SAND2015-9705PE

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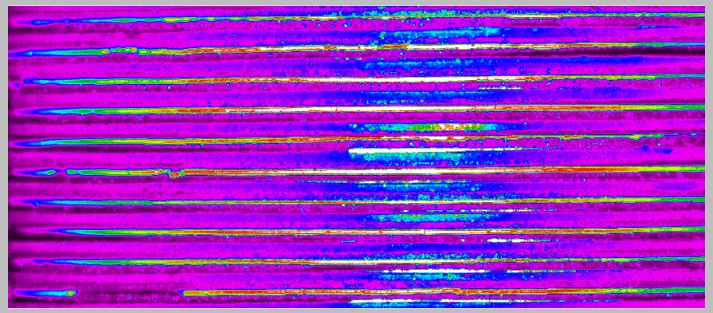
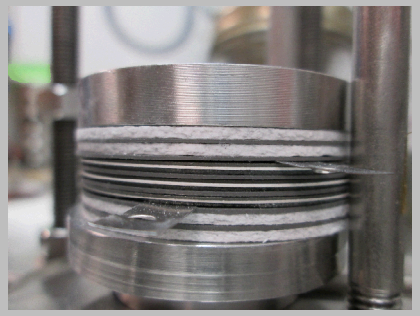
Sandia National Laboratories





Analyzing Deformation of Thermal Batteries *in Situ*

Solid Mechanics Department, Engineering Sciences Center

Sandia National Laboratories, Albuquerque NM

August 2015

Intern: Amy Jang Mentor: Kevin N. Long, Ph.D.

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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Project Motivation

Sandia National Laboratories

To produce a collection of data that can be used to validate future modeling results.

Project Overview

Sandia National Laboratories

Project Goals:

- Determine internal layer displacements as a function of time
- Compute strain of each layer relative to a user-defined layer as a function of time

Deliverables:

- For each battery:
  - Plot displacements of intensity maxima evenly dispersed throughout the battery
  - Plot strain between a given peak and 4 other peaks
  - Compare and summarize results
- Document the project

Analysis Approach

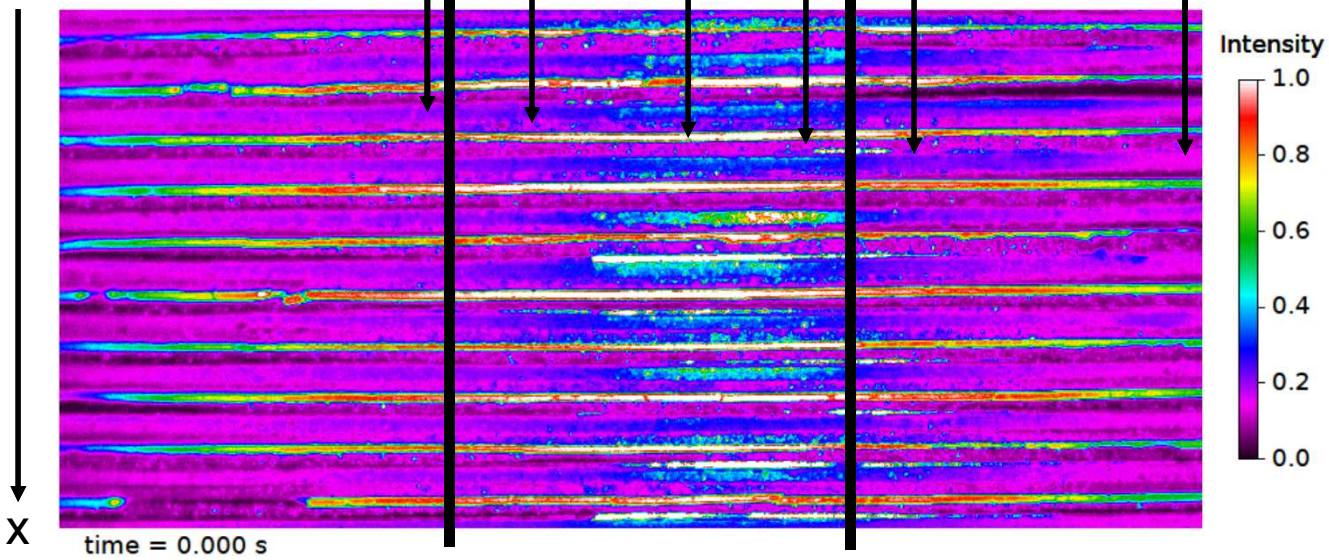
1. Intensity Analysis
2. Displacement Analysis
3. Strain Analysis

Step 1: Intensity Analysis

Sandia National Laboratories

Layers:
Heat Pellet, Cathode, Separator, Anode, Current Collector, Heat Pellet

Battery Stack in False Color

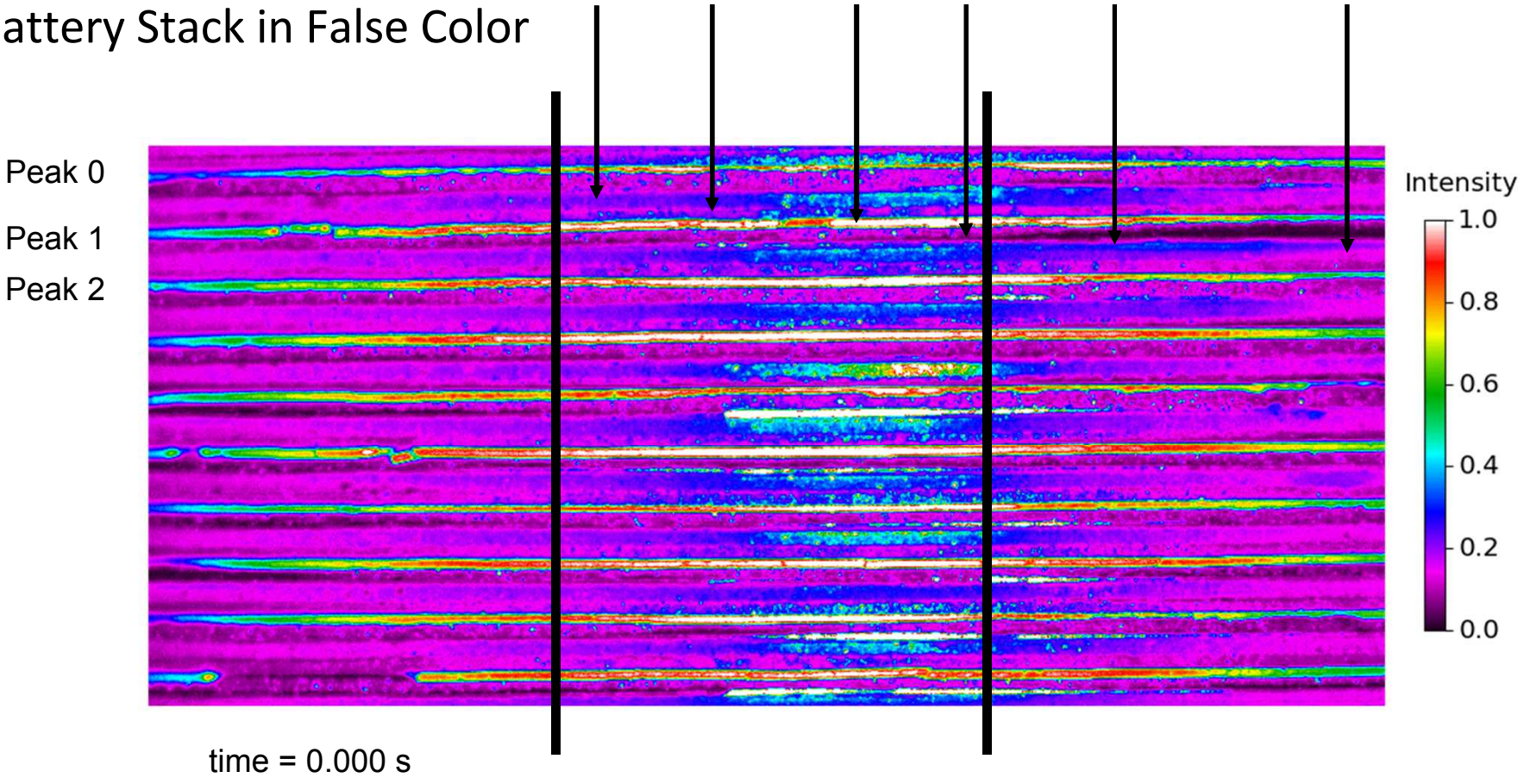


Step 2: Displacement Analysis

Sandia National Laboratories

Layers:
Heat Pellet, Cathode, Separator, Anode, Current Collector, Heat Pellet

Battery Stack in False Color



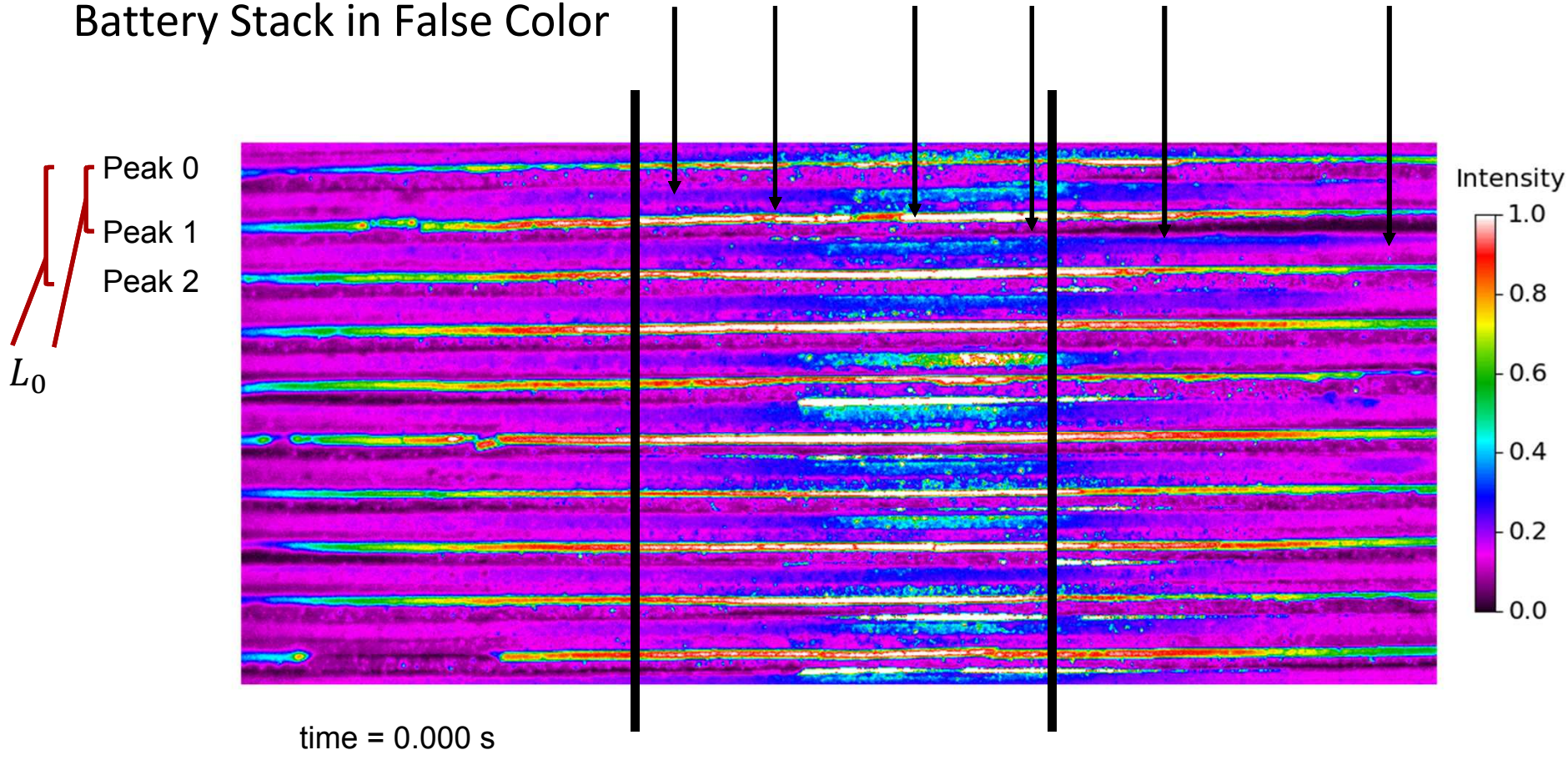
$$Displacement = s_n - s_0$$

Step 3: Strain Analysis

Sandia National Laboratories

Layers:
Heat Pellet, Cathode, Separator, Anode, Current Collector, Heat Pellet

Battery Stack in False Color



$$Strain = \frac{L_n - L_0}{L_0}$$

Results

- 3 cell MinK insulated battery stack
- 3 cell Fiberfrax insulated battery stack (9_9_3Cell_FF_3)
- 3 cell Fiberfrax insulated battery stack (9_18_3Cell_FF_4)
- Comparison between MinK and FF

- 5 cell MinK insulated battery stack
- 5 cell Fiberfrax insulated battery stack
- Comparison between MinK and FF

