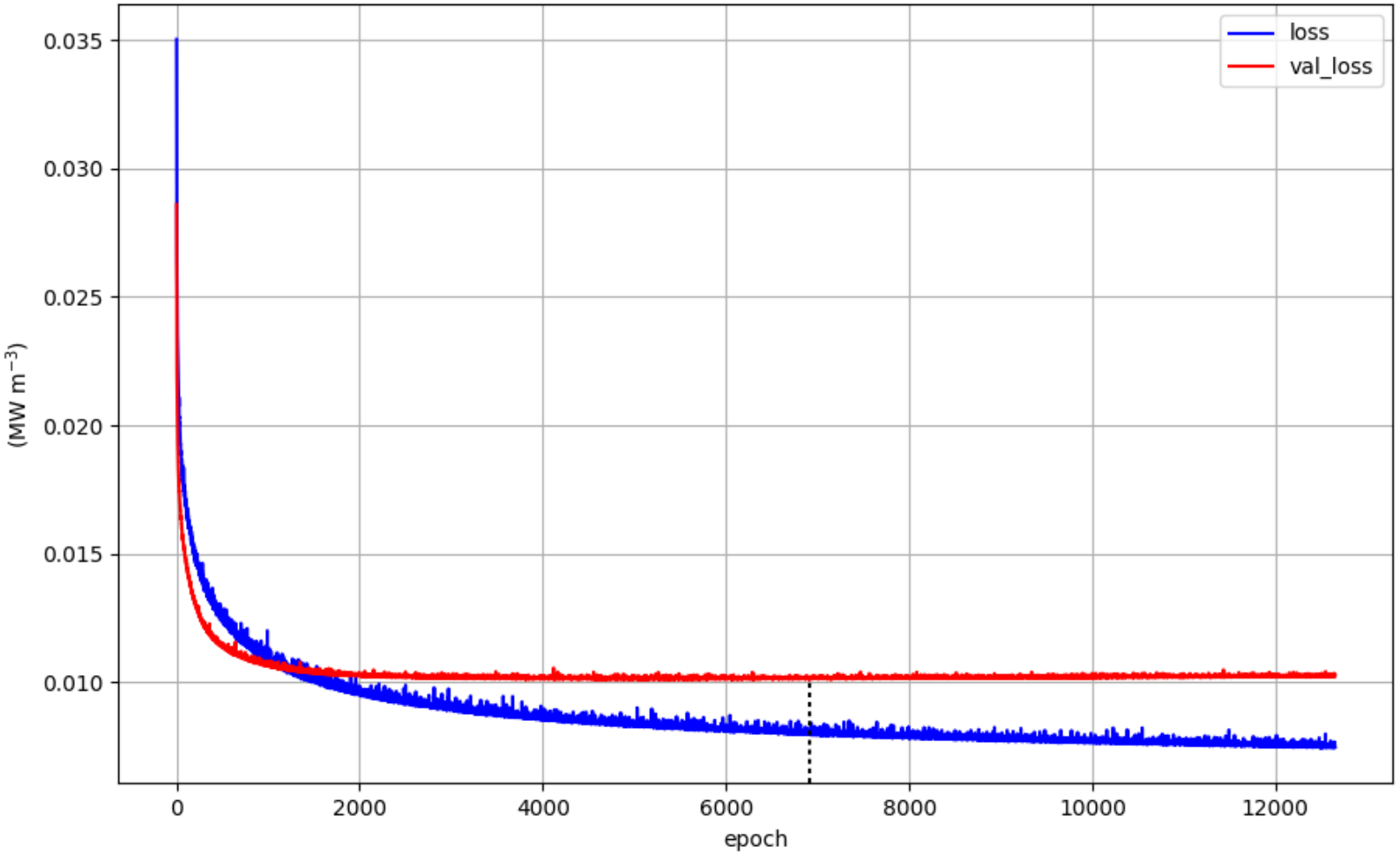


Training

- dataset
  - range of pulses: 79886 to 92504 (post-ILW)
  - 24203 sample reconstructions
  - 90% training (21783), 10% validation (2420)

- training
  - adaptive gradient descent (Adam)
  - learning rate: 0.0001 (10^{-4})
  - batch size: 411 (21783 / 411 = 53.0)
  - 53 batches = 53 updates/epoch

Training



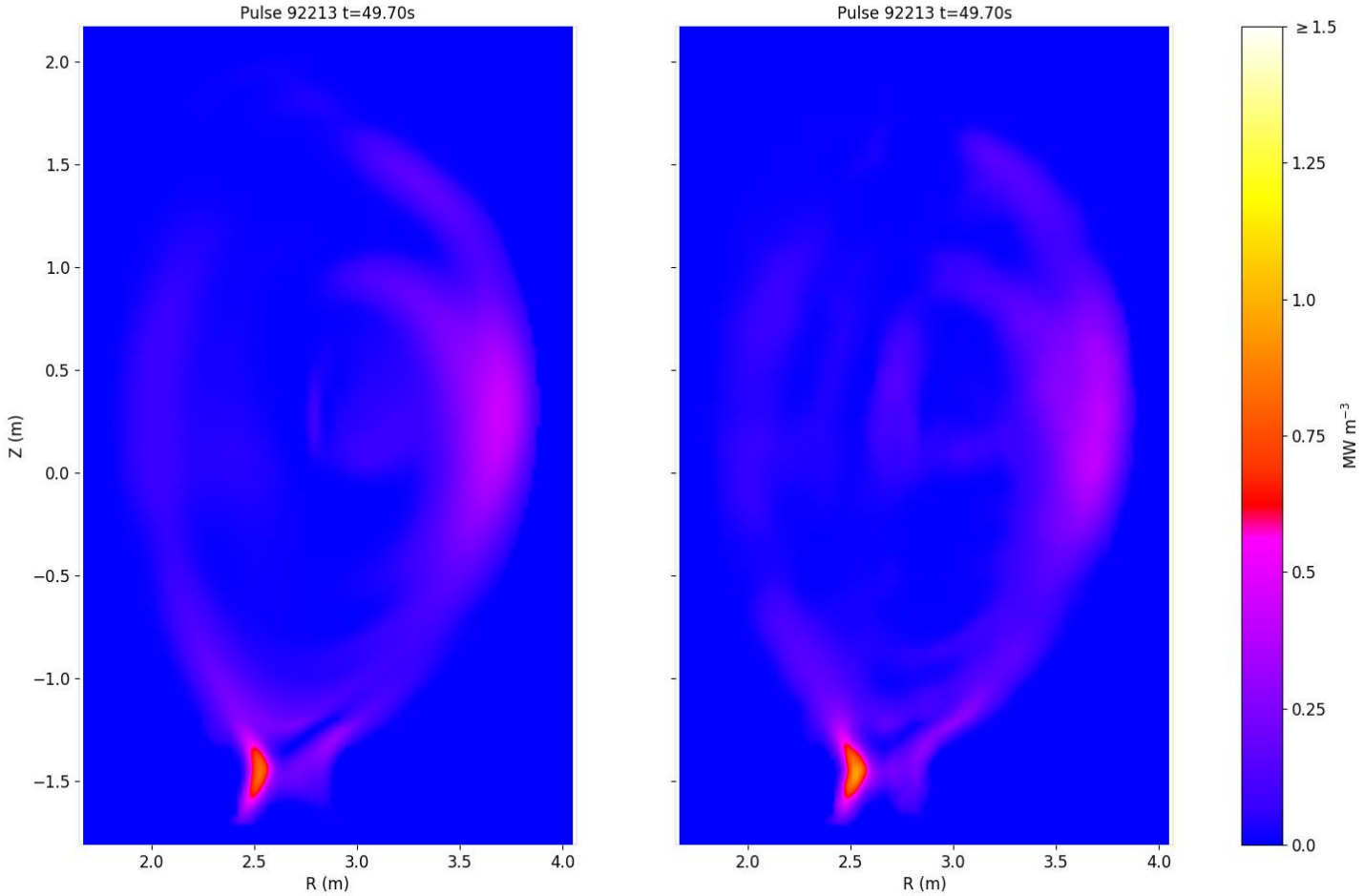
Hardware: Nvidia Titan X GPU
memory usage: 3759 MB

Training time: 60 hours
12652 epochs

Min. val. loss: 0.01010275
epoch 6911

Results

- Pulse 92213 t=49.70s (true vs. prediction)



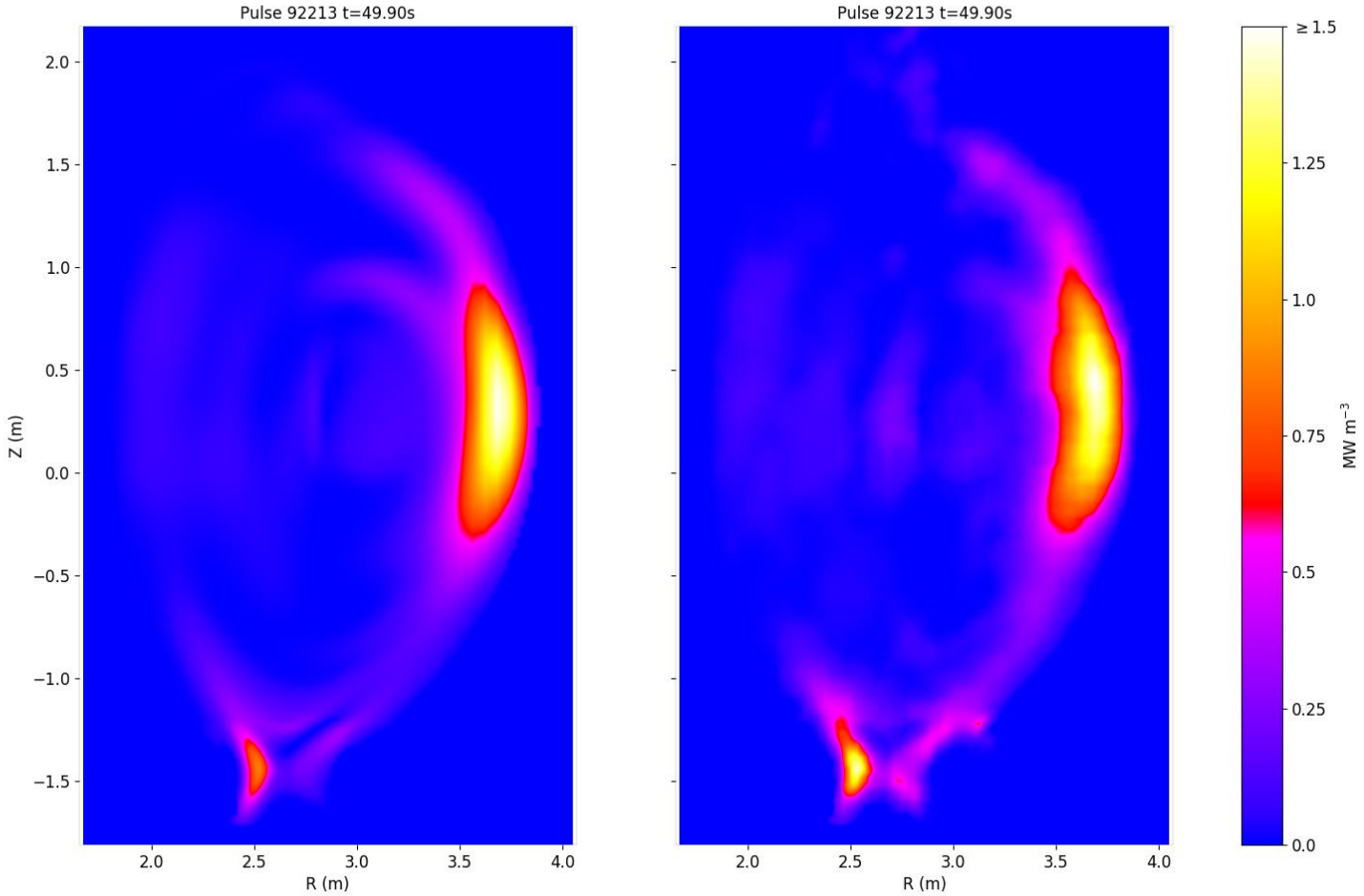
structural similarity
SSIM: 0.935401

peak signal-to-noise ratio
PSNR: 30.38582

normalized root-mean-square error
NRMSE: 0.069252

Results

- Pulse 92213 t=49.90s (true vs. prediction)