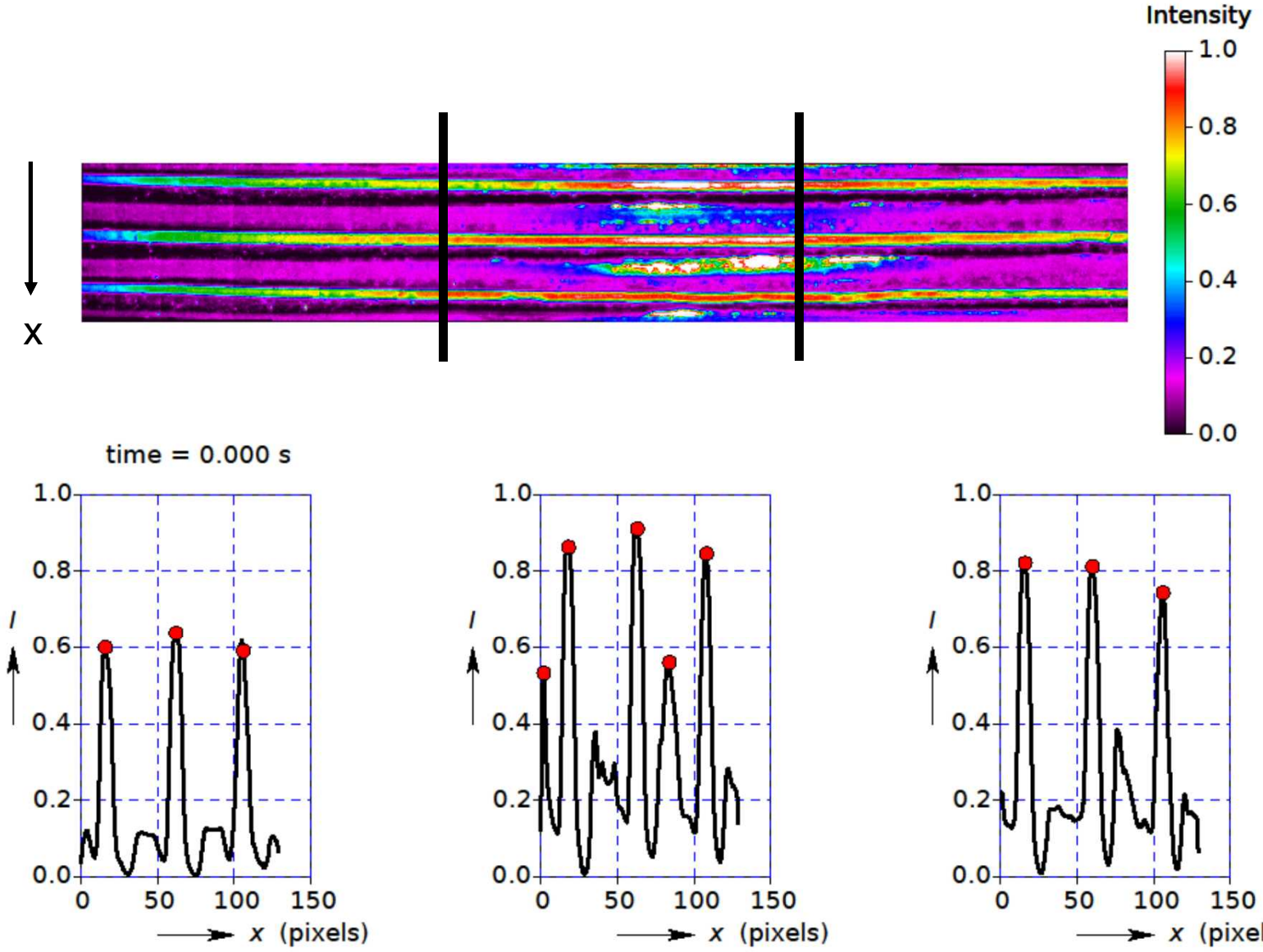
- 10 cell MinK insulated battery stack
- 10 cell Fiberfrax insulated battery stack
- Comparison between MinK and FF

3 Cell MinK Insulated Battery

9_18_3Cell_MinK_1

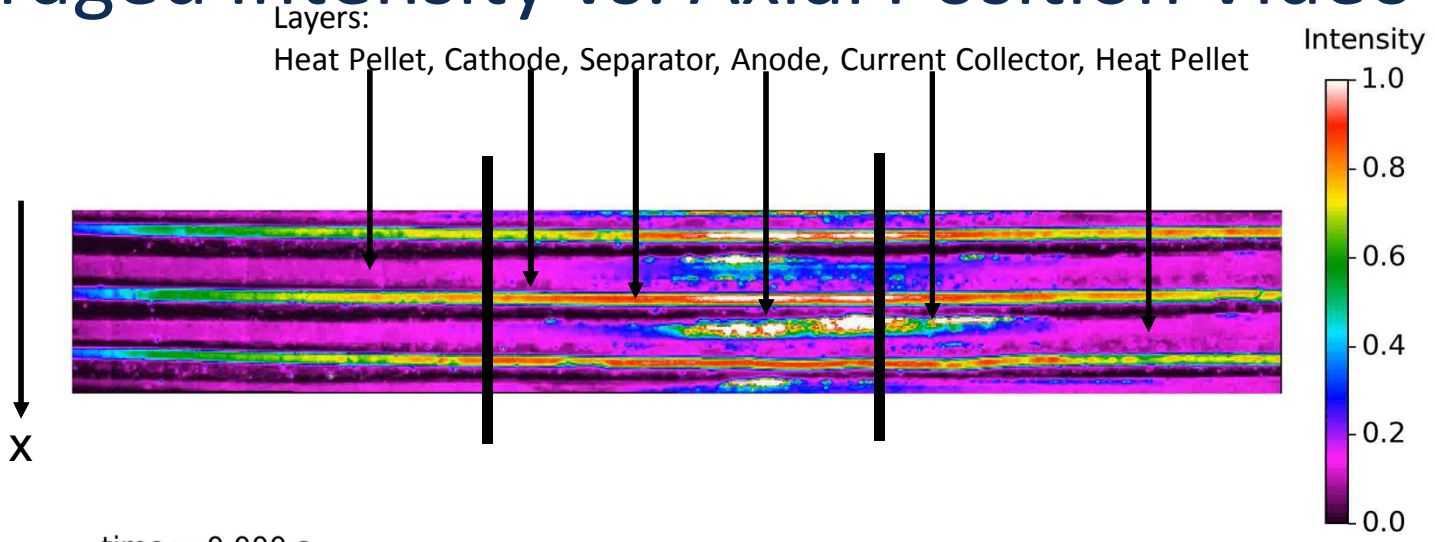
0th Frame Image with Intensity Plots

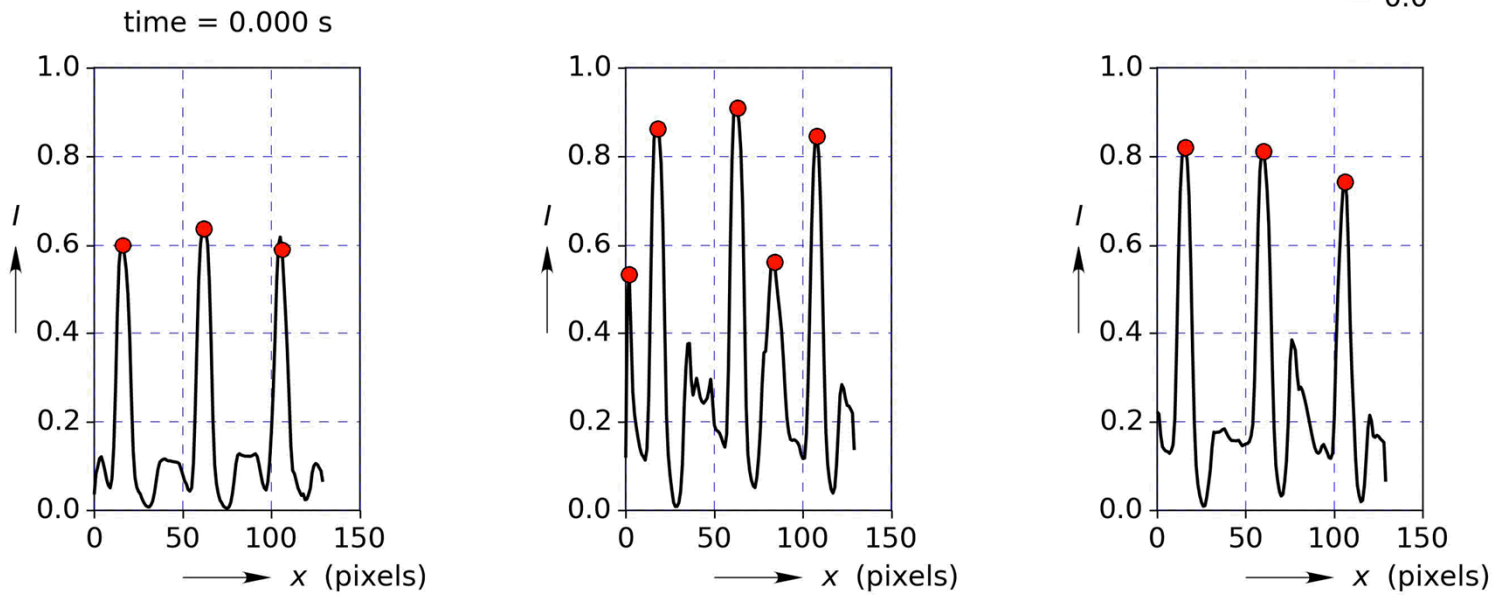
Sandia National Laboratories



Averaged Intensity vs. Axial Position Video

Battery Stack in False Color

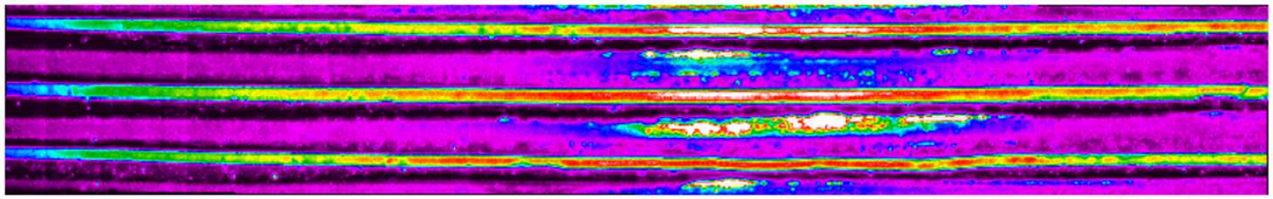




Row-Averaged Intensity Averaged Along the Stack Axis

Displacement vs. Time

Initial and Final Images



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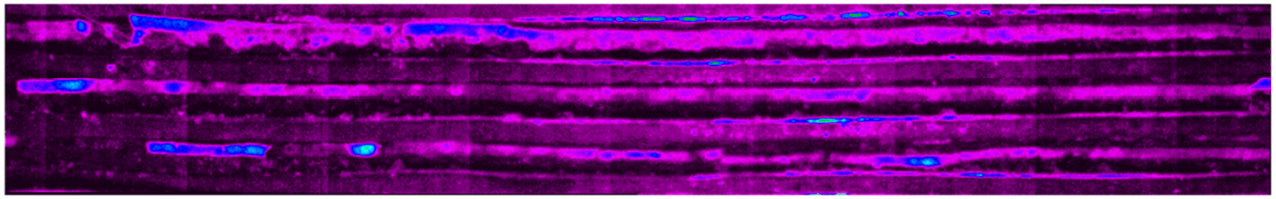
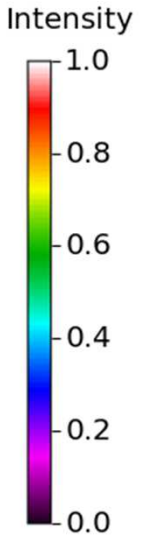
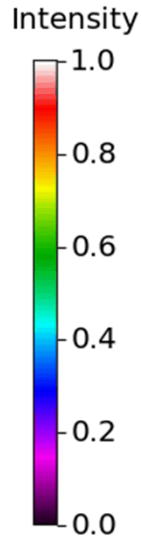