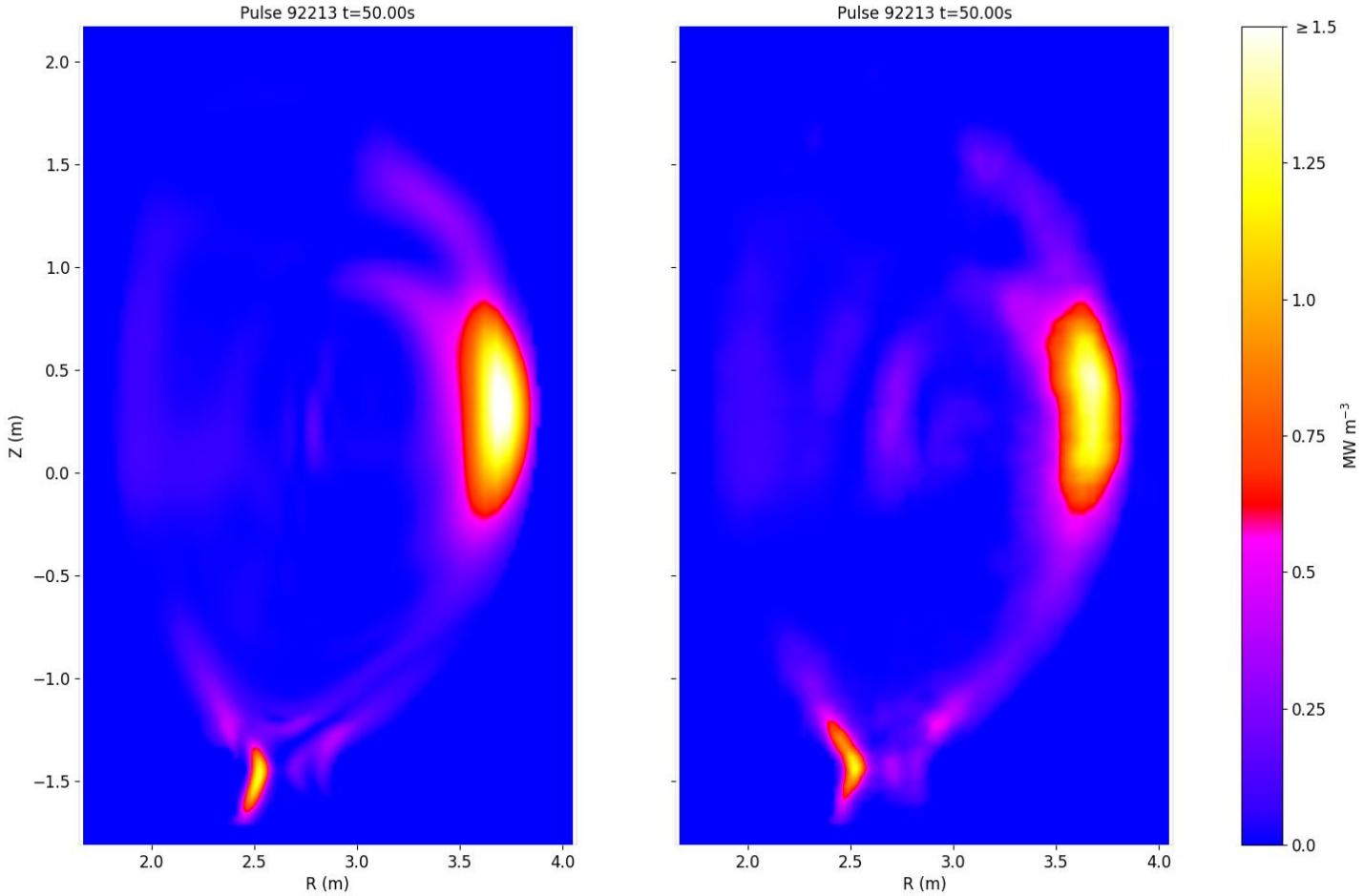
structural similarity
SSIM: 0.923945

peak signal-to-noise ratio
PSNR: 28.16129

normalized root-mean-square error
NRMSE: 0.084369

Results

- Pulse 92213 t=50.00s (true vs. prediction)



structural similarity
SSIM: 0.913419

peak signal-to-noise ratio
PSNR: 28.86369

normalized root-mean-square error
NRMSE: 0.077504

Results

- speed
  - 3000 reconstructions/sec (on GPU)
  - 250 days => 2 sec

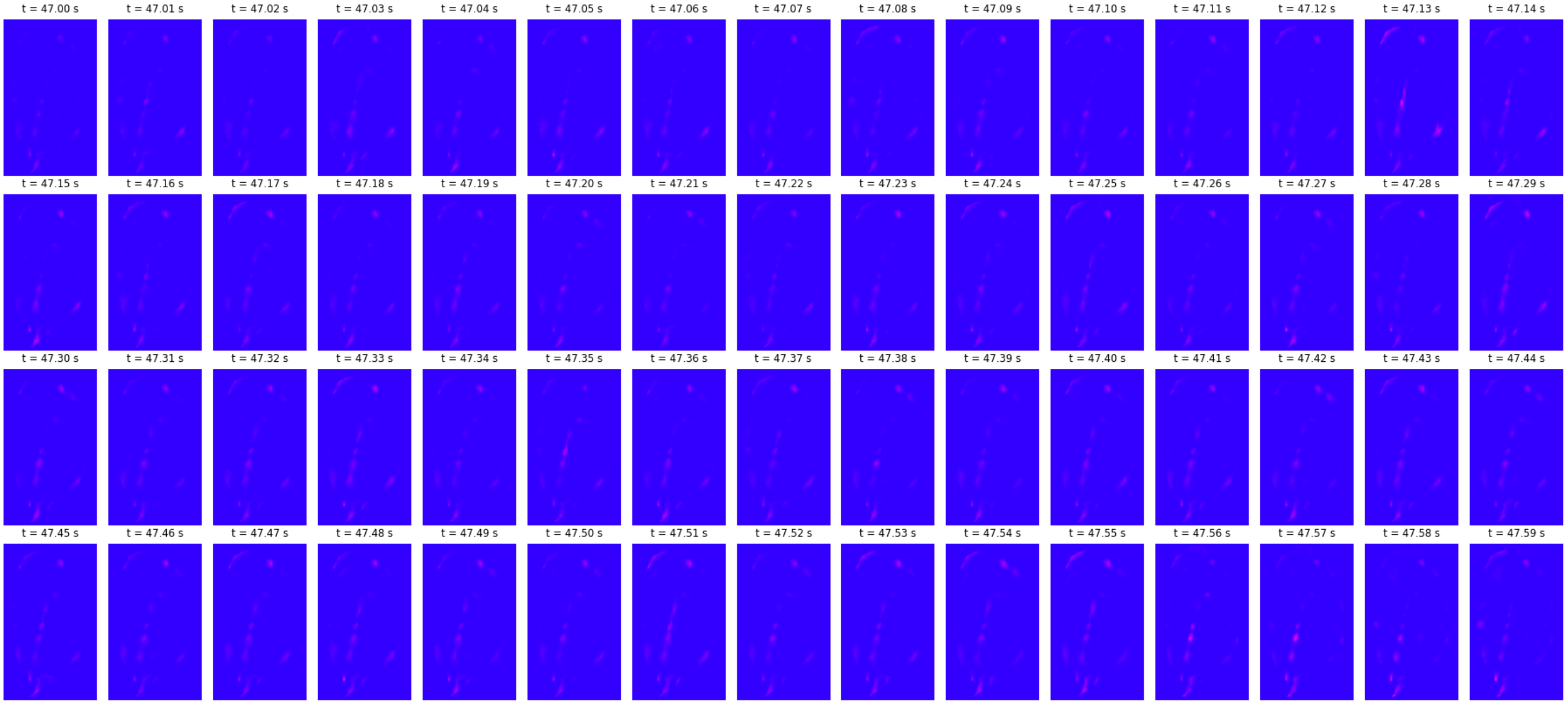
- viewing the results
  - plot the reconstructions
  - encode as video frames
  - use lossless compression
  - processing speed ~ 40 frames/sec
  - 6000 frames ~ 150 sec

92213 (baseline high power)