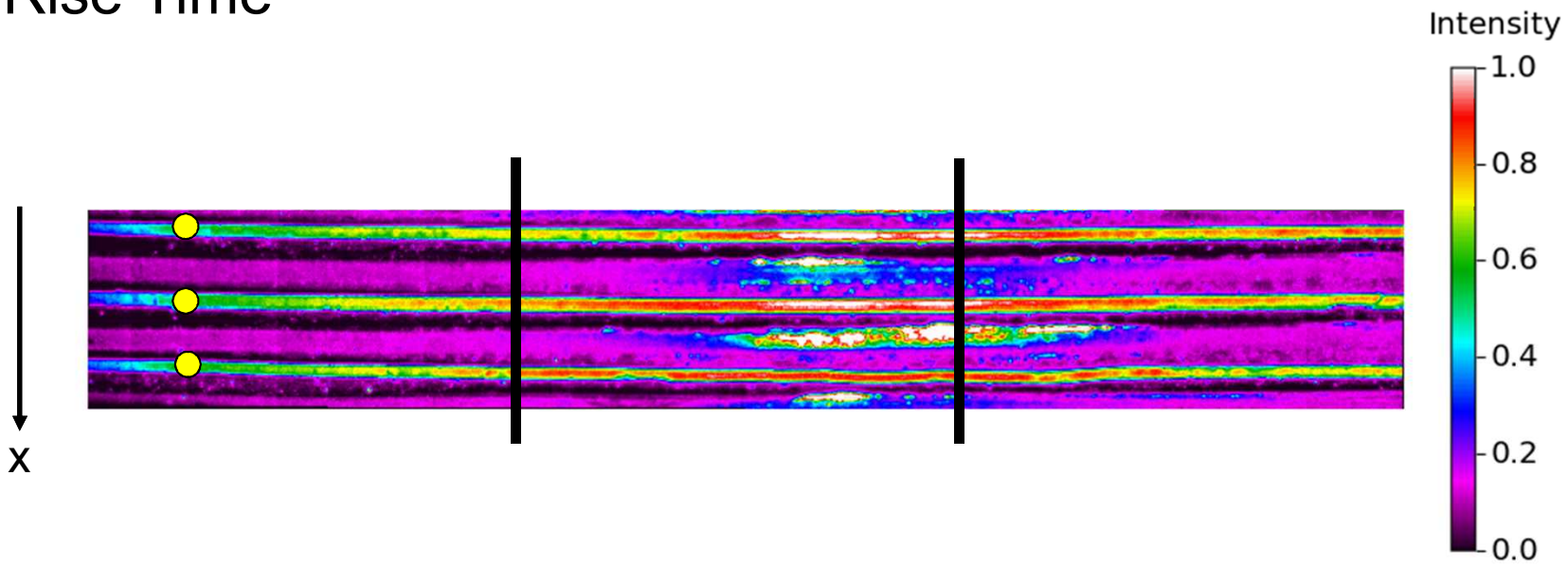
time = 200.804 s

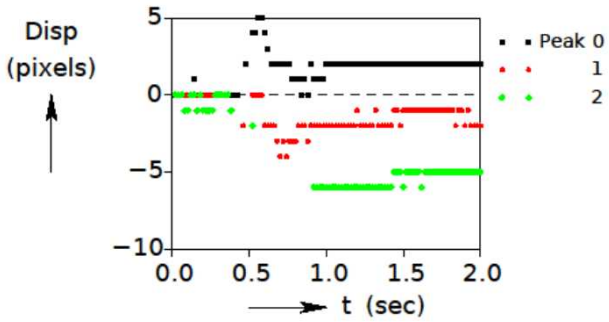


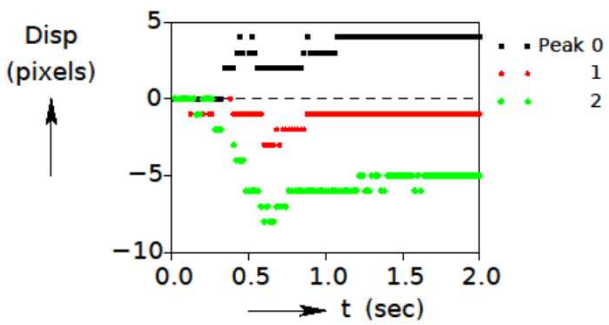


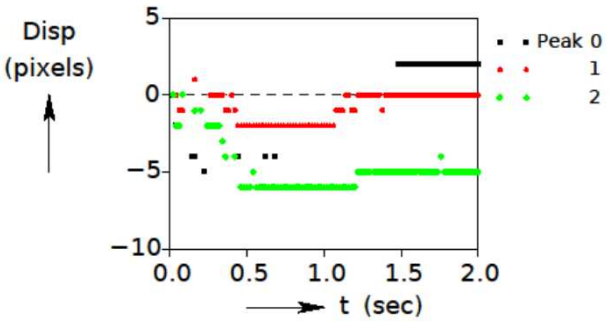
Displacement vs. Time

Rise Time



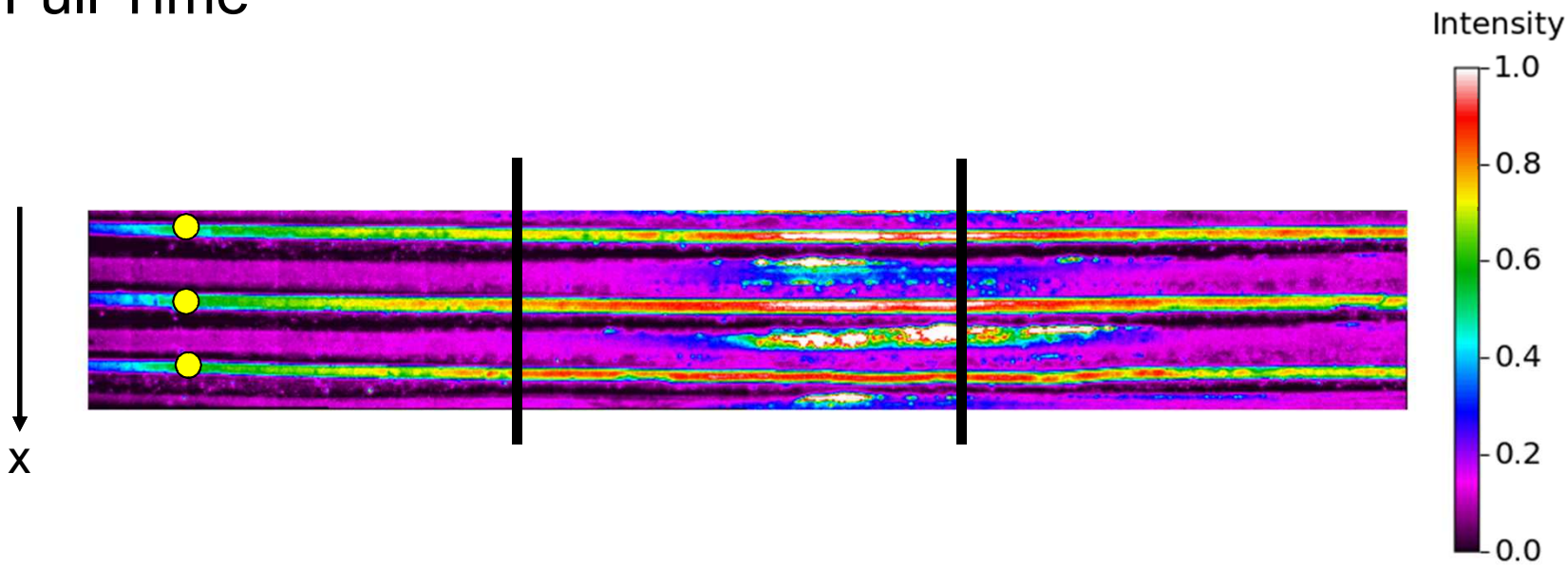


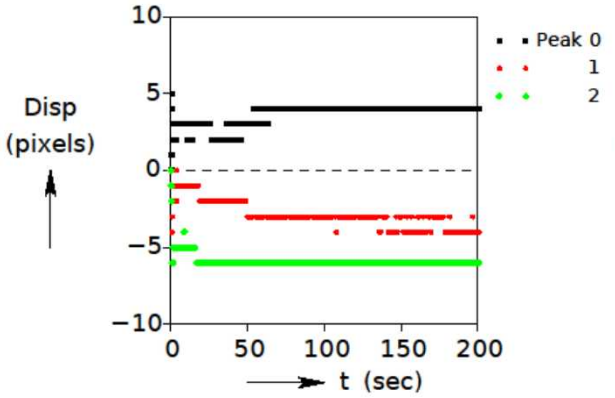


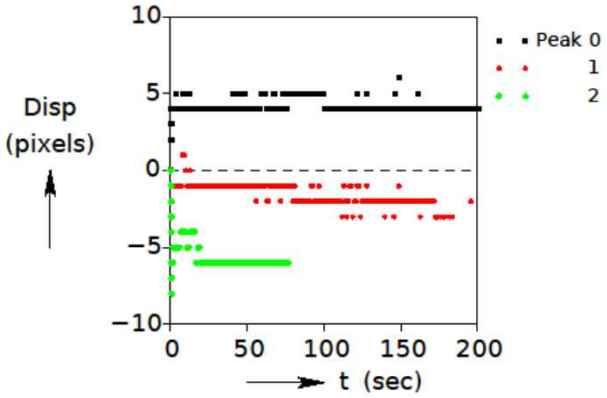


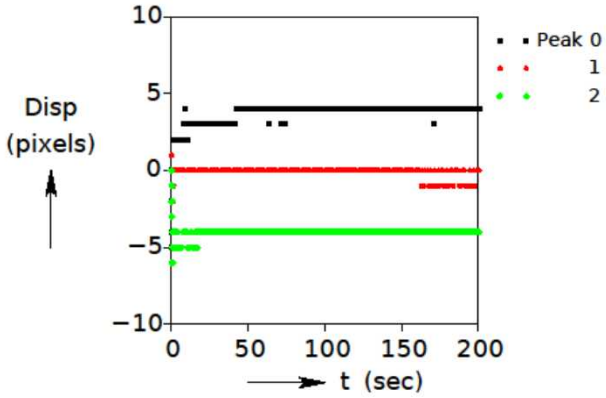
Displacement vs. Time

Full Time







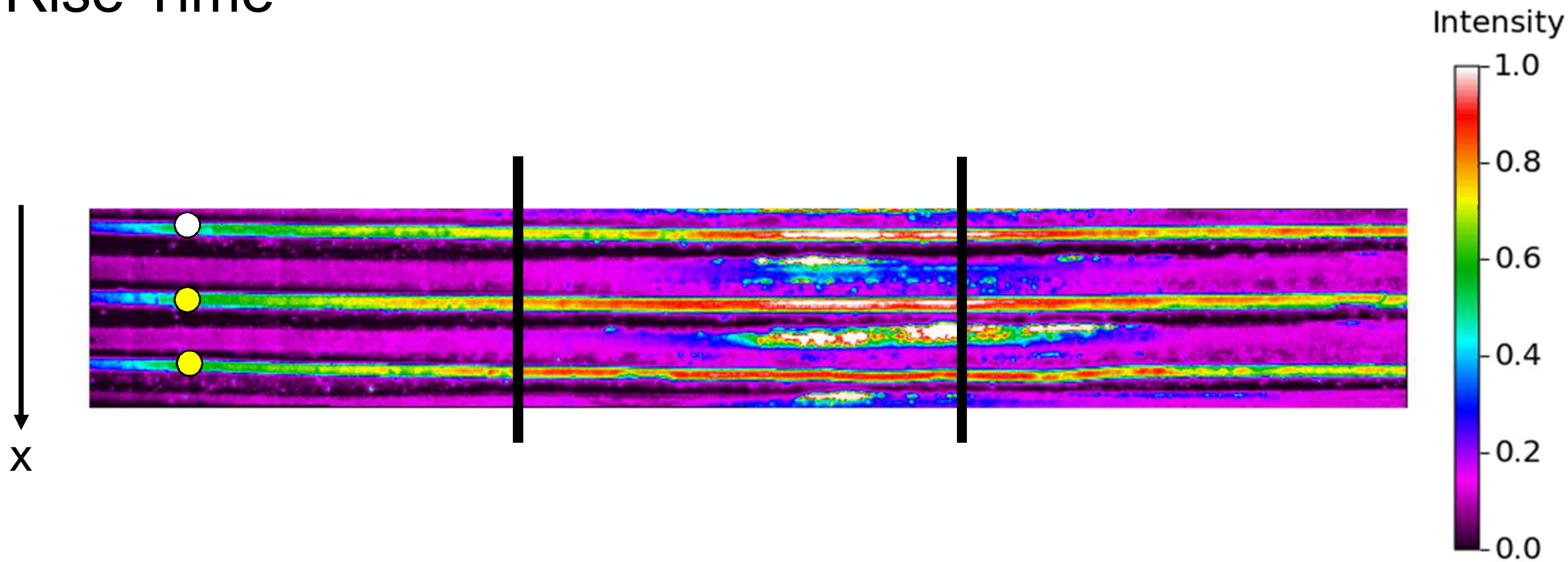


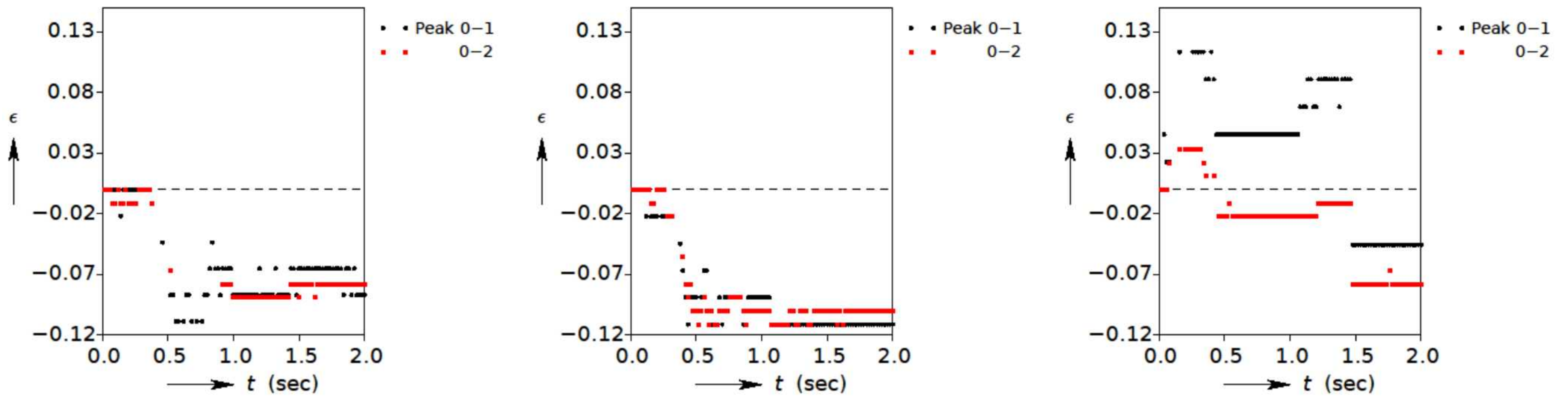
Slide 14

JA7 Missing data in interval 1 for peak 2 because hard to detect.
Jang, Amy, 8/3/2015