time range: **t=47.00s** to **t=54.19s**

dynamic range: **$0 \leq P_{rad} \leq 1.5$ MW m^{-3}**

92213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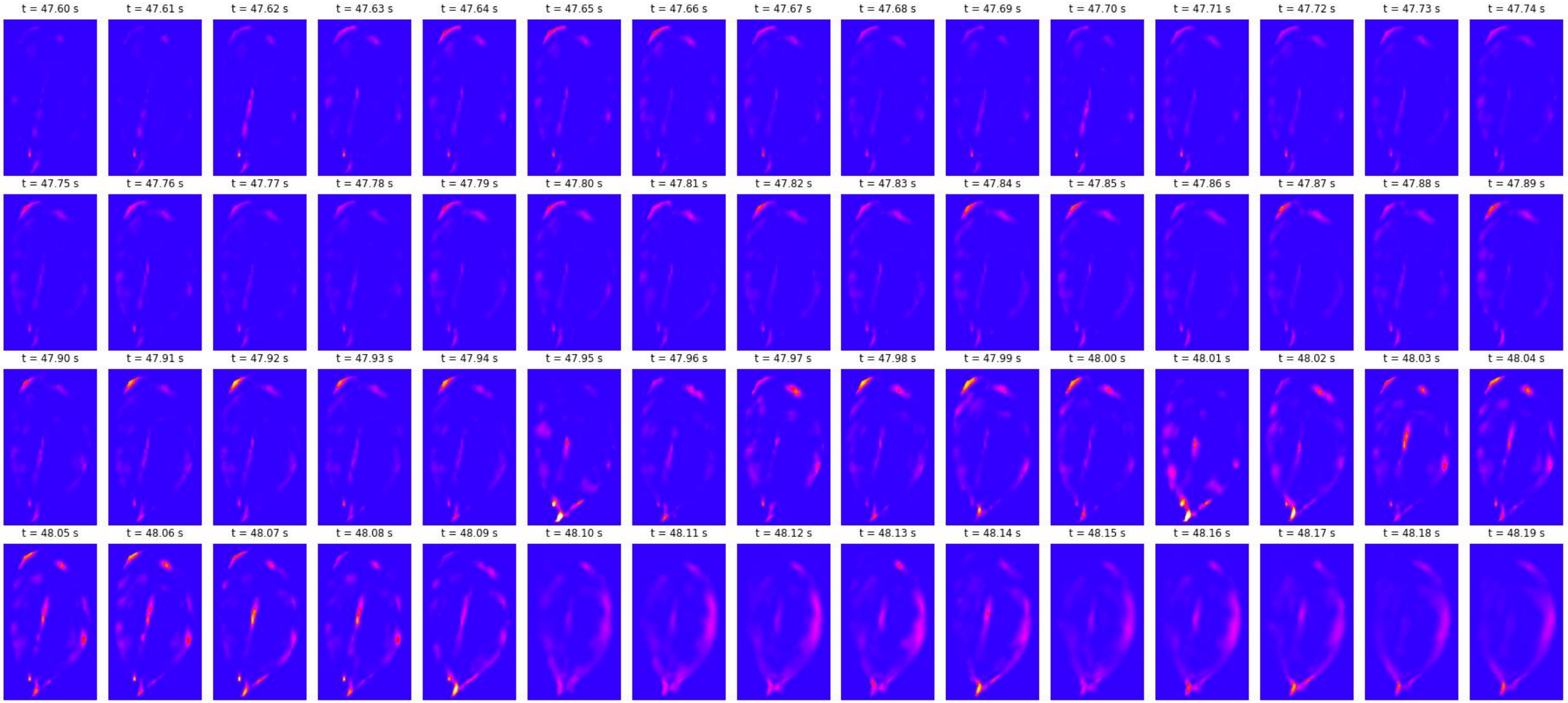
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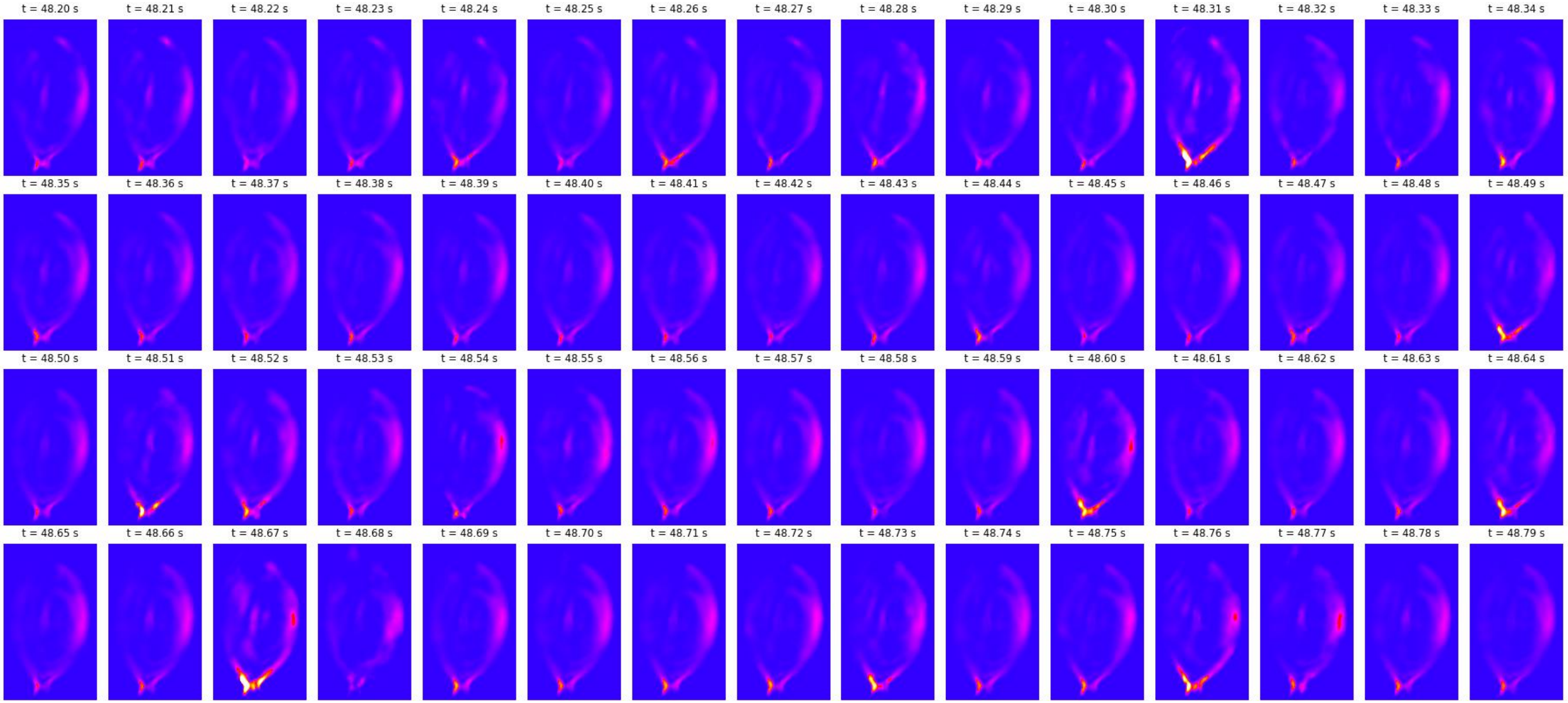
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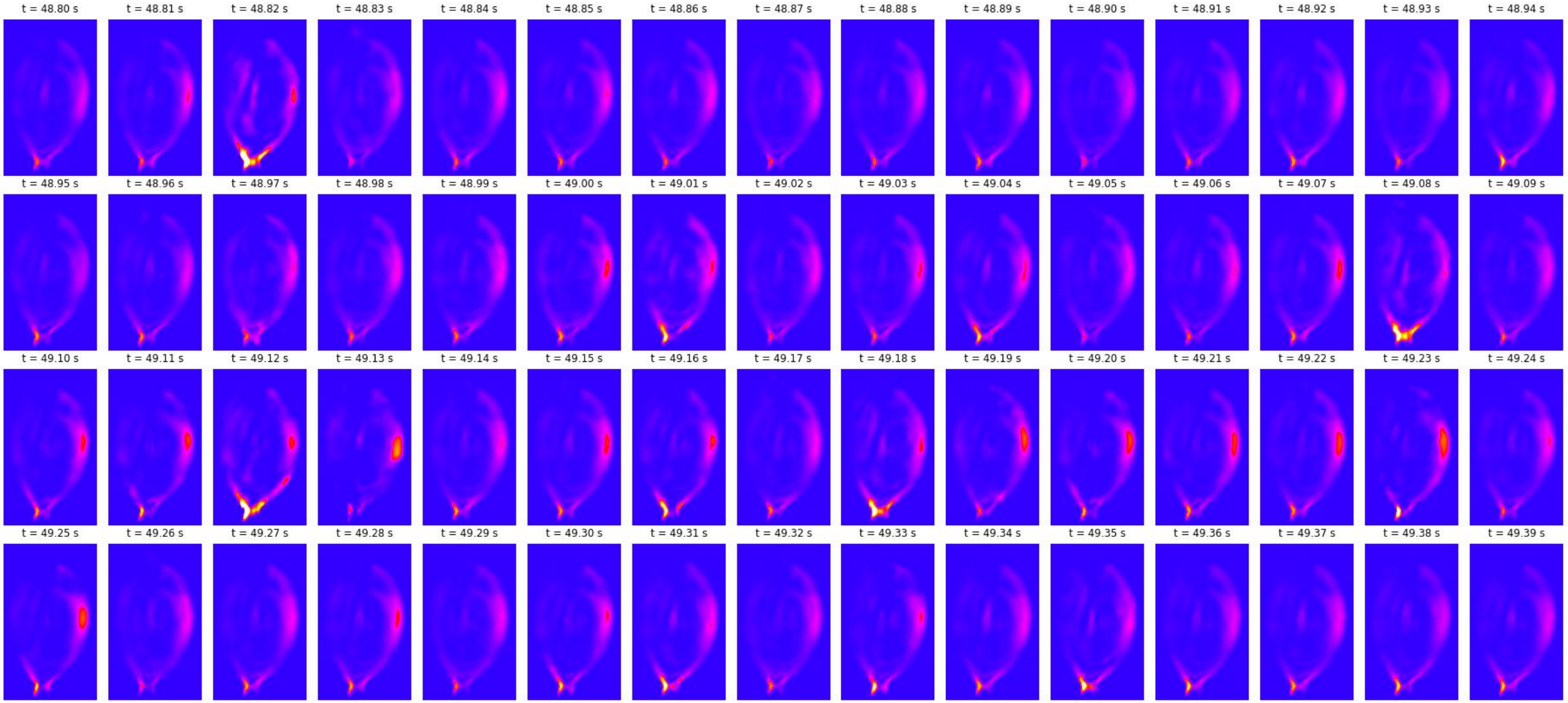
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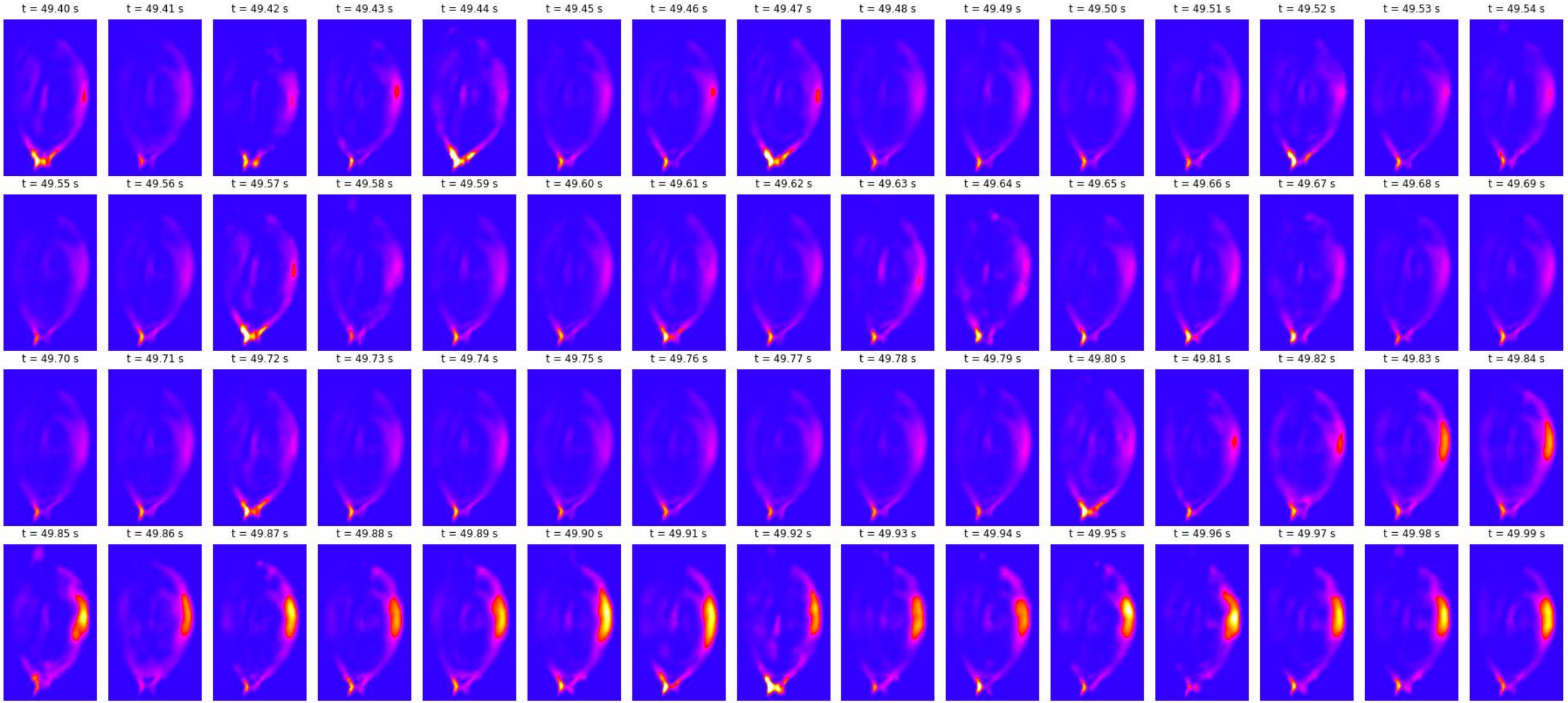
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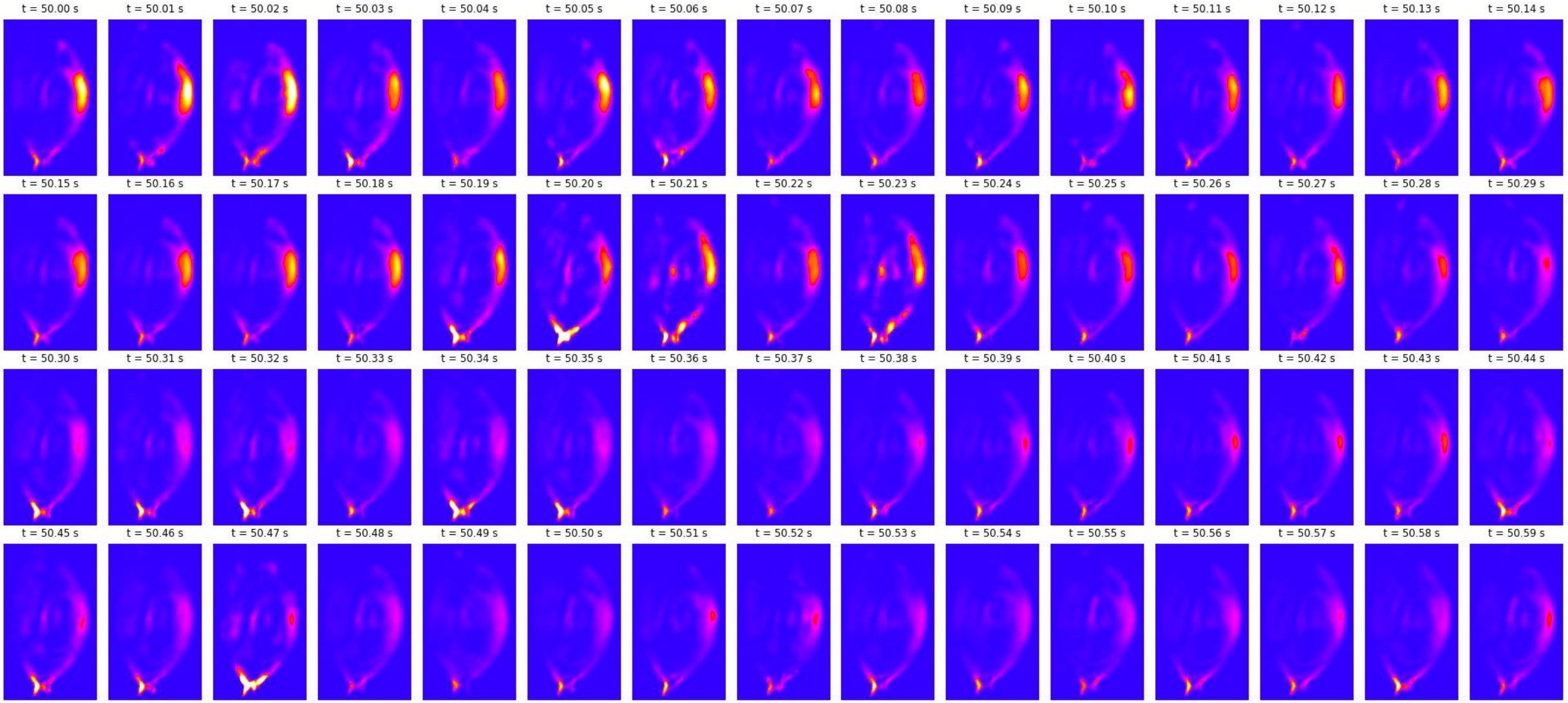
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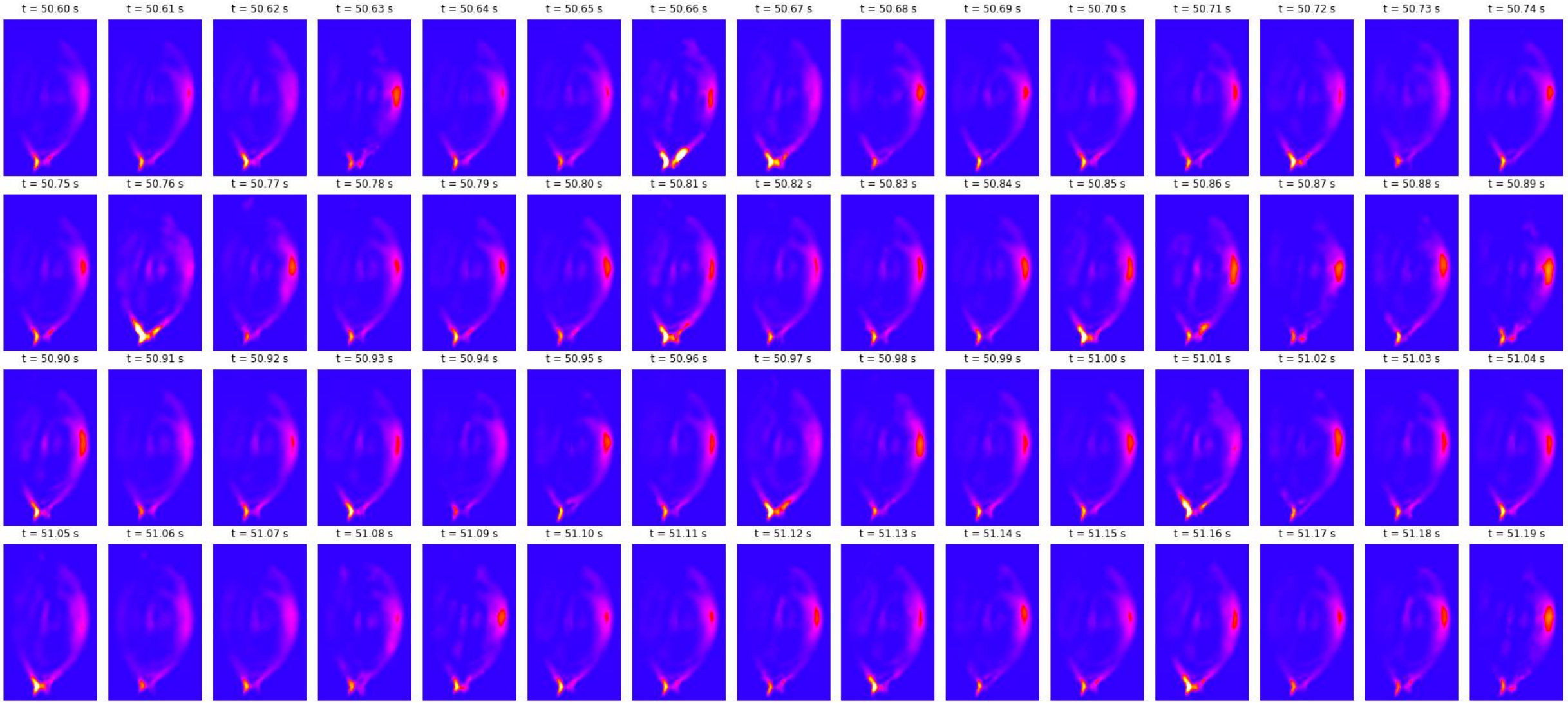
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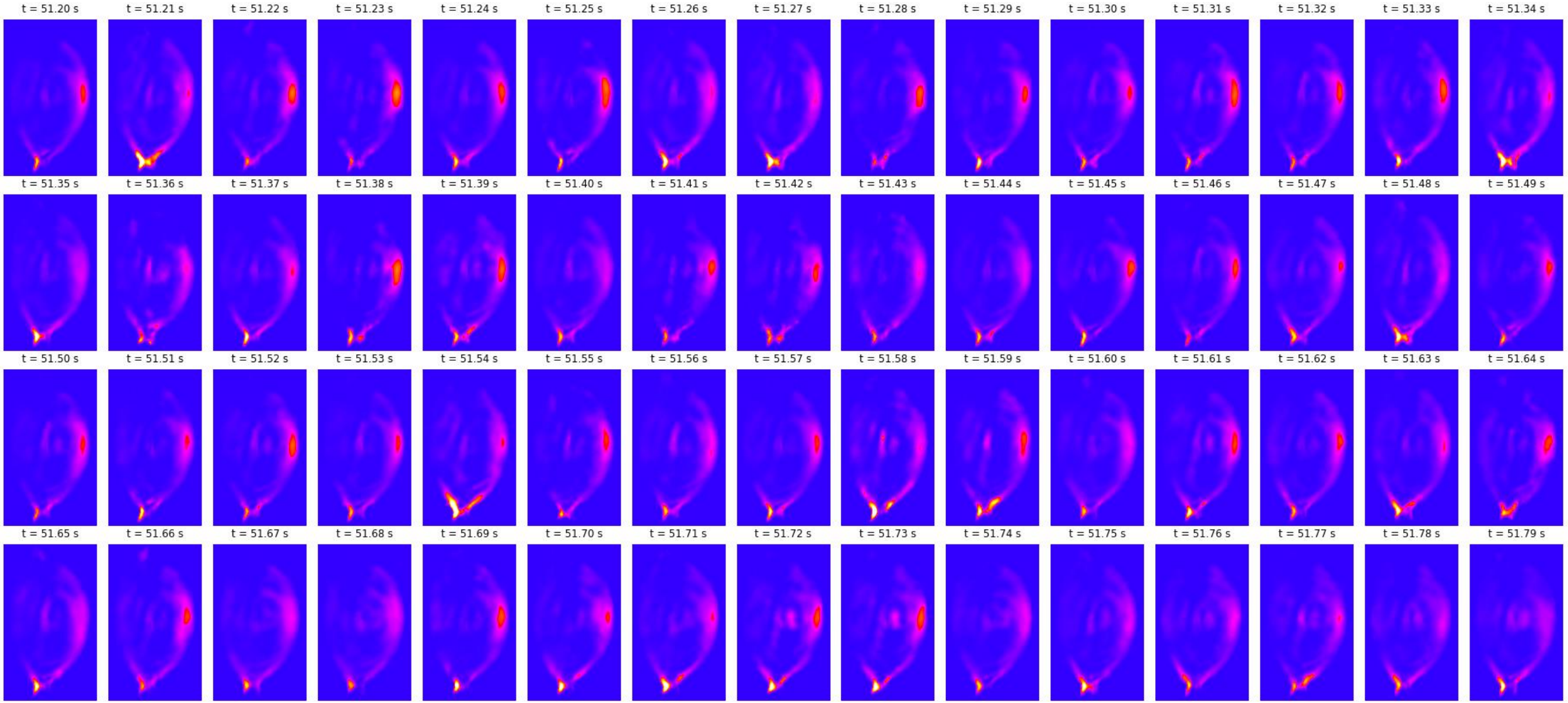
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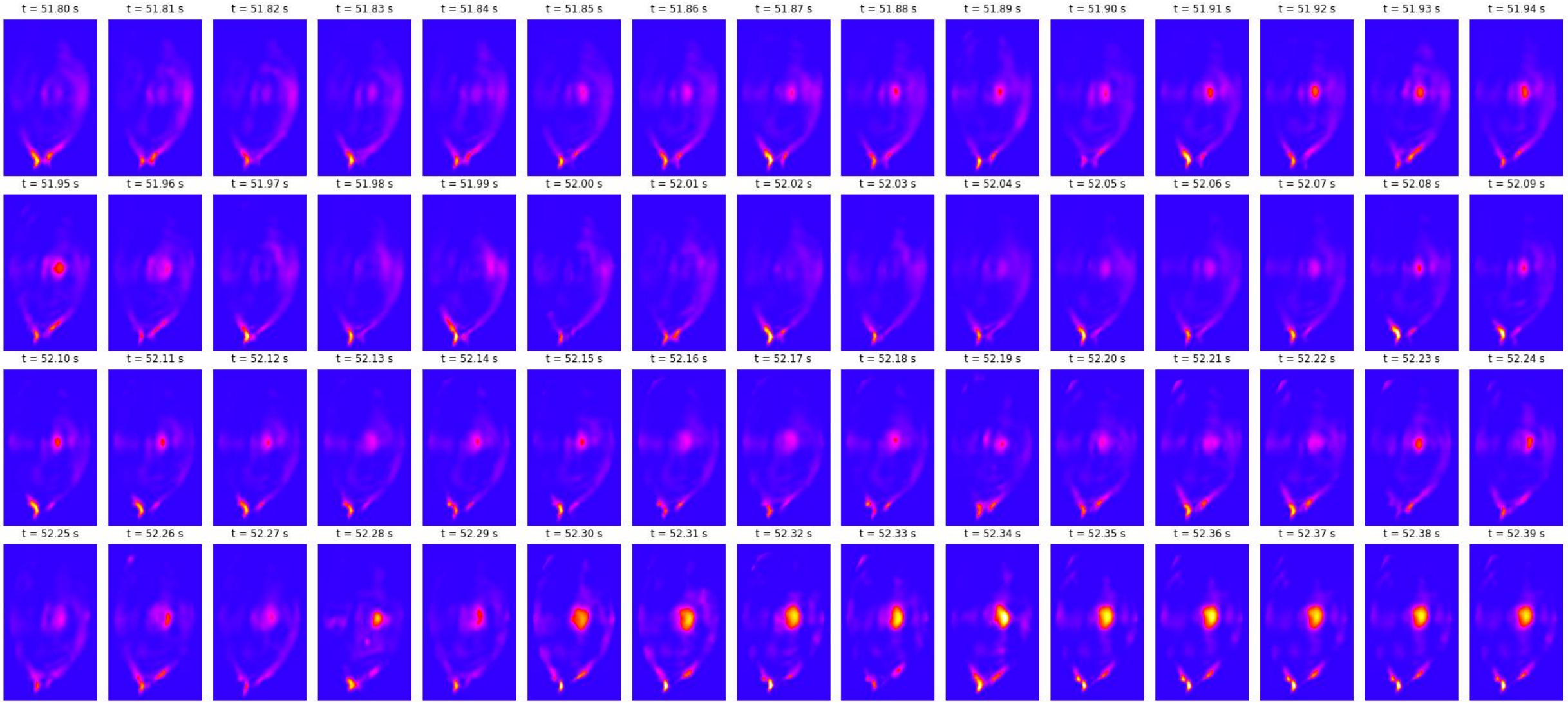
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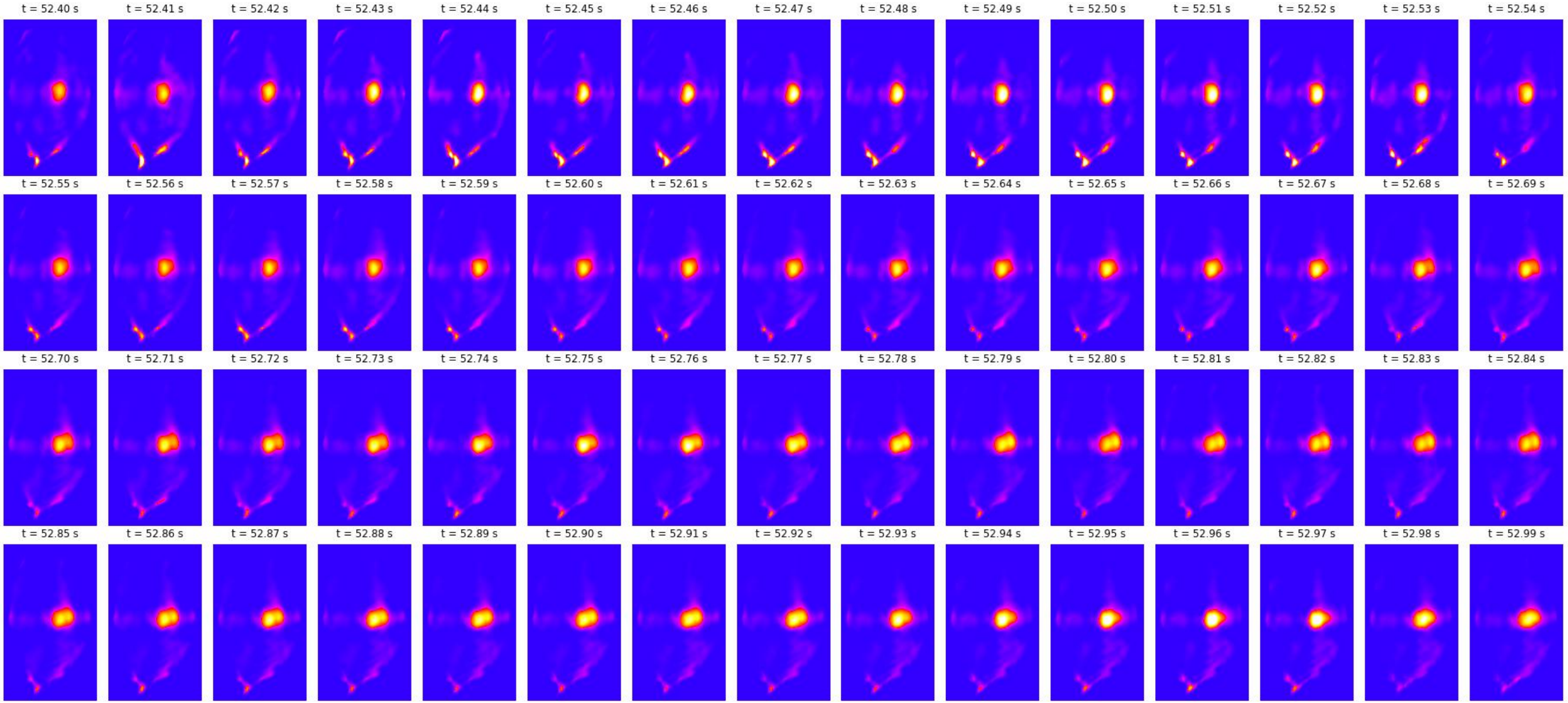
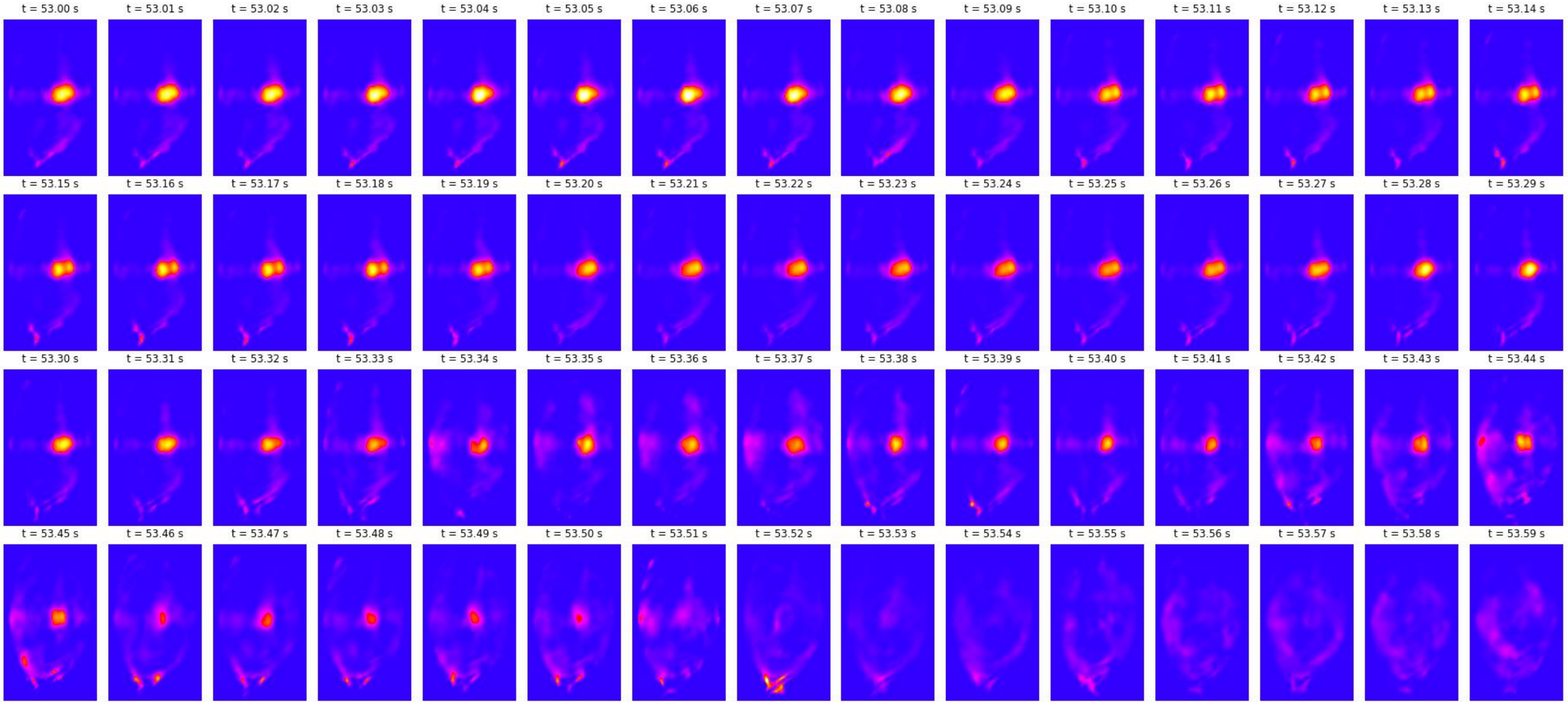
t = 52.32 s
t = 52.33 s
t = 52.34 s
t = 52.35 s
t = 52.36 s
t = 52.37 s
t = 52.38 s
t = 52.39 s

92213


t = 52.40 s
t = 52.41 s
t = 52.42 s
t = 52.43 s
t = 52.44 s
t = 52.45 s
t = 52.46 s
t = 52.47 s
t = 52.48 s
t = 52.49 s
t = 52.50 s
t = 52.51 s
t = 52.52 s
t = 52.53 s
t = 52.54 s
t = 52.55 s
t = 52.56 s
t = 52.57 s
t = 52.58 s
t = 52.59 s
t = 52.60 s
t = 52.61 s
t = 52.62 s
t = 52.63 s
t = 52.64 s
t = 52.65 s
t = 52.66 s
t = 52.67 s
t = 52.68 s
t = 52.69 s
t = 52.70 s
t = 52.71 s
t = 52.72 s
t = 52.73 s
t = 52.74 s
t = 52.75 s
t = 52.76 s
t = 52.77 s
t = 52.78 s
t = 52.79 s
t = 52.80 s
t = 52.81 s
t = 52.82 s
t = 52.83 s
t = 52.84 s
t = 52.85 s
t = 52.86 s
t = 52.87 s
t = 52.88 s
t = 52.89 s
t = 52.90 s
t = 52.91 s
t = 52.92 s
t = 52.93 s
t = 52.94 s
t = 52.95 s
t = 52.96 s
t = 52.97 s
t = 52.98 s
t = 52.99 s