Strain vs. Time

Rise Time



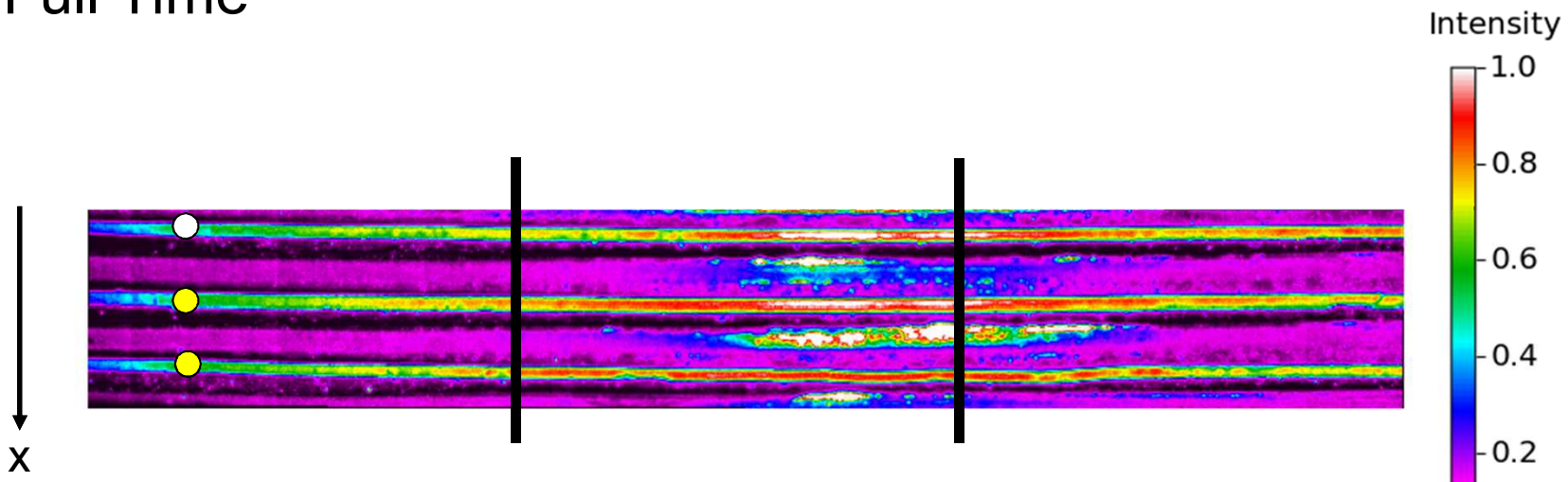


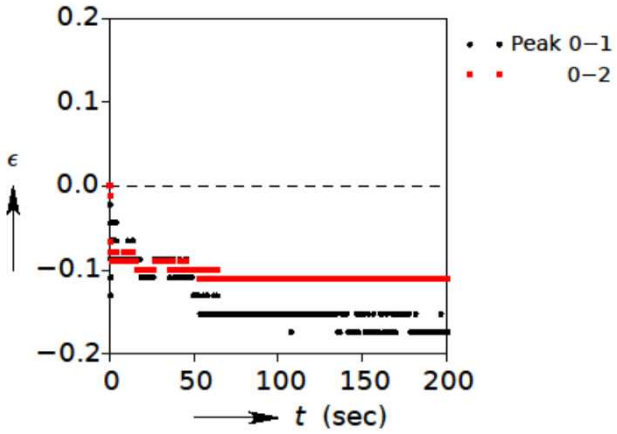
Slide 15

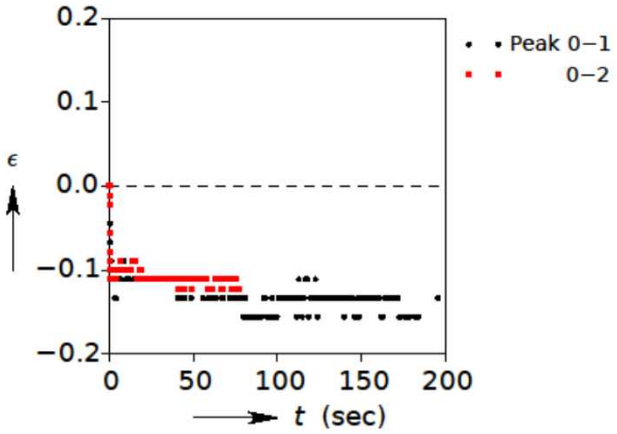
JA5 I think interval 2's jumping data is correct.
Jang, Amy, 8/3/2015

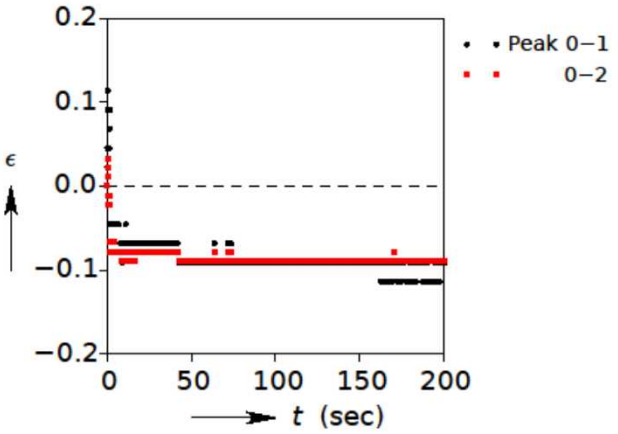
Strain vs. Time

Full Time









Slide 16

JA6 Interval 1 missing peak 0-2 data because peak 2 is hard to detect.
Jang, Amy, 8/3/2015

3 Cell Fiberfrax Insulated Battery

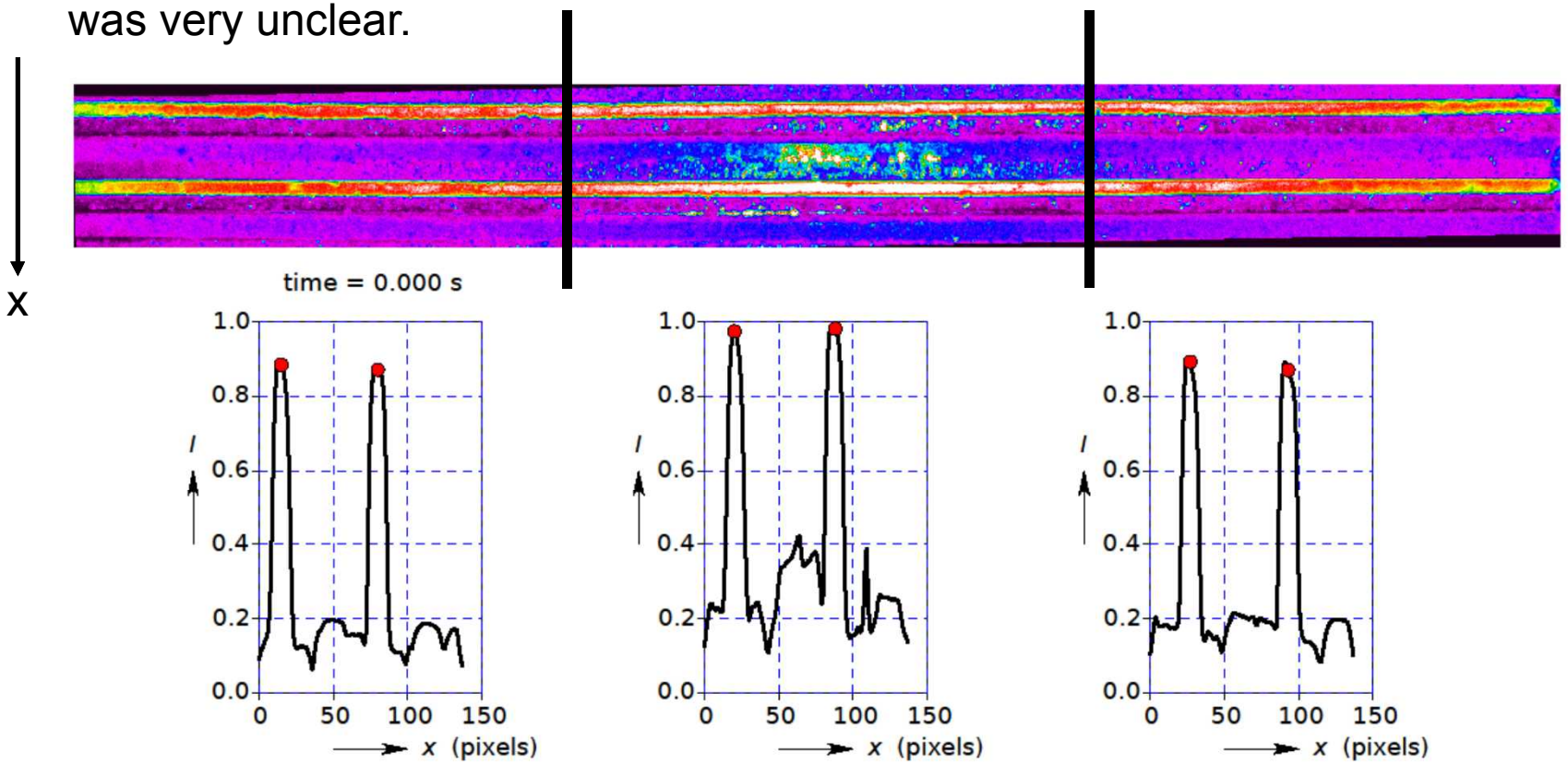
Sandia National Laboratories

9_9_3Cell_FF_3

0th Frame Image with Intensity Plots

Sandia National Laboratories

Note: 3rd cell not shown because it was very unclear.

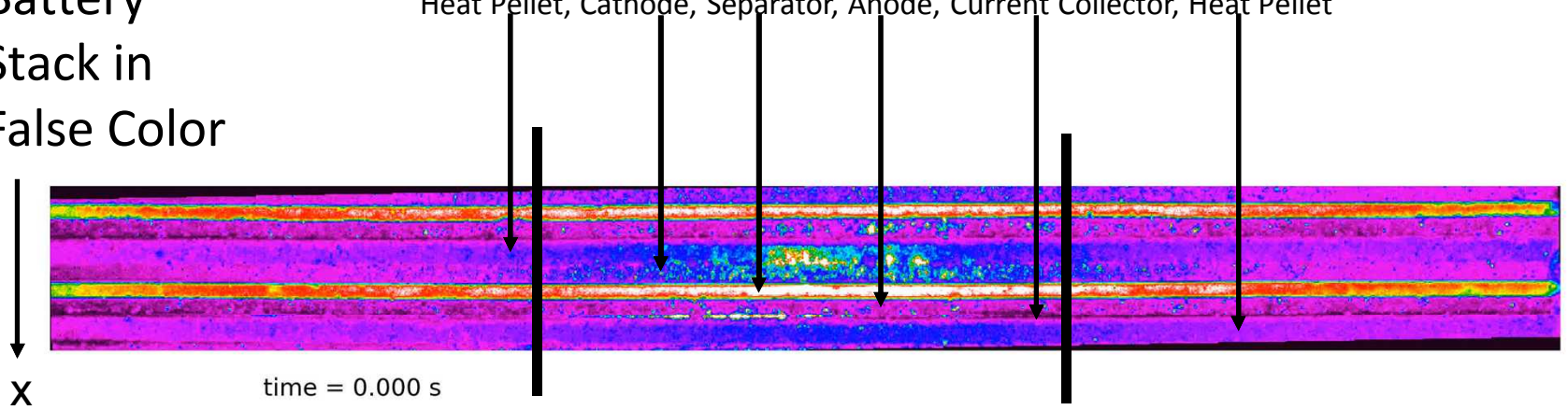


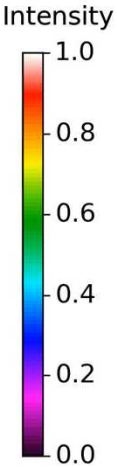
Averaged Intensity vs. Axial Position Video

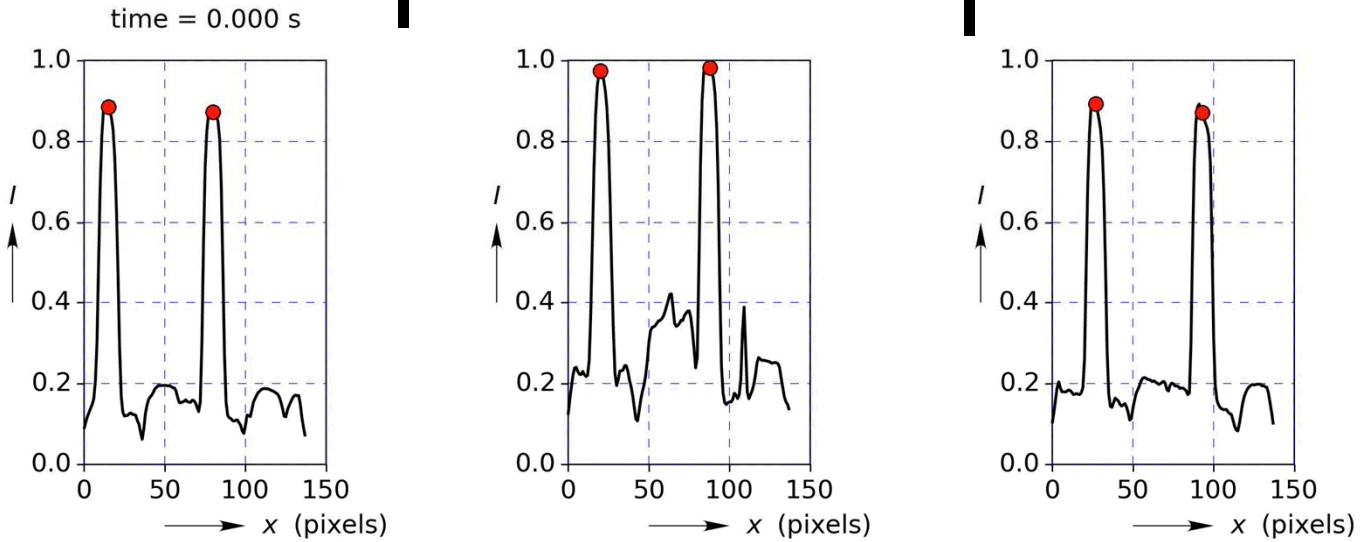
Sandia National Laboratories

Battery Stack in False Color

Layers:
Heat Pellet, Cathode, Separator, Anode, Current Collector, Heat Pellet





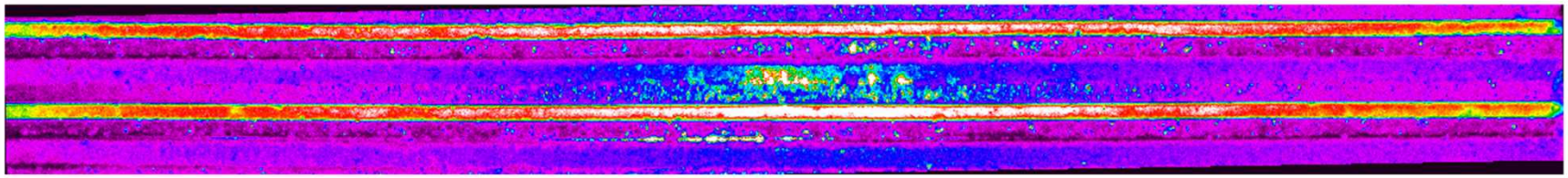


Row-Averaged Intensity Averaged Along the Stack Axis

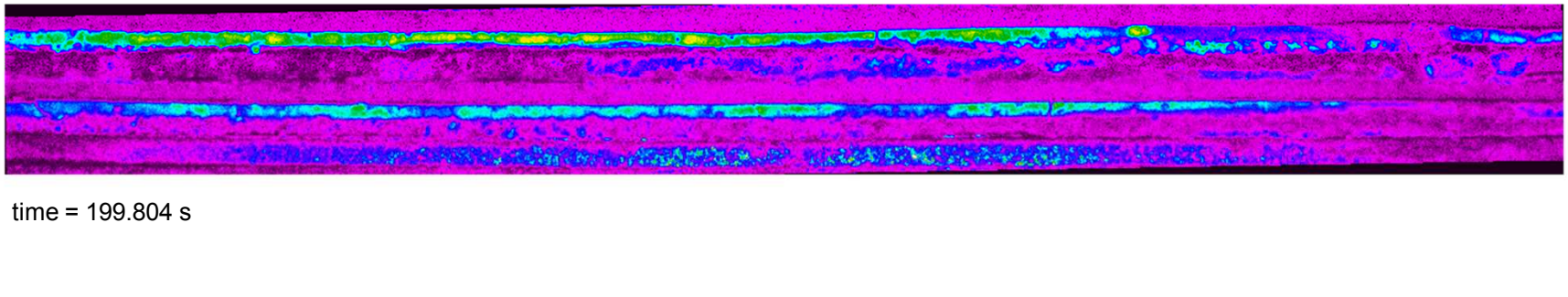
Displacement vs. Time

Sandia National Laboratories

Initial and Final Images



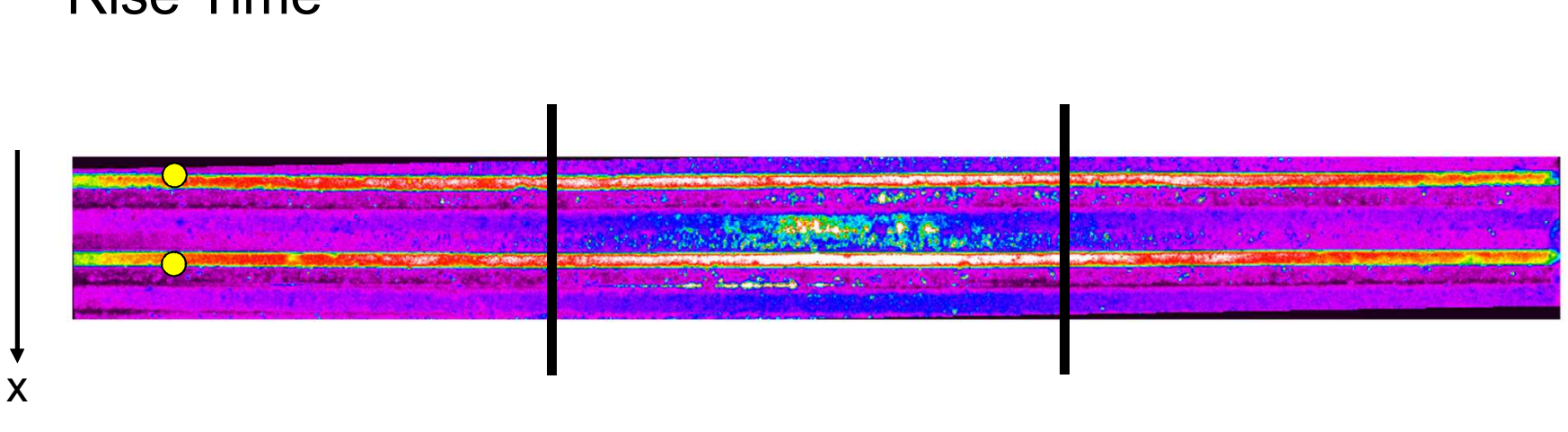
time = 0.000 s

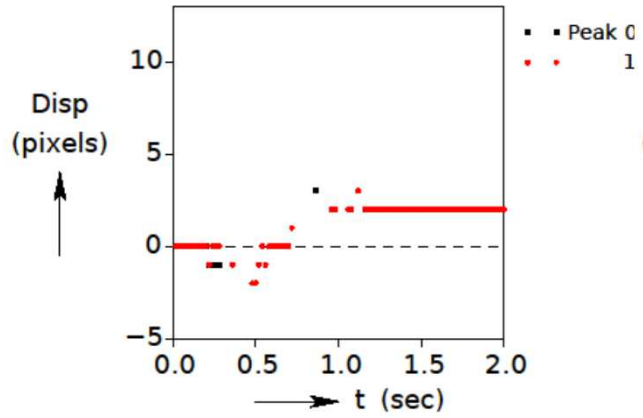


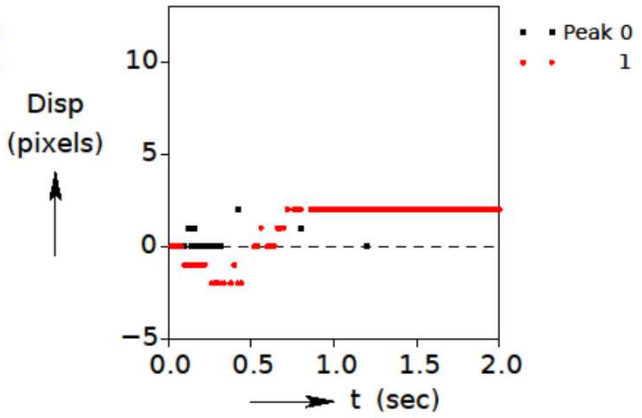
time = 199.804 s

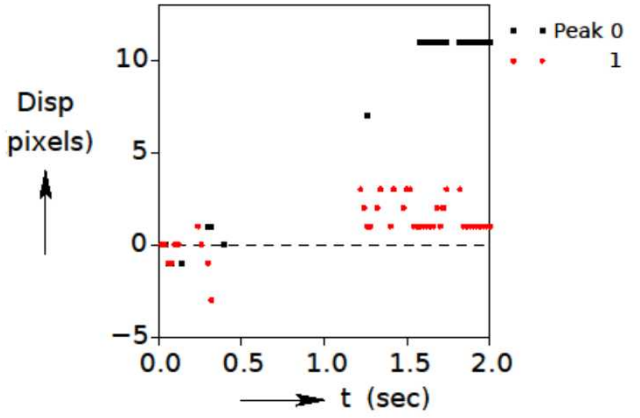