92213


t = 53.00 s
t = 53.01 s
t = 53.02 s
t = 53.03 s
t = 53.04 s
t = 53.05 s
t = 53.06 s
t = 53.07 s
t = 53.08 s
t = 53.09 s
t = 53.10 s
t = 53.11 s
t = 53.12 s
t = 53.13 s
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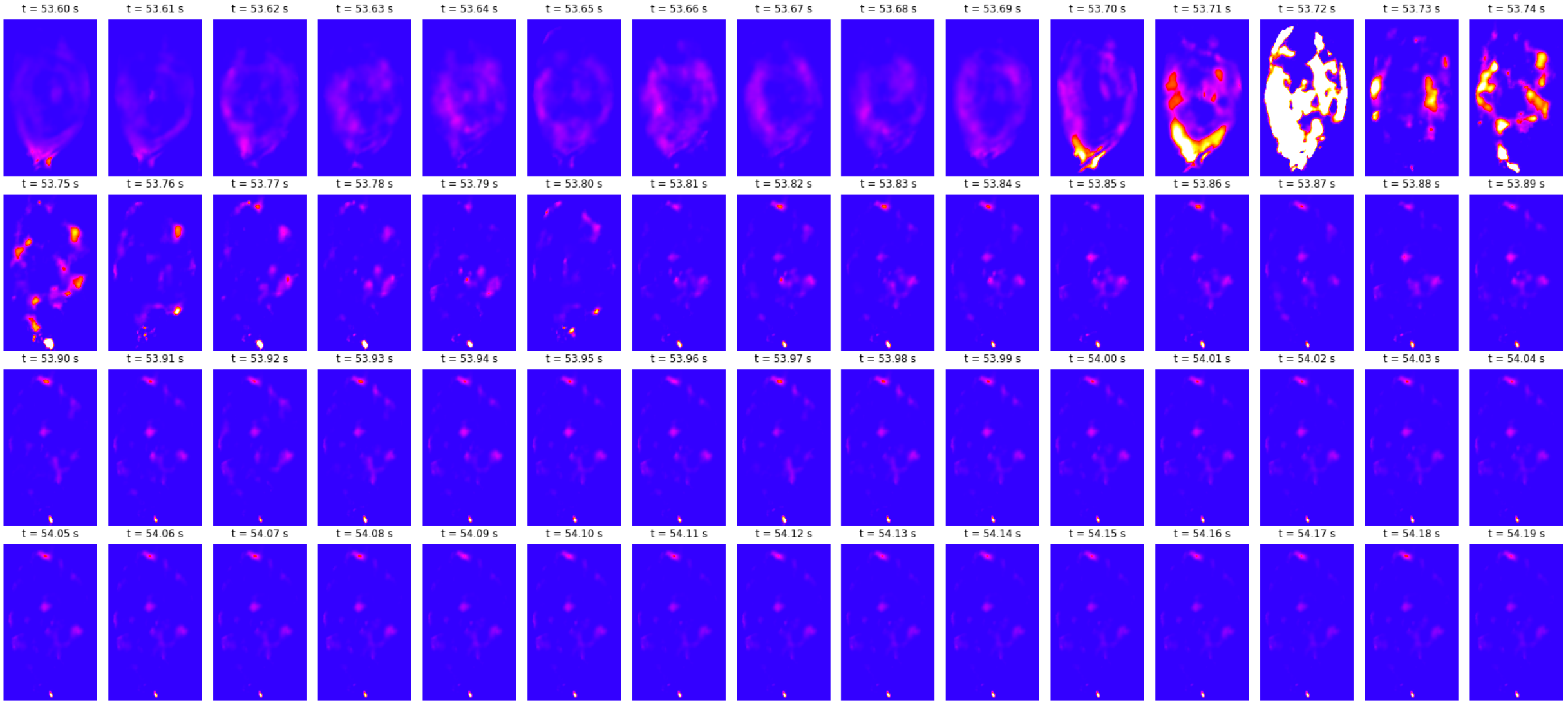
t = 53.30 s
t = 53.31 s
t = 53.32 s
t = 53.33 s
t = 53.34 s
t = 53.35 s
t = 53.36 s
t = 53.37 s
t = 53.38 s
t = 53.39 s
t = 53.40 s
t = 53.41 s
t = 53.42 s
t = 53.43 s
t = 53.44 s
t = 53.45 s
t = 53.46 s
t = 53.47 s
t = 53.48 s
t = 53.49 s
t = 53.50 s
t = 53.51 s
t = 53.52 s
t = 53.53 s
t = 53.54 s
t = 53.55 s
t = 53.56 s
t = 53.57 s
t = 53.58 s
t = 53.59 s

92213

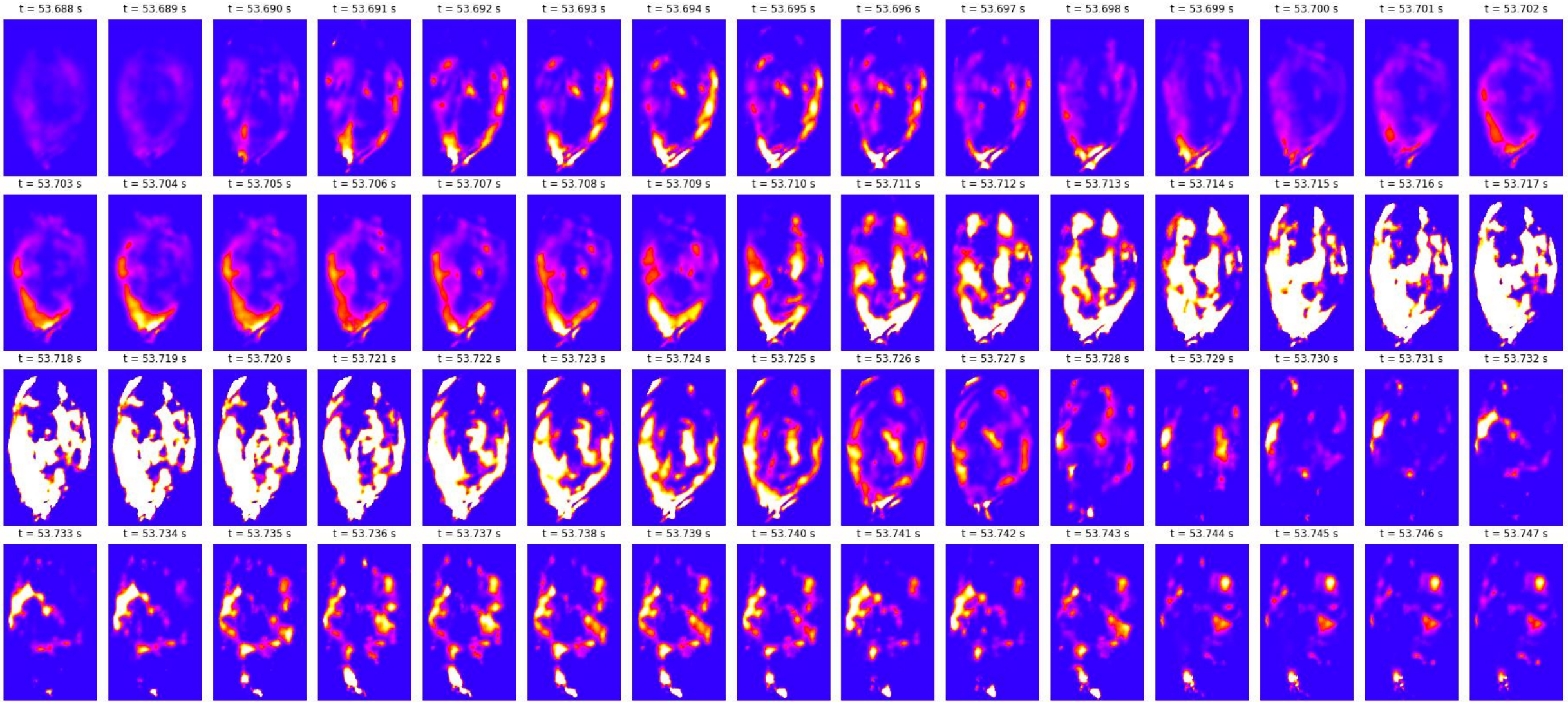

t = 53.60 s
t = 53.61 s
t = 53.62 s
t = 53.63 s
t = 53.64 s
t = 53.65 s
t = 53.66 s
t = 53.67 s
t = 53.68 s
t = 53.69 s
t = 53.70 s
t = 53.71 s
t = 53.72 s
t = 53.73 s
t = 53.74 s
t = 53.75 s
t = 53.76 s
t = 53.77 s
t = 53.78 s
t = 53.79 s
t = 53.80 s
t = 53.81 s
t = 53.82 s
t = 53.83 s
t = 53.84 s
t = 53.85 s
t = 53.86 s
t = 53.87 s
t = 53.88 s
t = 53.89 s
t = 53.90 s
t = 53.91 s
t = 53.92 s
t = 53.93 s
t = 53.94 s
t = 53.95 s
t = 53.96 s
t = 53.97 s
t = 53.98 s
t = 53.99 s
t = 54.00 s
t = 54.01 s
t = 54.02 s
t = 54.03 s
t = 54.04 s
t = 54.05 s
t = 54.06 s
t = 54.07 s
t = 54.08 s
t = 54.09 s
t = 54.10 s
t = 54.11 s
t = 54.12 s
t = 54.13 s
t = 54.14 s
t = 54.15 s
t = 54.16 s
t = 54.17 s
t = 54.18 s
t = 54.19 s

92213 *disruption*

time range: **t=53.668*s*** to **t=53.747*s***

dynamic range: **$0 \leq P_{rad} \leq 1.5\ MW\ m^{-3}$**

92213

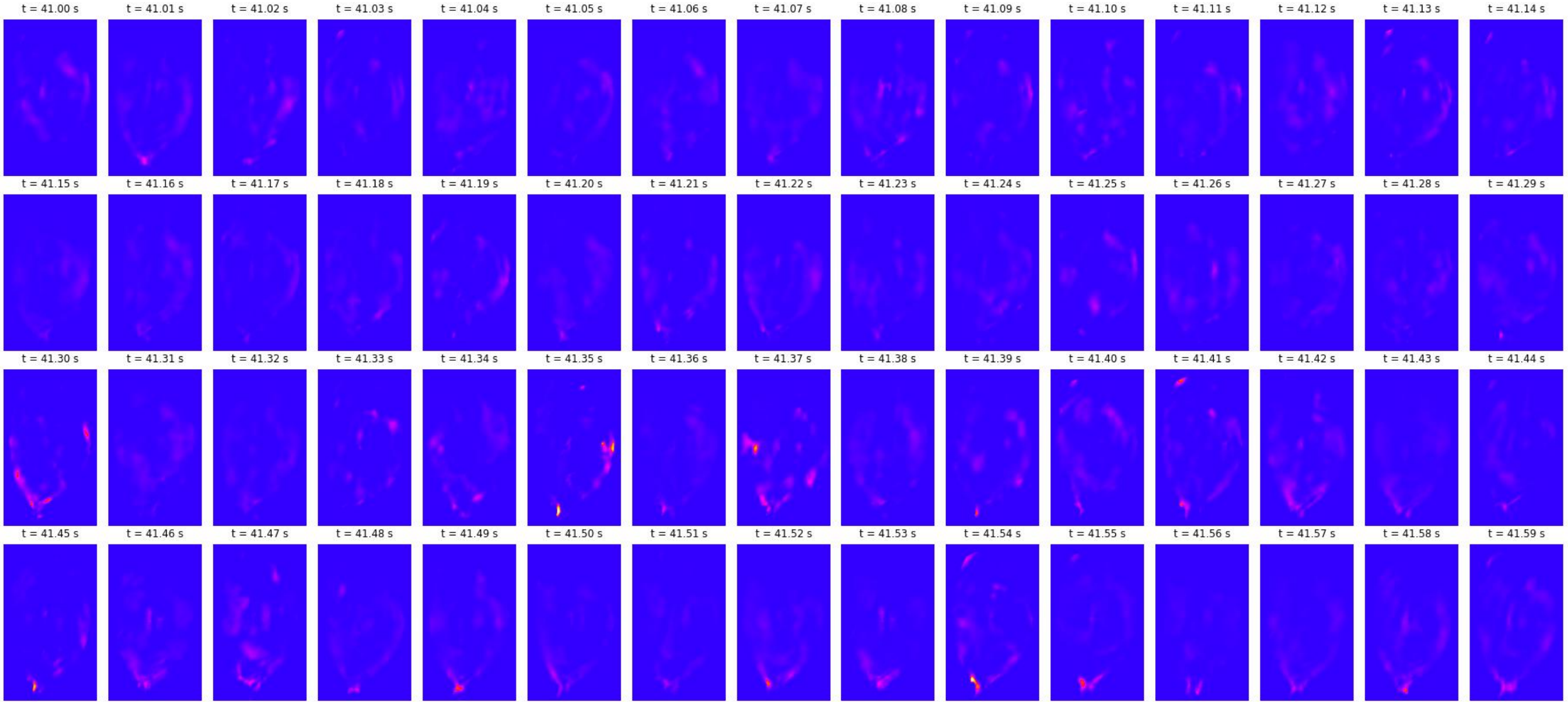

t = 53.688 s
t = 53.689 s
t = 53.690 s
t = 53.691 s
t = 53.692 s
t = 53.693 s
t = 53.694 s
t = 53.695 s
t = 53.696 s
t = 53.697 s
t = 53.698 s
t = 53.699 s
t = 53.700 s
t = 53.701 s
t = 53.702 s
t = 53.703 s
t = 53.704 s
t = 53.705 s
t = 53.706 s
t = 53.707 s
t = 53.708 s
t = 53.709 s
t = 53.710 s
t = 53.711 s
t = 53.712 s
t = 53.713 s
t = 53.714 s
t = 53.715 s
t = 53.716 s
t = 53.717 s
t = 53.718 s
t = 53.719 s
t = 53.720 s
t = 53.721 s
t = 53.722 s
t = 53.723 s
t = 53.724 s
t = 53.725 s
t = 53.726 s
t = 53.727 s
t = 53.728 s
t = 53.729 s
t = 53.730 s
t = 53.731 s
t = 53.732 s
t = 53.733 s
t = 53.734 s
t = 53.735 s
t = 53.736 s
t = 53.737 s
t = 53.738 s
t = 53.739 s
t = 53.740 s
t = 53.741 s
t = 53.742 s
t = 53.743 s
t = 53.744 s
t = 53.745 s
t = 53.746 s
t = 53.747 s

92286 (tungsten ablation)

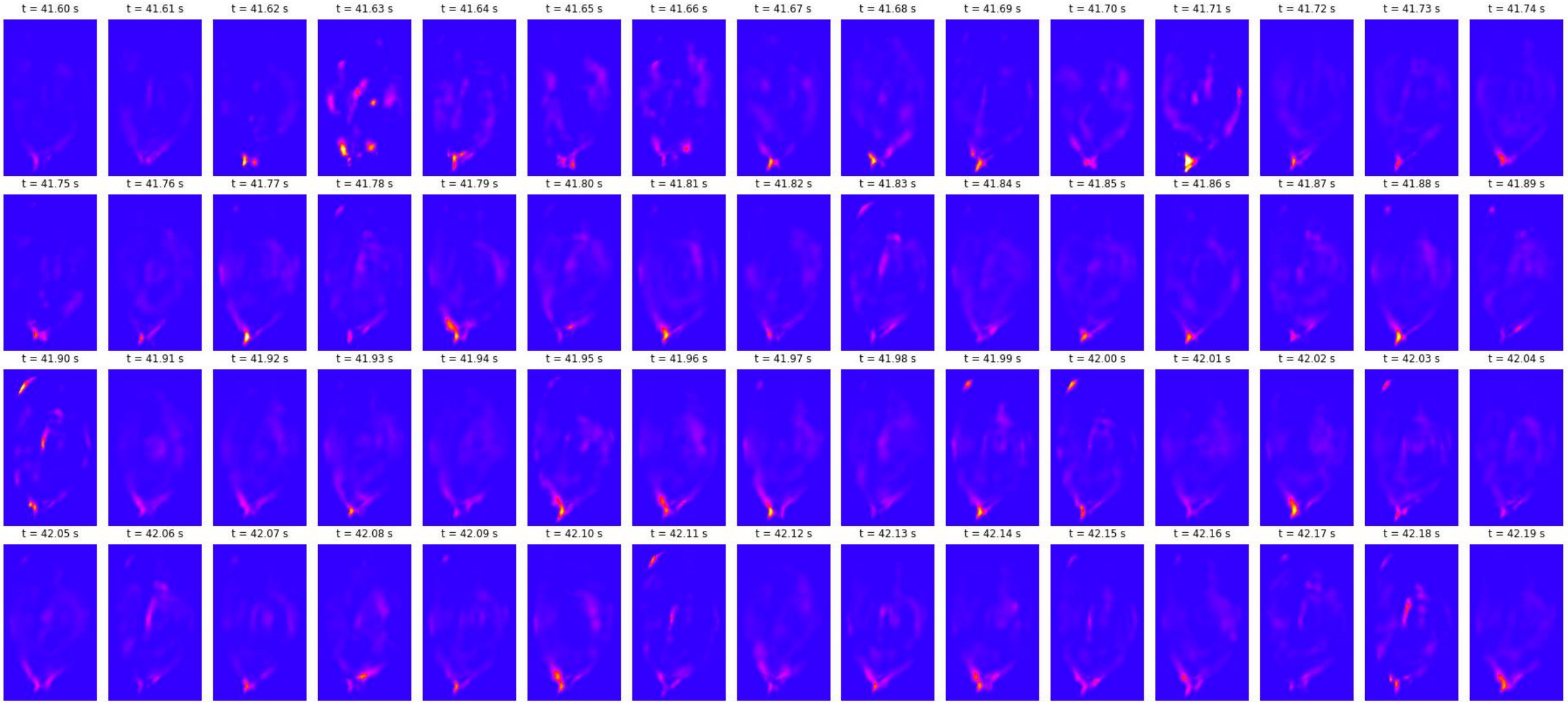
time range: **t=41.00s** to **t=45.79s**

dynamic range: **$0 \leq P_{rad} \leq 150$ kW m^{-3}**

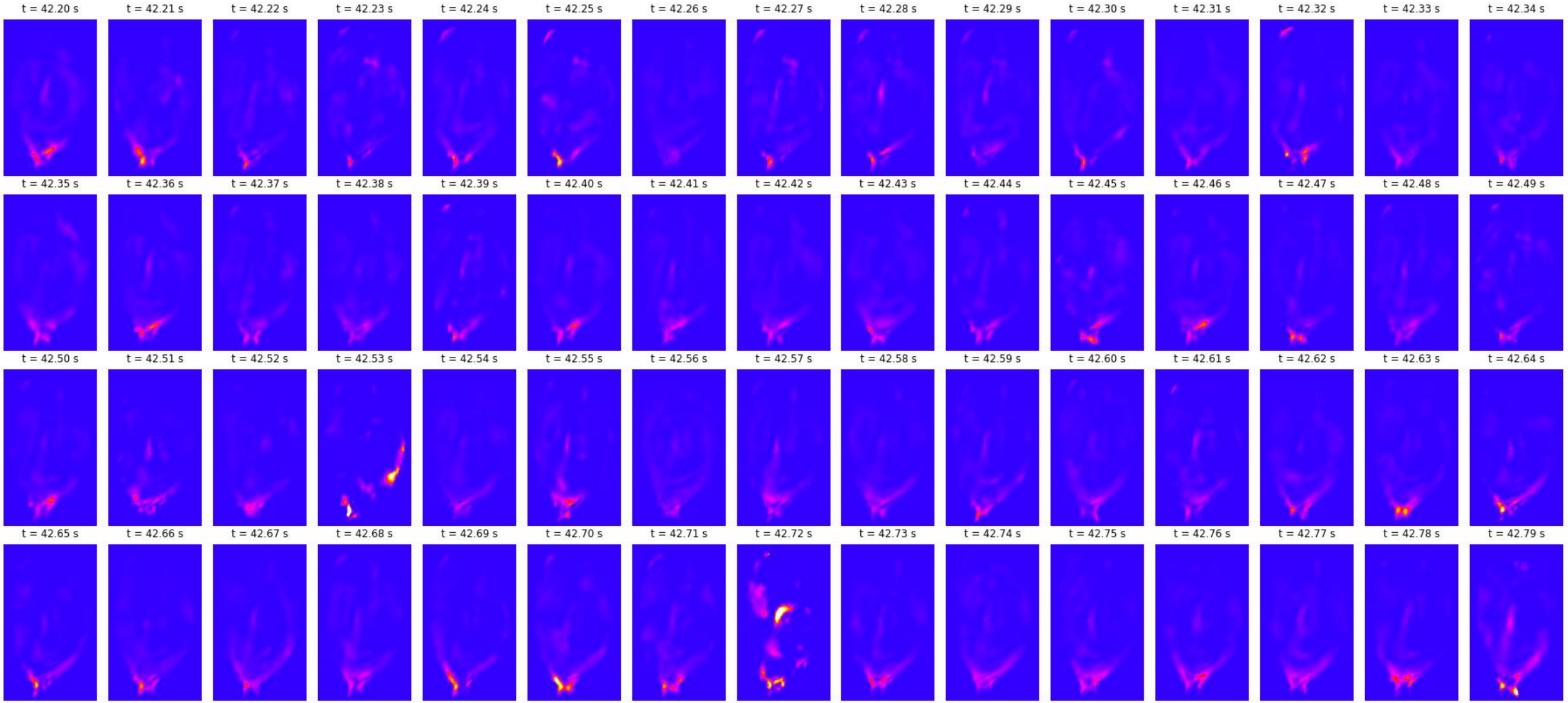
92286


t = 41.00 s
t = 41.01 s
t = 41.02 s
t = 41.03 s
t = 41.04 s
t = 41.05 s
t = 41.06 s
t = 41.07 s
t = 41.08 s
t = 41.09 s
t = 41.10 s
t = 41.11 s
t = 41.12 s
t = 41.13 s
t = 41.14 s
t = 41.15 s
t = 41.16 s
t = 41.17 s
t = 41.18 s
t = 41.19 s
t = 41.20 s
t = 41.21 s
t = 41.22 s
t = 41.23 s
t = 41.24 s
t = 41.25 s
t = 41.26 s
t = 41.27 s
t = 41.28 s
t = 41.29 s
t = 41.30 s
t = 41.31 s
t = 41.32 s
t = 41.33 s
t = 41.34 s
t = 41.35 s
t = 41.36 s
t = 41.37 s
t = 41.38 s
t = 41.39 s
t = 41.40 s
t = 41.41 s
t = 41.42 s
t = 41.43 s
t = 41.44 s
t = 41.45 s
t = 41.46 s
t = 41.47 s
t = 41.48 s
t = 41.49 s
t = 41.50 s
t = 41.51 s
t = 41.52 s
t = 41.53 s
t = 41.54 s
t = 41.55 s
t = 41.56 s
t = 41.57 s
t = 41.58 s
t = 41.59 s

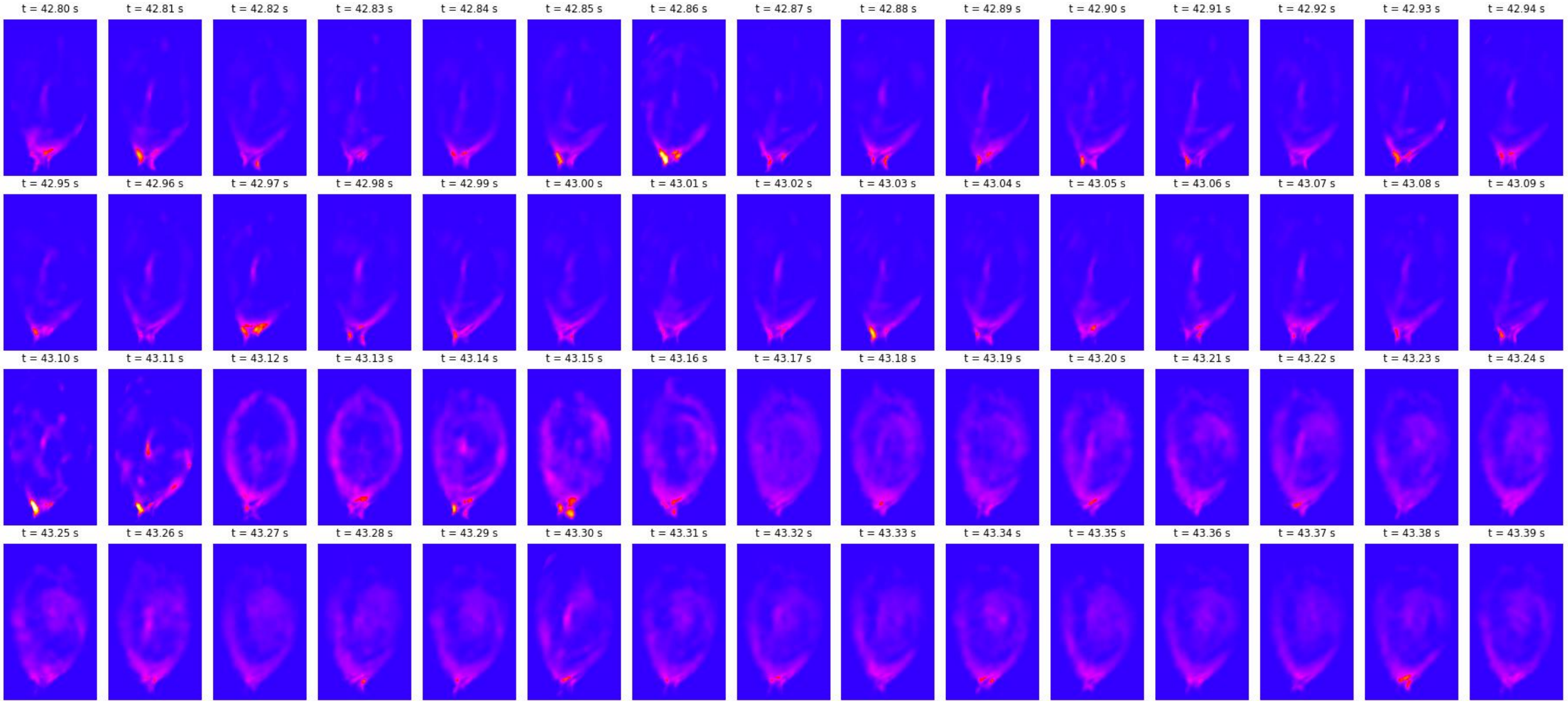
92286


t = 41.60 s
t = 41.61 s
t = 41.62 s
t = 41.63 s
t = 41.64 s
t = 41.65 s
t = 41.66 s
t = 41.67 s
t = 41.68 s
t = 41.69 s
t = 41.70 s
t = 41.71 s
t = 41.72 s
t = 41.73 s
t = 41.74 s
t = 41.75 s
t = 41.76 s
t = 41.77 s
t = 41.78 s
t = 41.79 s
t = 41.80 s
t = 41.81 s
t = 41.82 s
t = 41.83 s
t = 41.84 s
t = 41.85 s
t = 41.86 s
t = 41.87 s
t = 41.88 s
t = 41.89 s
t = 41.90 s
t = 41.91 s
t = 41.92 s
t = 41.93 s
t = 41.94 s
t = 41.95 s
t = 41.96 s
t = 41.97 s
t = 41.98 s
t = 41.99 s
t = 42.00 s
t = 42.01 s
t = 42.02 s
t = 42.03 s
t = 42.04 s
t = 42.05 s
t = 42.06 s
t = 42.07 s
t = 42.08 s
t = 42.09 s
t = 42.10 s
t = 42.11 s
t = 42.12 s
t = 42.13 s
t = 42.14 s
t = 42.15 s
t = 42.16 s
t = 42.17 s
t = 42.18 s
t = 42.19 s