Displacement vs. Time

Rise Time



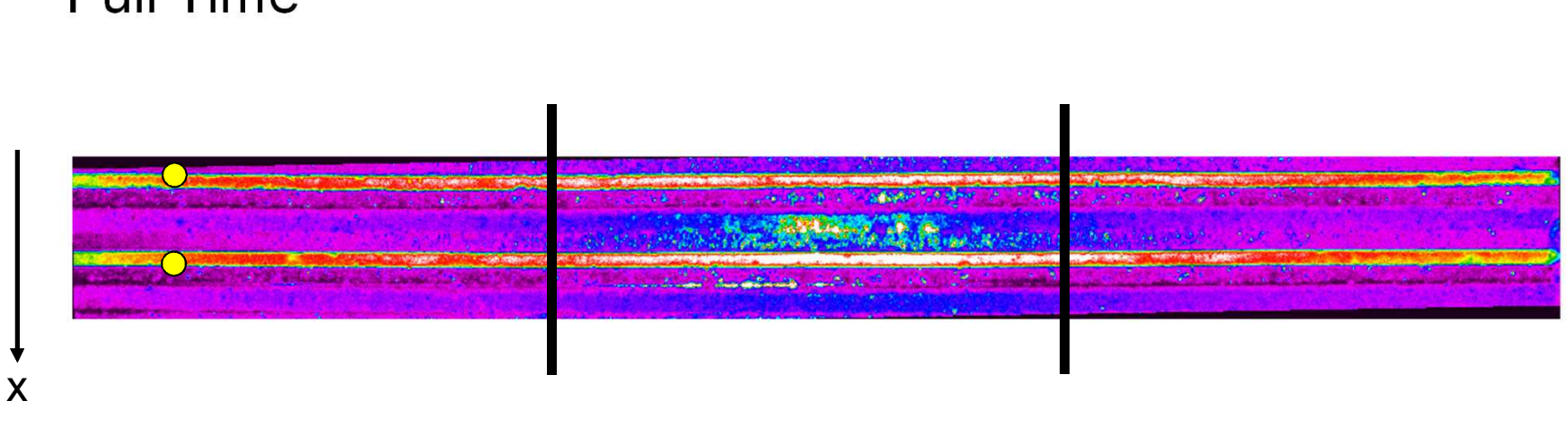


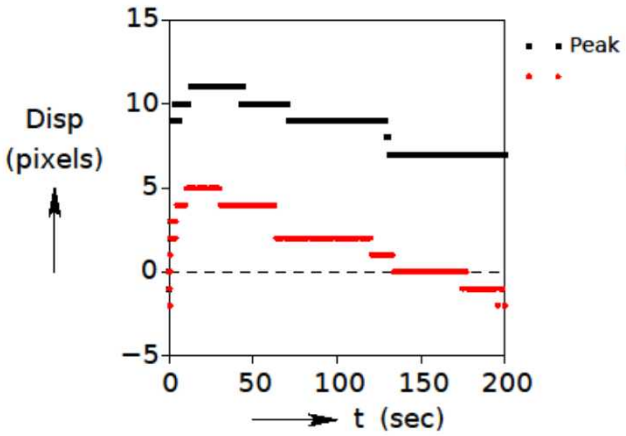


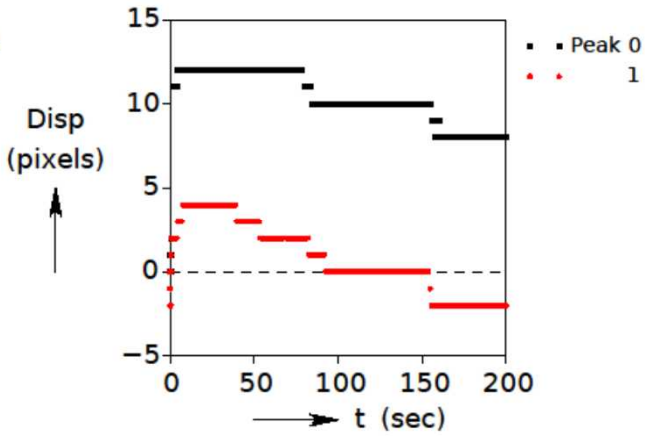


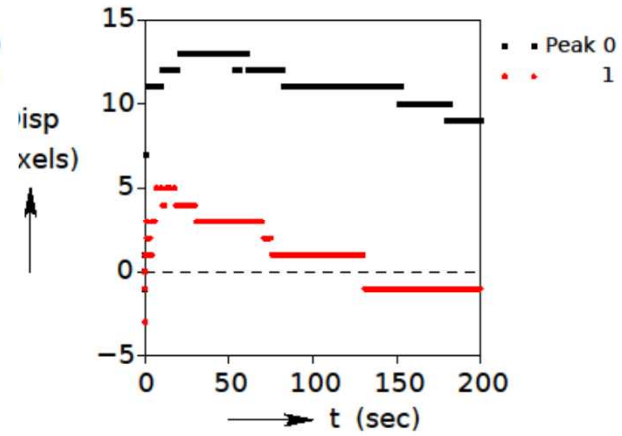
Displacement vs. Time

Full Time





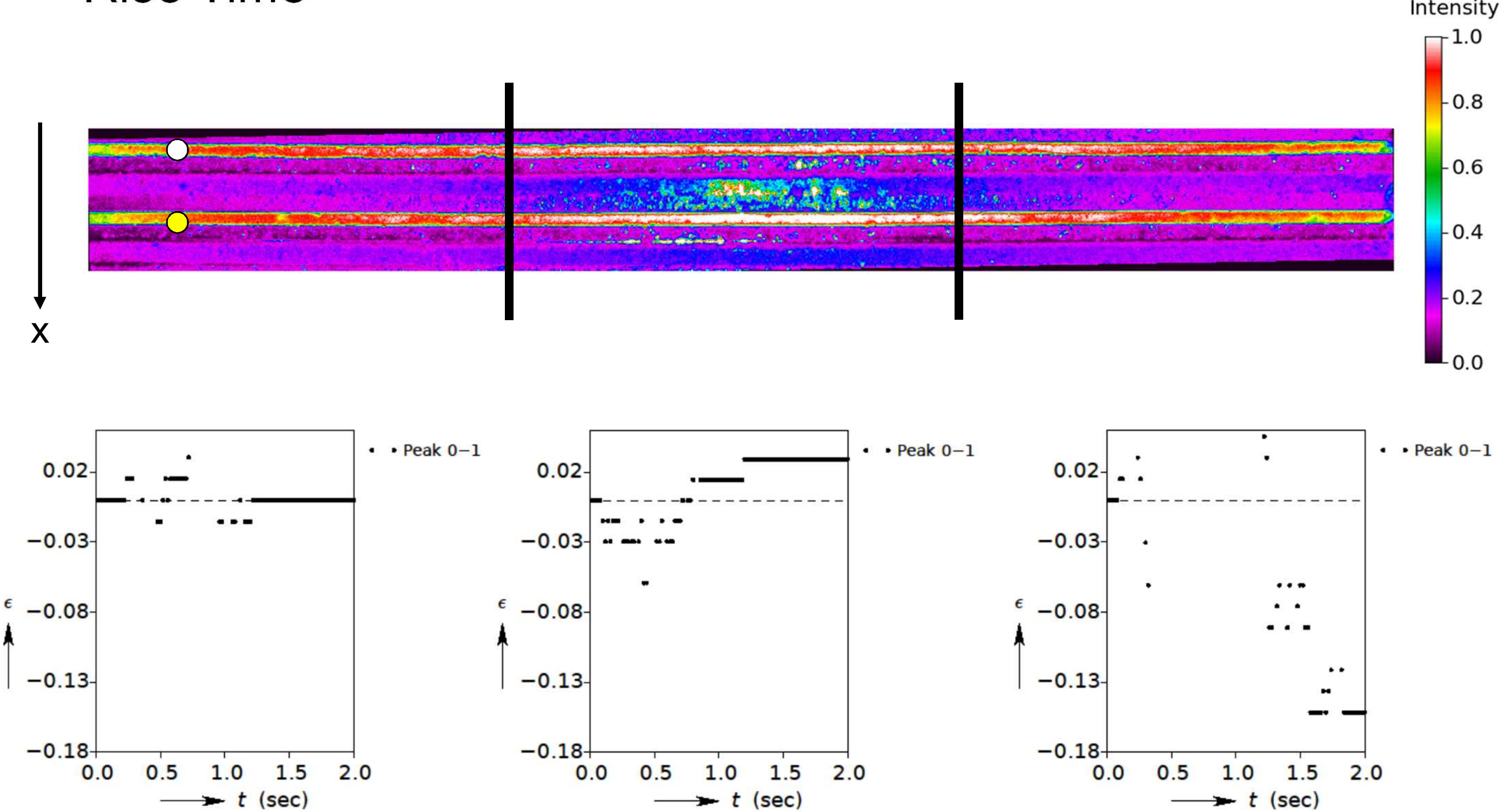




JA11

Strain vs. Time

Rise Time



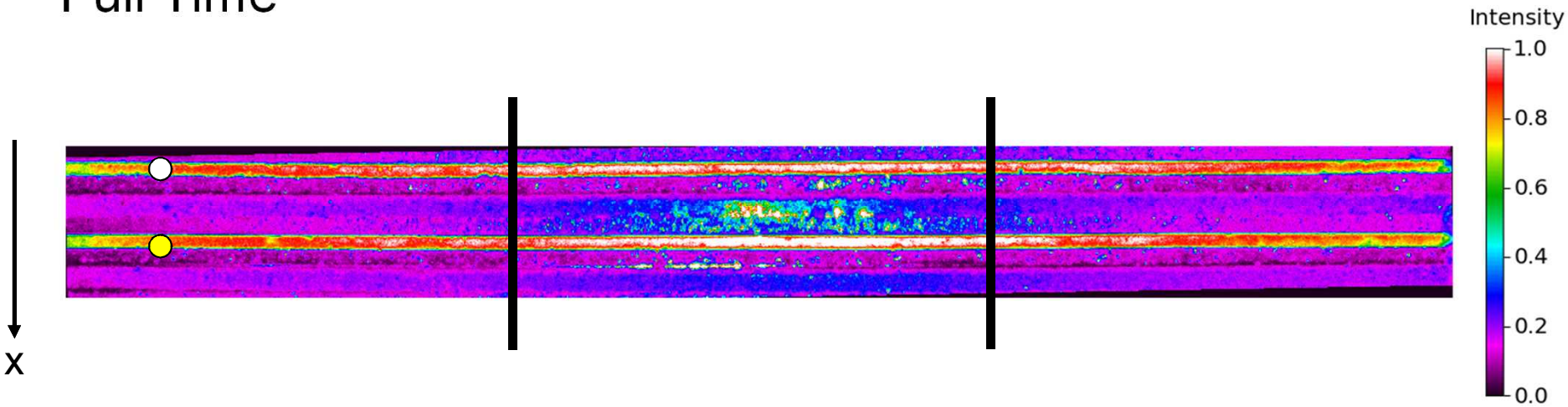
Slide 23

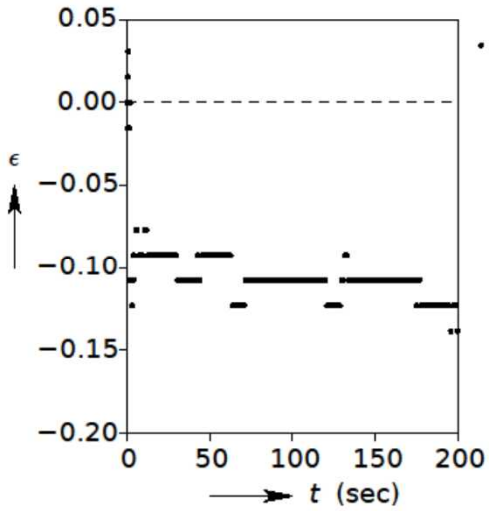
JA11 Have positive strain across the intervals because peak 1 is detected and displaces positively but peak 0 is not detected -> calculating strain relative to last known position of peak 0.