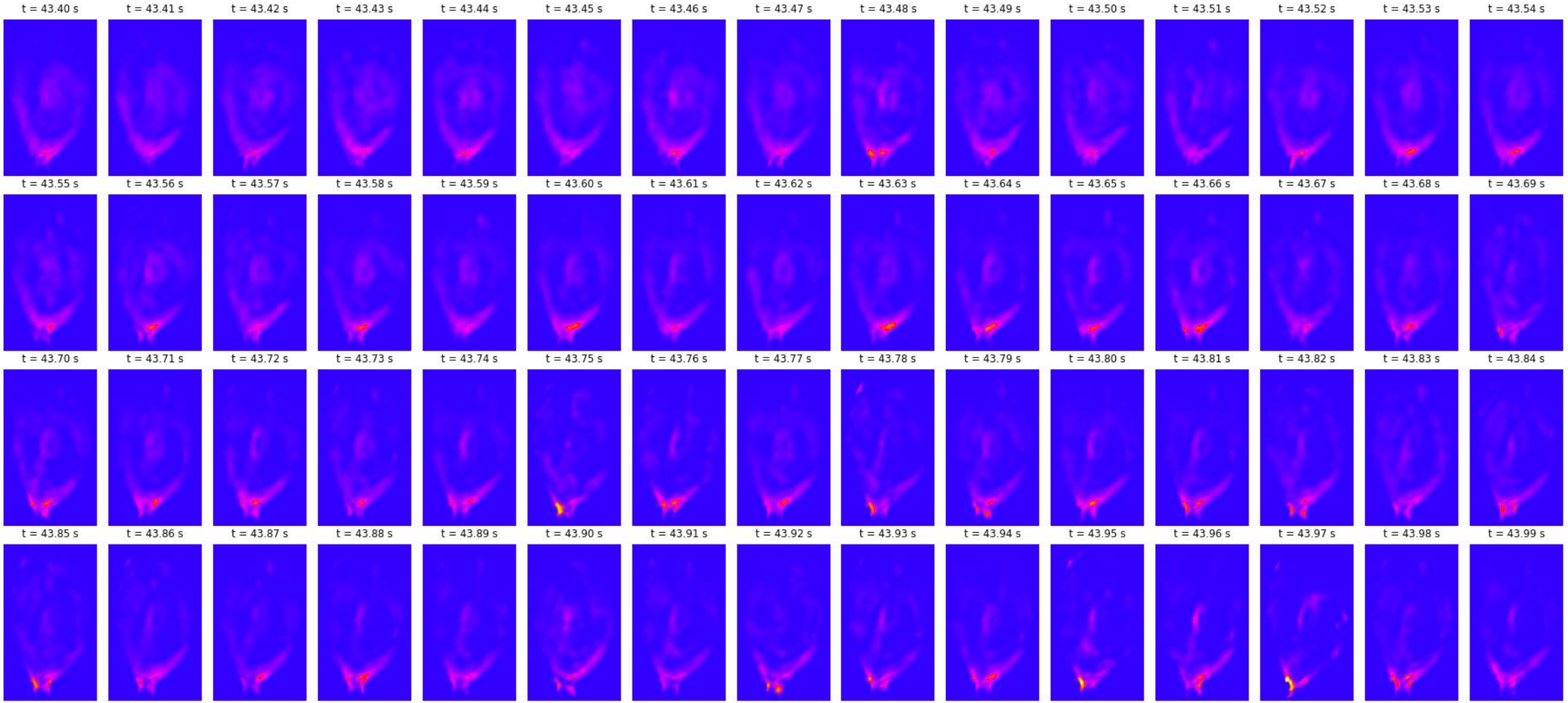
92286


t = 42.20 s
t = 42.21 s
t = 42.22 s
t = 42.23 s
t = 42.24 s
t = 42.25 s
t = 42.26 s
t = 42.27 s
t = 42.28 s
t = 42.29 s
t = 42.30 s
t = 42.31 s
t = 42.32 s
t = 42.33 s
t = 42.34 s
t = 42.35 s
t = 42.36 s
t = 42.37 s
t = 42.38 s
t = 42.39 s
t = 42.40 s
t = 42.41 s
t = 42.42 s
t = 42.43 s
t = 42.44 s
t = 42.45 s
t = 42.46 s
t = 42.47 s
t = 42.48 s
t = 42.49 s
t = 42.50 s
t = 42.51 s
t = 42.52 s
t = 42.53 s
t = 42.54 s
t = 42.55 s
t = 42.56 s
t = 42.57 s
t = 42.58 s
t = 42.59 s
t = 42.60 s
t = 42.61 s
t = 42.62 s
t = 42.63 s
t = 42.64 s
t = 42.65 s
t = 42.66 s
t = 42.67 s
t = 42.68 s
t = 42.69 s
t = 42.70 s
t = 42.71 s
t = 42.72 s
t = 42.73 s
t = 42.74 s
t = 42.75 s
t = 42.76 s
t = 42.77 s
t = 42.78 s
t = 42.79 s

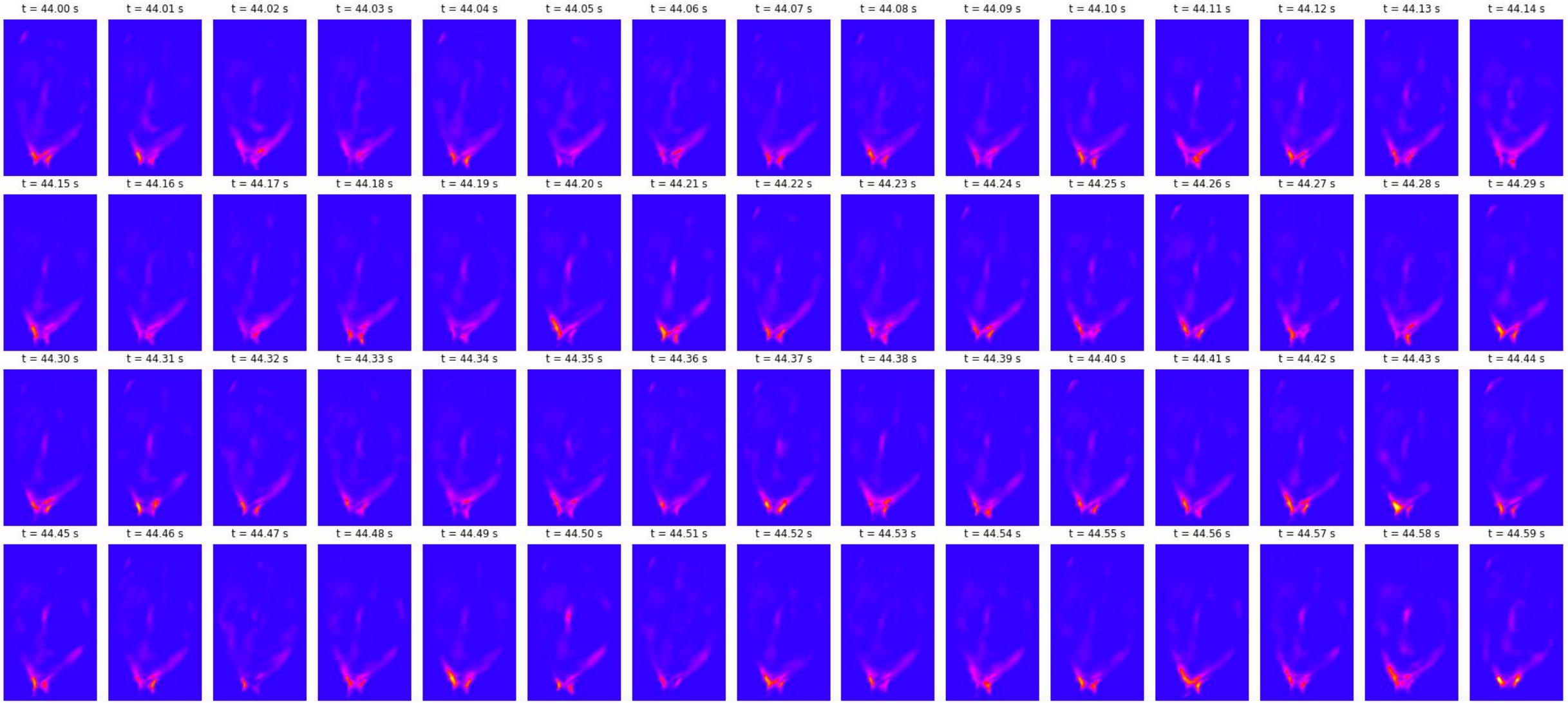
92286


t = 42.80 s
t = 42.81 s
t = 42.82 s
t = 42.83 s
t = 42.84 s
t = 42.85 s
t = 42.86 s
t = 42.87 s
t = 42.88 s
t = 42.89 s
t = 42.90 s
t = 42.91 s
t = 42.92 s
t = 42.93 s
t = 42.94 s
t = 42.95 s
t = 42.96 s
t = 42.97 s
t = 42.98 s
t = 42.99 s
t = 43.00 s
t = 43.01 s
t = 43.02 s
t = 43.03 s
t = 43.04 s
t = 43.05 s
t = 43.06 s
t = 43.07 s
t = 43.08 s
t = 43.09 s
t = 43.10 s
t = 43.11 s
t = 43.12 s
t = 43.13 s
t = 43.14 s
t = 43.15 s
t = 43.16 s
t = 43.17 s
t = 43.18 s
t = 43.19 s
t = 43.20 s
t = 43.21 s
t = 43.22 s
t = 43.23 s
t = 43.24 s
t = 43.25 s
t = 43.26 s
t = 43.27 s
t = 43.28 s
t = 43.29 s
t = 43.30 s
t = 43.31 s
t = 43.32 s
t = 43.33 s
t = 43.34 s
t = 43.35 s
t = 43.36 s
t = 43.37 s
t = 43.38 s
t = 43.39 s

92286


t = 43.40 s
t = 43.41 s
t = 43.42 s
t = 43.43 s
t = 43.44 s
t = 43.45 s
t = 43.46 s
t = 43.47 s
t = 43.48 s
t = 43.49 s
t = 43.50 s
t = 43.51 s
t = 43.52 s
t = 43.53 s
t = 43.54 s
t = 43.55 s
t = 43.56 s
t = 43.57 s
t = 43.58 s
t = 43.59 s
t = 43.60 s
t = 43.61 s
t = 43.62 s
t = 43.63 s
t = 43.64 s
t = 43.65 s
t = 43.66 s
t = 43.67 s
t = 43.68 s
t = 43.69 s
t = 43.70 s
t = 43.71 s
t = 43.72 s
t = 43.73 s
t = 43.74 s
t = 43.75 s
t = 43.76 s
t = 43.77 s
t = 43.78 s
t = 43.79 s
t = 43.80 s
t = 43.81 s
t = 43.82 s
t = 43.83 s
t = 43.84 s
t = 43.85 s
t = 43.86 s
t = 43.87 s
t = 43.88 s
t = 43.89 s
t = 43.90 s
t = 43.91 s
t = 43.92 s
t = 43.93 s
t = 43.94 s
t = 43.95 s
t = 43.96 s
t = 43.97 s
t = 43.98 s
t = 43.99 s

92286


t = 44.00 s
t = 44.01 s
t = 44.02 s
t = 44.03 s
t = 44.04 s
t = 44.05 s
t = 44.06 s
t = 44.07 s
t = 44.08 s
t = 44.09 s
t = 44.10 s
t = 44.11 s
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t = 44.15 s
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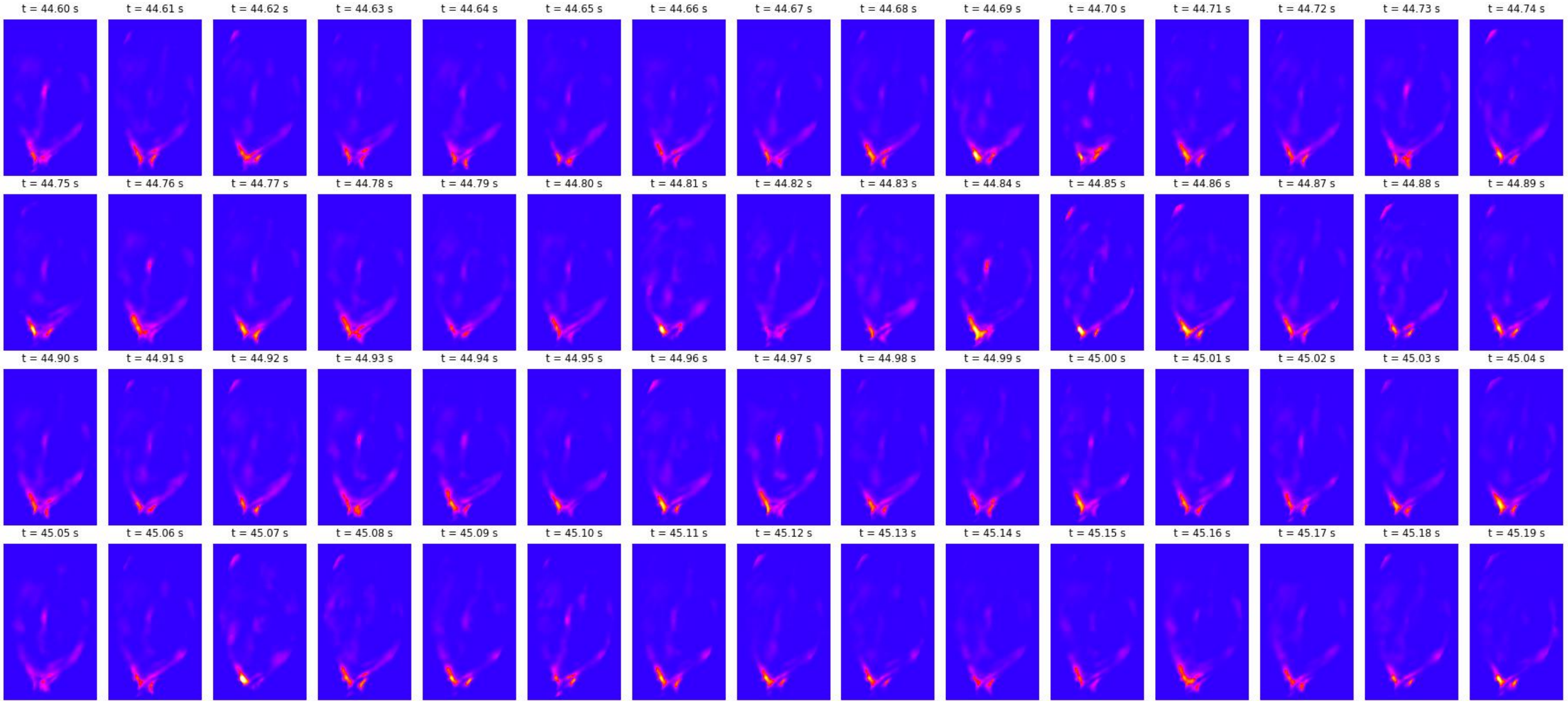
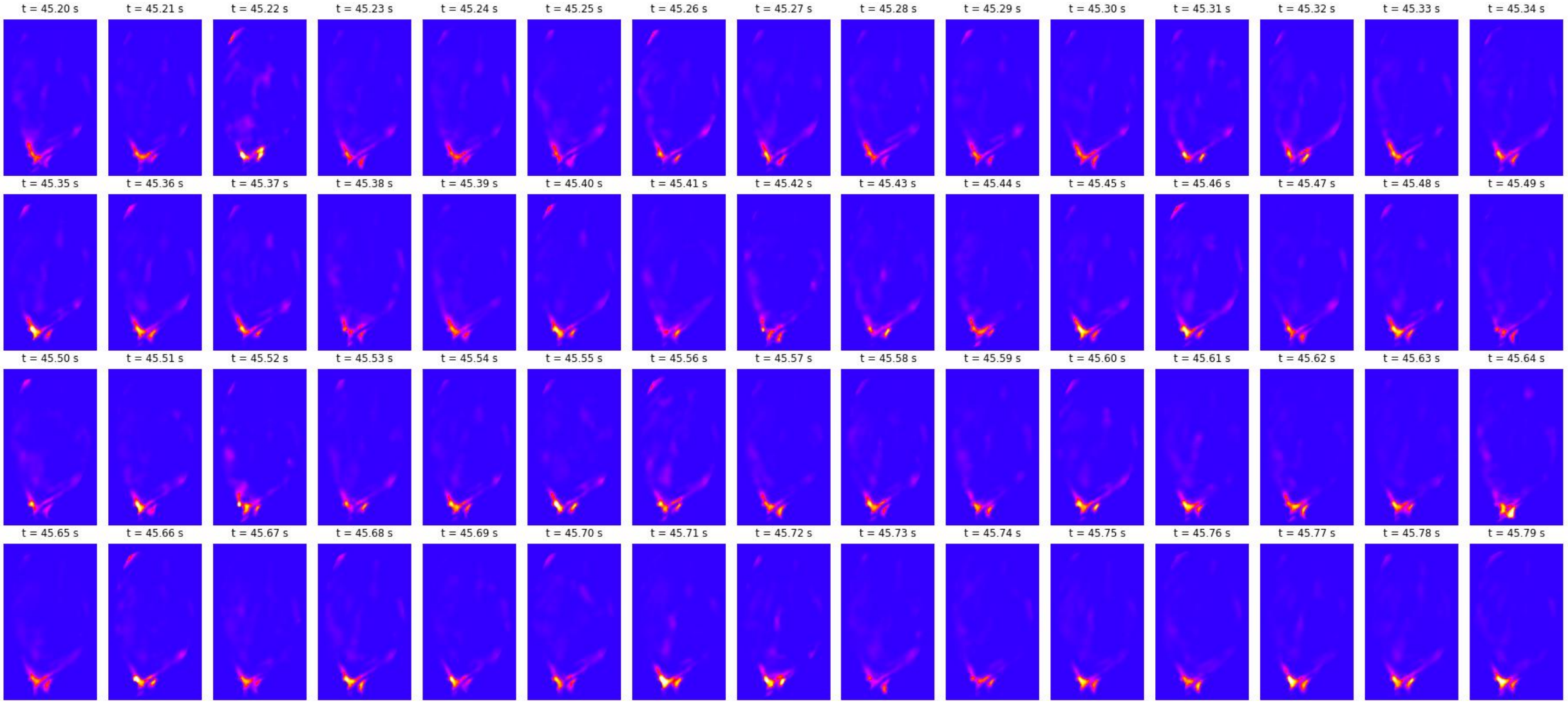
t = 44.30 s
t = 44.31 s
t = 44.32 s
t = 44.33 s
t = 44.34 s
t = 44.35 s
t = 44.36 s
t = 44.37 s
t = 44.38 s
t = 44.39 s
t = 44.40 s
t = 44.41 s
t = 44.42 s
t = 44.43 s
t = 44.44 s
t = 44.45 s
t = 44.46 s
t = 44.47 s
t = 44.48 s
t = 44.49 s
t = 44.50 s
t = 44.51 s
t = 44.52 s
t = 44.53 s
t = 44.54 s
t = 44.55 s
t = 44.56 s
t = 44.57 s
t = 44.58 s
t = 44.59 s

92286


t = 44.60 s
t = 44.61 s
t = 44.62 s
t = 44.63 s
t = 44.64 s
t = 44.65 s
t = 44.66 s
t = 44.67 s
t = 44.68 s
t = 44.69 s
t = 44.70 s
t = 44.71 s
t = 44.72 s
t = 44.73 s
t = 44.74 s
t = 44.75 s
t = 44.76 s
t = 44.77 s
t = 44.78 s
t = 44.79 s
t = 44.80 s
t = 44.81 s
t = 44.82 s
t = 44.83 s
t = 44.84 s
t = 44.85 s
t = 44.86 s
t = 44.87 s
t = 44.88 s
t = 44.89 s
t = 44.90 s
t = 44.91 s
t = 44.92 s
t = 44.93 s
t = 44.94 s
t = 44.95 s
t = 44.96 s
t = 44.97 s
t = 44.98 s
t = 44.99 s
t = 45.00 s
t = 45.01 s
t = 45.02 s
t = 45.03 s
t = 45.04 s
t = 45.05 s
t = 45.06 s
t = 45.07 s
t = 45.08 s
t = 45.09 s
t = 45.10 s
t = 45.11 s
t = 45.12 s
t = 45.13 s
t = 45.14 s
t = 45.15 s
t = 45.16 s
t = 45.17 s
t = 45.18 s
t = 45.19 s

92286

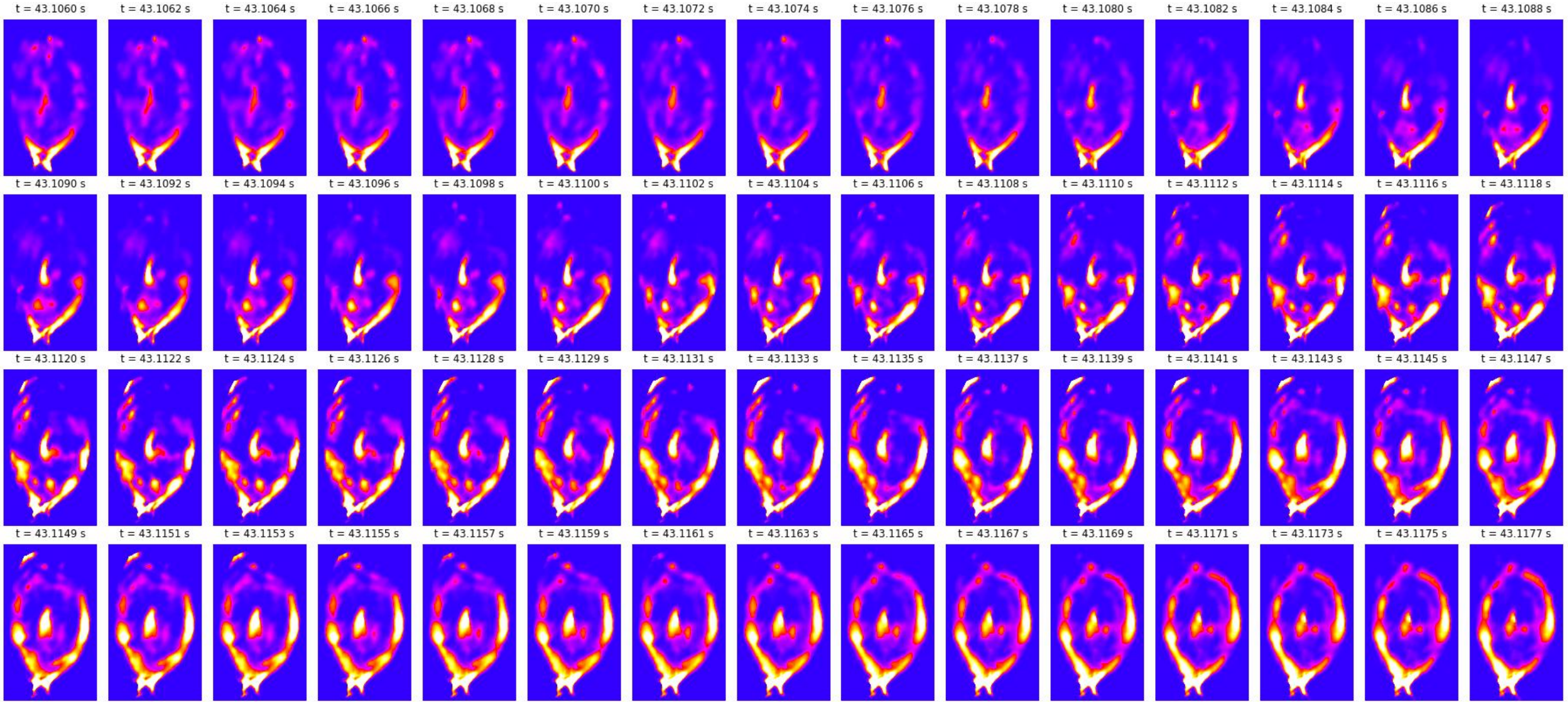

t = 45.20 s
t = 45.21 s
t = 45.22 s
t = 45.23 s
t = 45.24 s
t = 45.25 s
t = 45.26 s
t = 45.27 s
t = 45.28 s
t = 45.29 s
t = 45.30 s
t = 45.31 s
t = 45.32 s
t = 45.33 s
t = 45.34 s
t = 45.35 s
t = 45.36 s
t = 45.37 s
t = 45.38 s
t = 45.39 s
t = 45.40 s
t = 45.41 s
t = 45.42 s
t = 45.43 s
t = 45.44 s
t = 45.45 s
t = 45.46 s
t = 45.47 s
t = 45.48 s
t = 45.49 s
t = 45.50 s
t = 45.51 s
t = 45.52 s
t = 45.53 s
t = 45.54 s
t = 45.55 s
t = 45.56 s
t = 45.57 s
t = 45.58 s
t = 45.59 s
t = 45.60 s
t = 45.61 s
t = 45.62 s
t = 45.63 s
t = 45.64 s
t = 45.65 s
t = 45.66 s
t = 45.67 s
t = 45.68 s
t = 45.69 s
t = 45.70 s
t = 45.71 s
t = 45.72 s
t = 45.73 s
t = 45.74 s
t = 45.75 s
t = 45.76 s
t = 45.77 s
t = 45.78 s
t = 45.79 s

92286 tungsten event

time range: **t=43.1060s** to **t=43.1177s**

dynamic range: **$0 \leq P_{rad} \leq 40$ kW m^{-3}**

92286


t = 43.1060 s
t = 43.1062 s
t = 43.1064 s
t = 43.1066 s
t = 43.1068 s
t = 43.1070 s
t = 43.1072 s
t = 43.1074 s
t = 43.1076 s
t = 43.1078 s
t = 43.1080 s
t = 43.1082 s
t = 43.1084 s
t = 43.1086 s
t = 43.1088 s
t = 43.1090 s
t = 43.1092 s
t = 43.1094 s
t = 43.1096 s
t = 43.1098 s
t = 43.1100 s
t = 43.1102 s
t = 43.1104 s
t = 43.1106 s
t = 43.1108 s
t = 43.1110 s
t = 43.1112 s
t = 43.1114 s
t = 43.1116 s
t = 43.1118 s
t = 43.1120 s
t = 43.1122 s
t = 43.1124 s
t = 43.1126 s
t = 43.1128 s
t = 43.1129 s
t = 43.1131 s
t = 43.1133 s
t = 43.1135 s
t = 43.1137 s
t = 43.1139 s
t = 43.1141 s
t = 43.1143 s
t = 43.1145 s
t = 43.1147 s
t = 43.1149 s
t = 43.1151 s
t = 43.1153 s
t = 43.1155 s
t = 43.1157 s
t = 43.1159 s
t = 43.1161 s
t = 43.1163 s
t = 43.1165 s
t = 43.1167 s
t = 43.1169 s
t = 43.1171 s
t = 43.1173 s
t = 43.1175 s
t = 43.1177 s

Conclusion

- some remarks
  - speed, accuracy, usefulness
  - generally applicable, with training data

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