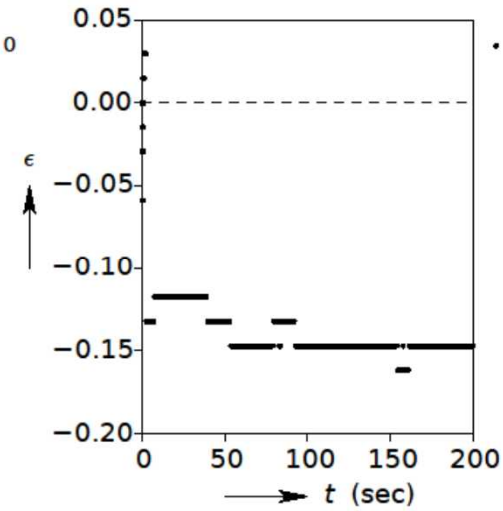
Jang, Amy, 8/3/2015

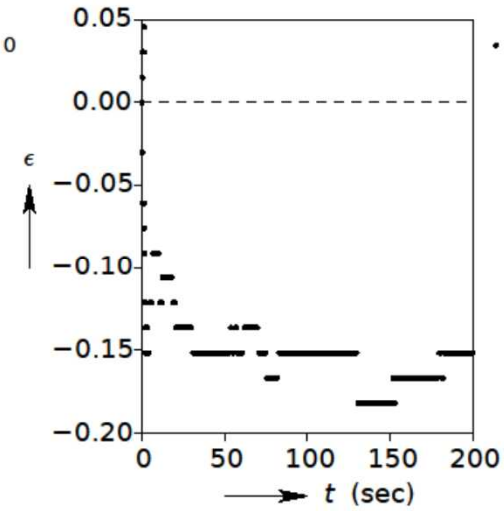
Strain vs. Time

Full Time







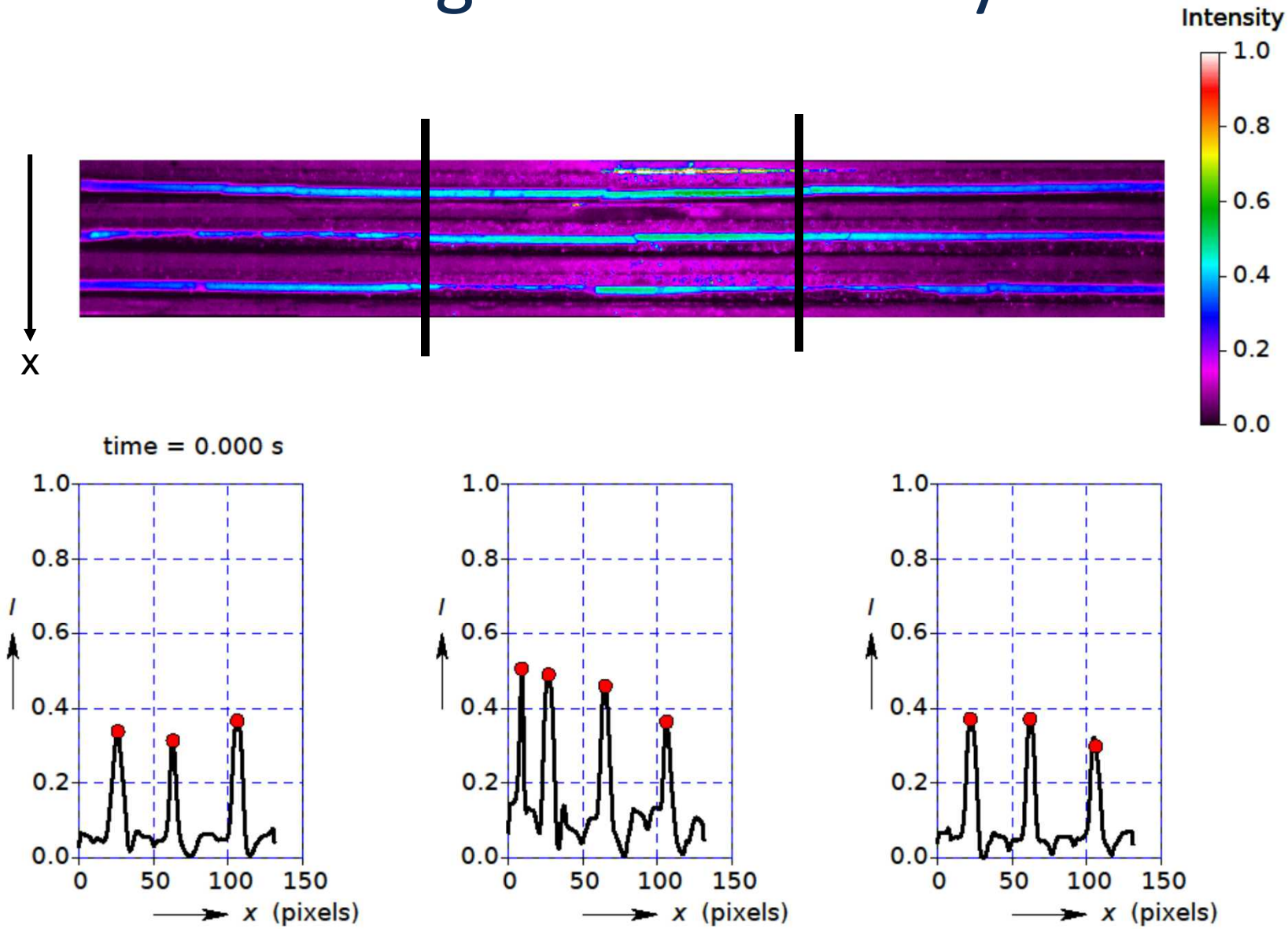


3 Cell Fiberfrax Insulated Battery

Sandia National Laboratories

9_18_3Cell_FF_4

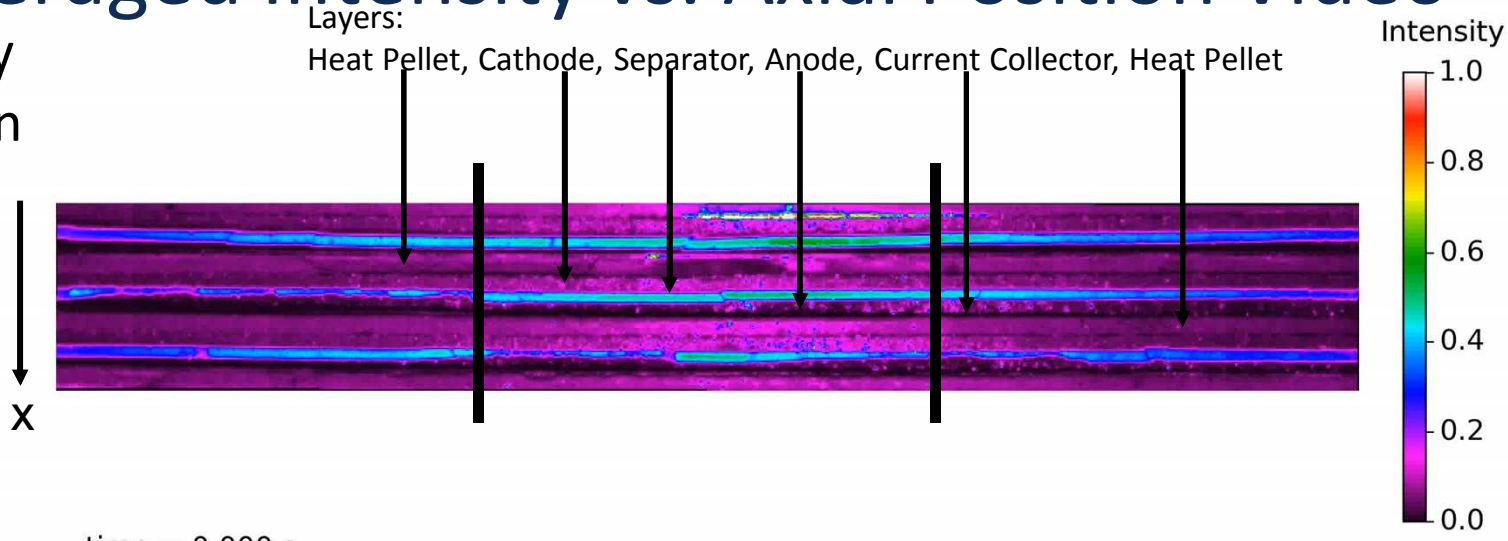
0th Frame Image with Intensity Plots

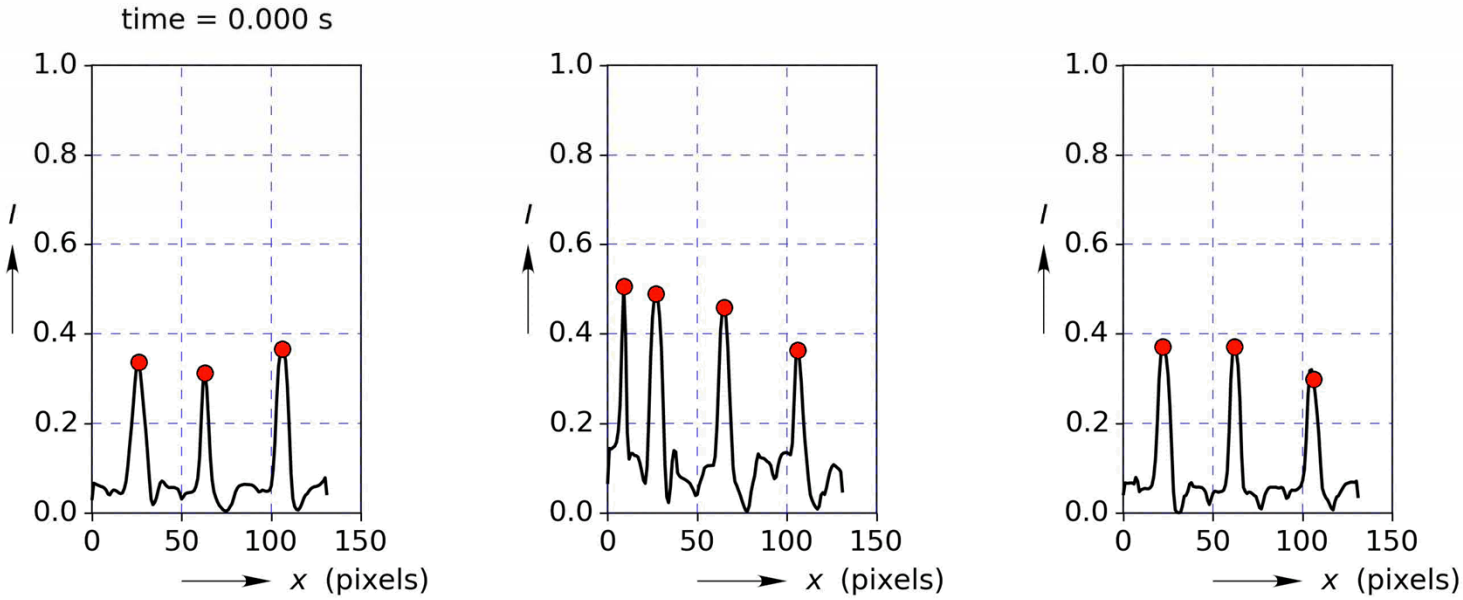


Averaged Intensity vs. Axial Position Video

Sandia National Laboratories

Battery Stack in False Color



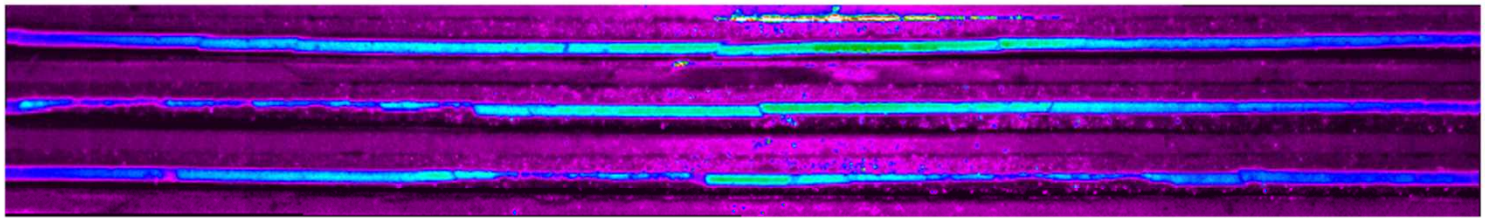


Row-Averaged Intensity Averaged Along the Stack Axis

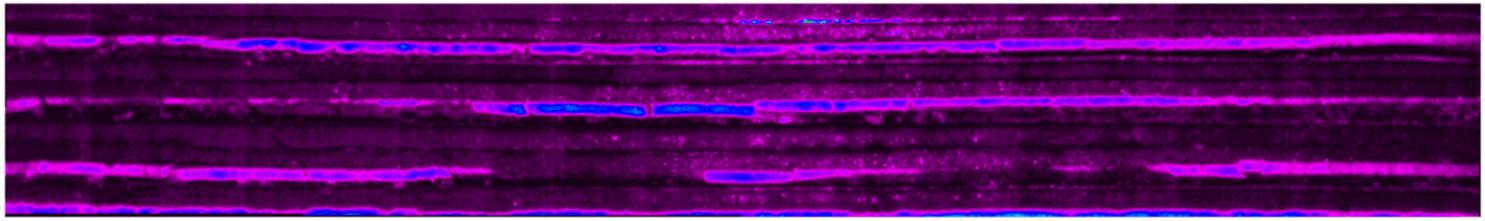
Displacement vs. Time

Sandia National Laboratories

Initial and Final Images



time = 0.000 s



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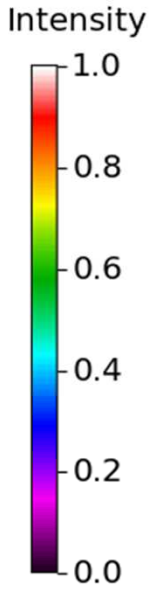
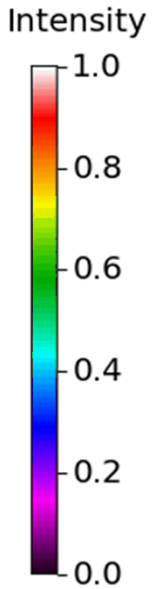
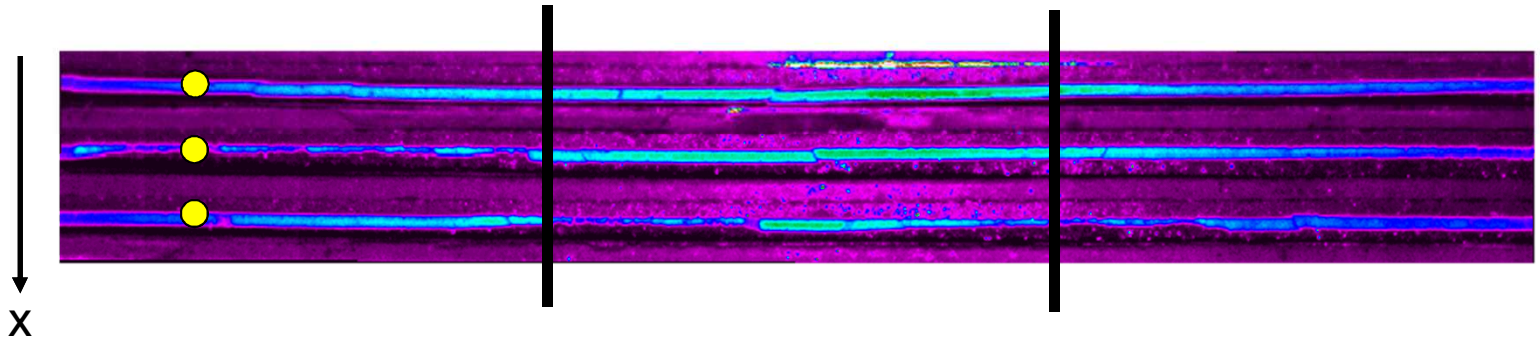
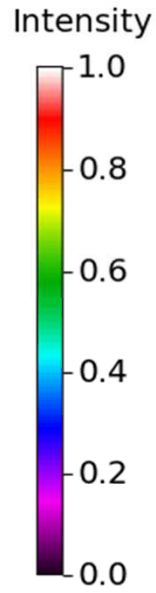


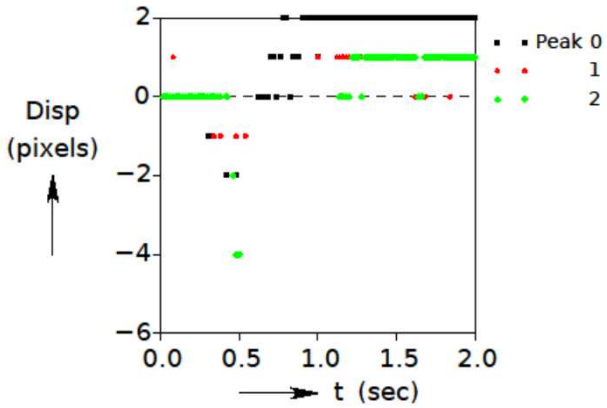


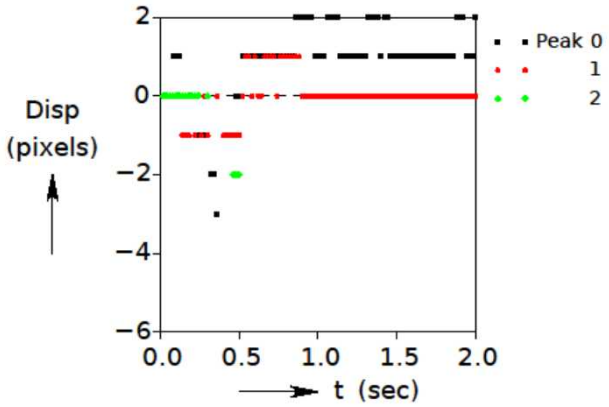
Displacement vs. Time

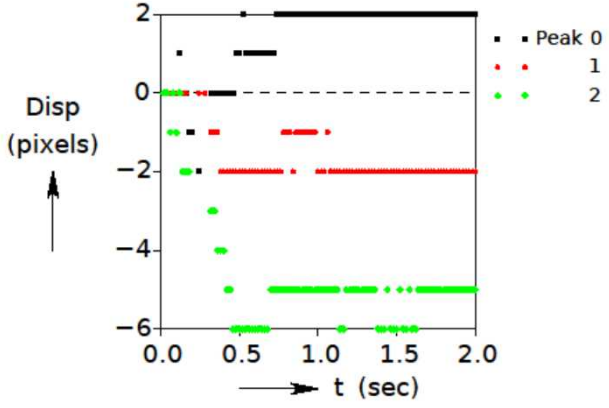
Rise Time







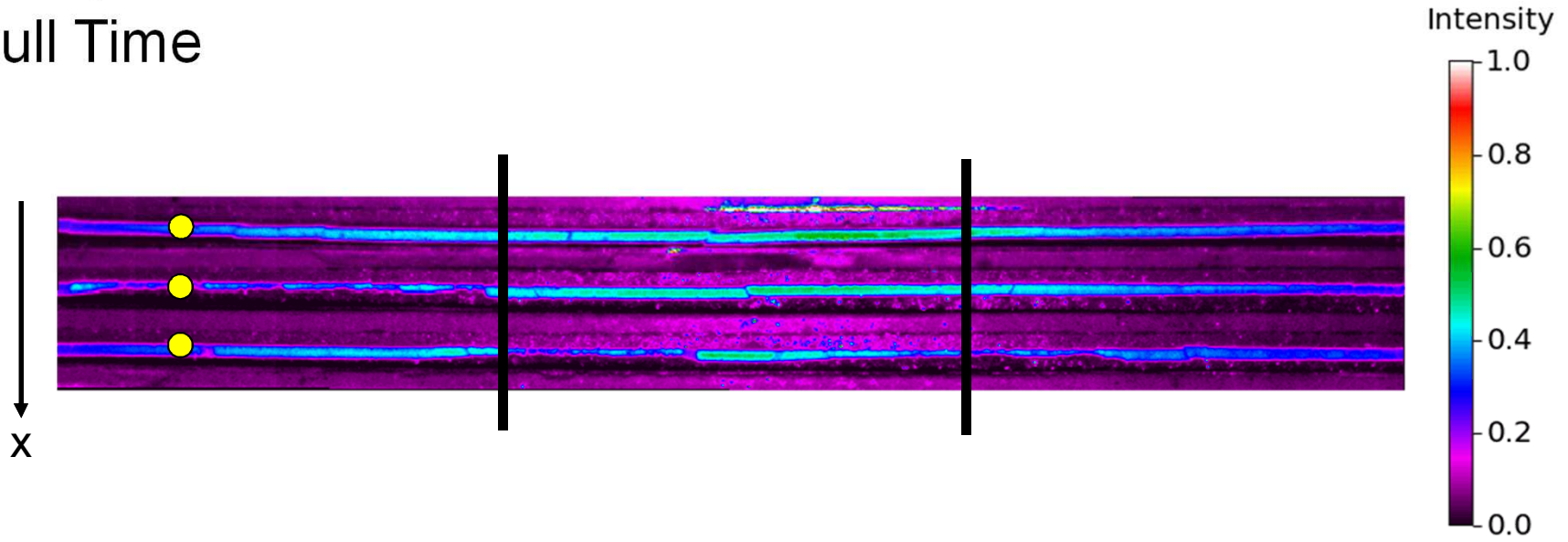


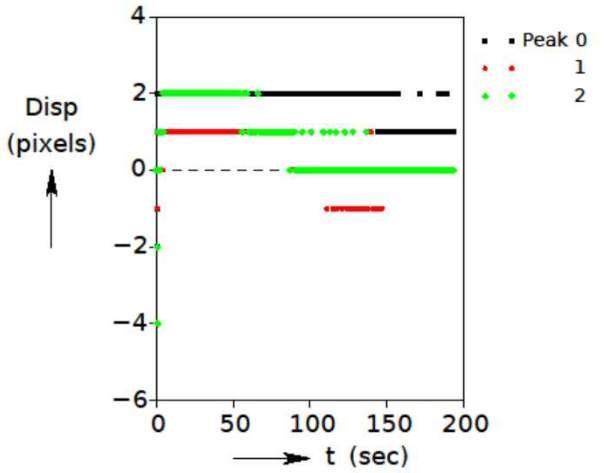


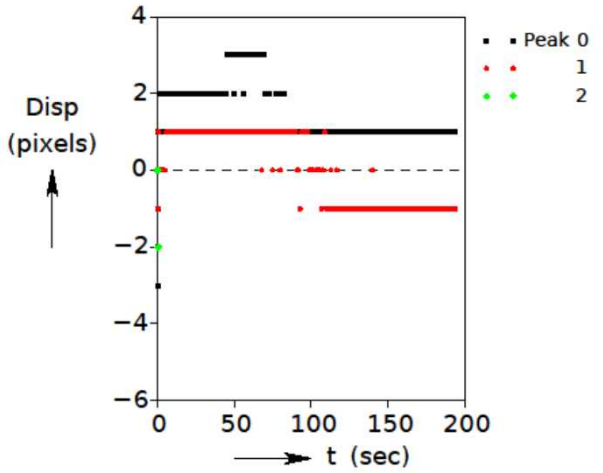
Displacement vs. Time

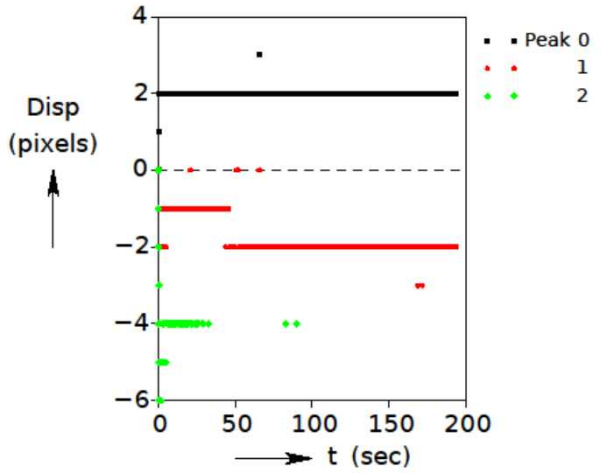
Full Time

Sandia National Laboratories









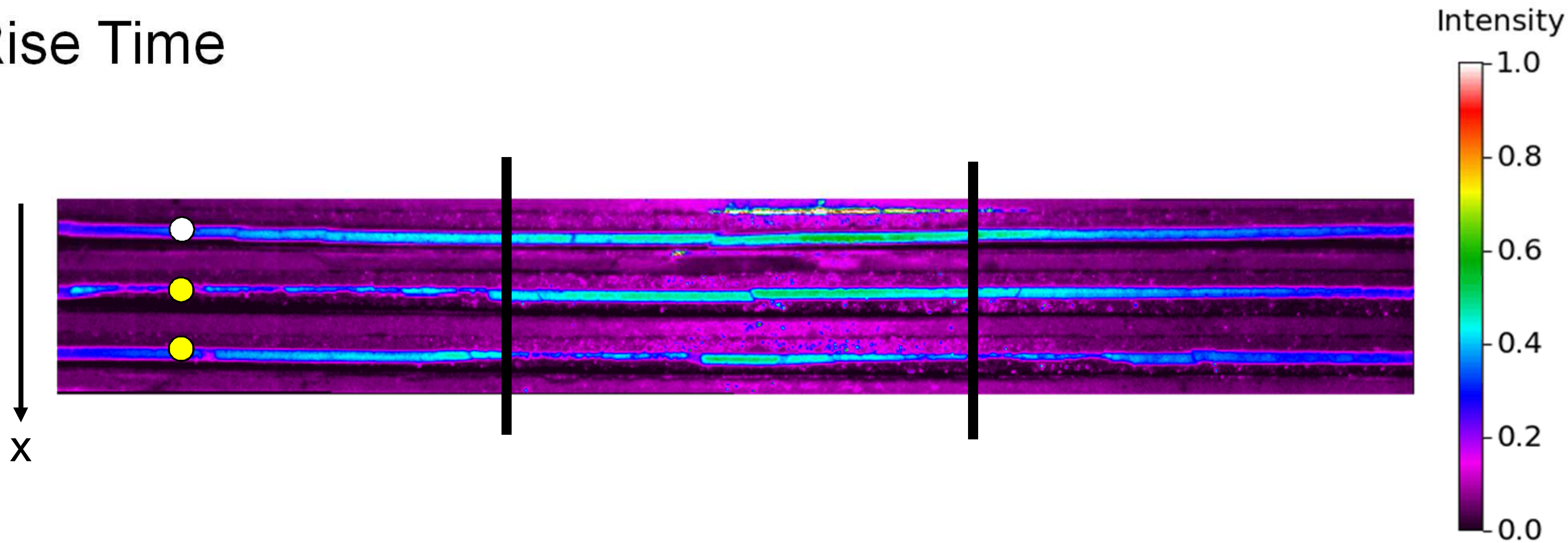
Slide 30

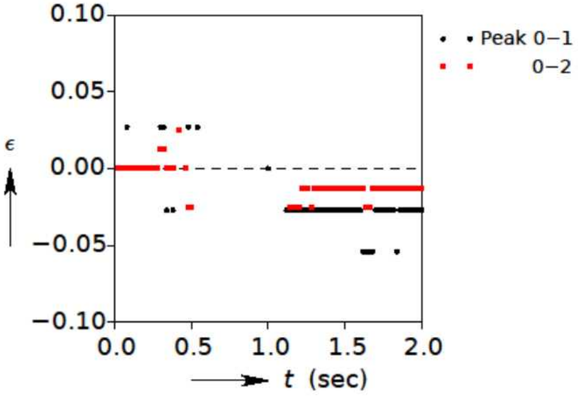
JA8 Intervals 1 and 2 don't have much data for peak 2 because it disappeared.
Jang, Amy, 8/3/2015

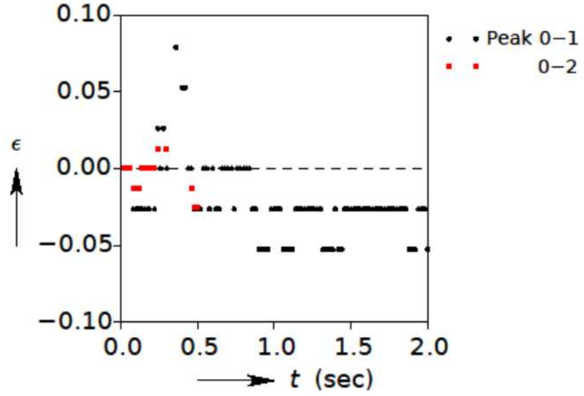
JA9

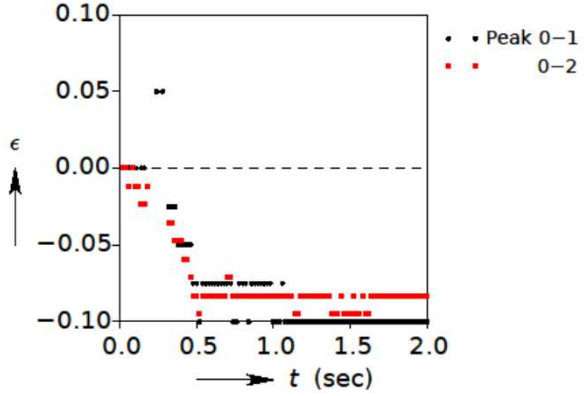
Strain vs. Time

Rise Time









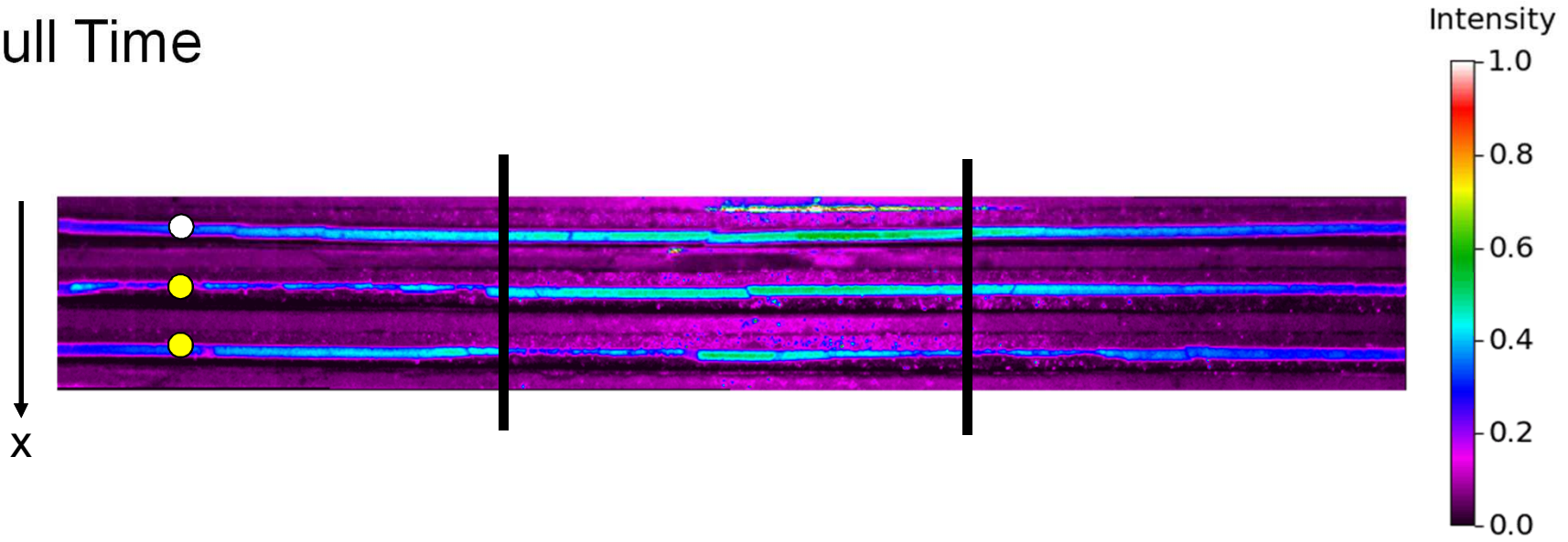
Slide 31

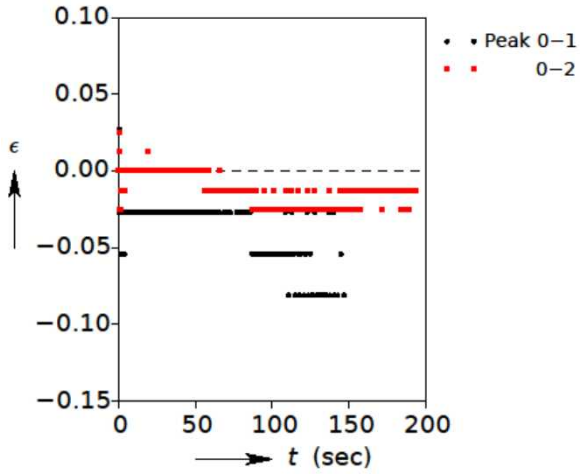
JA9 Interval 1, peak 0-1 has positive strain because the flame is being picked up.
Jang, Amy, 8/3/2015

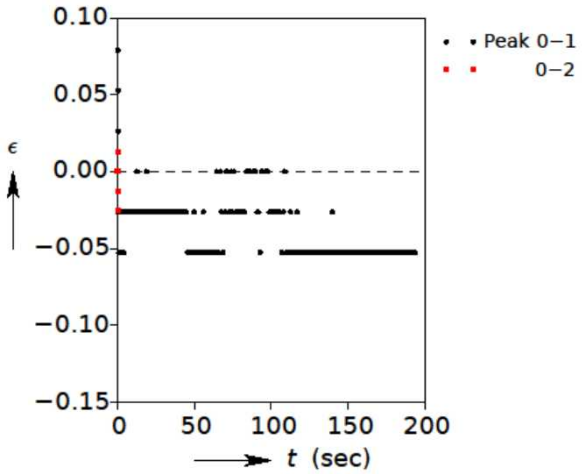
Strain vs. Time

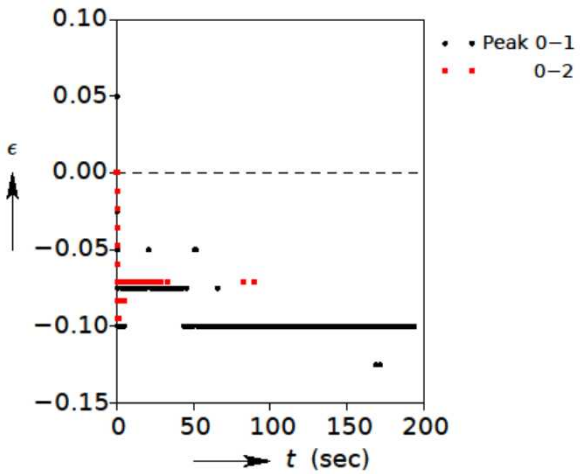
Full Time

Sandia National Laboratories









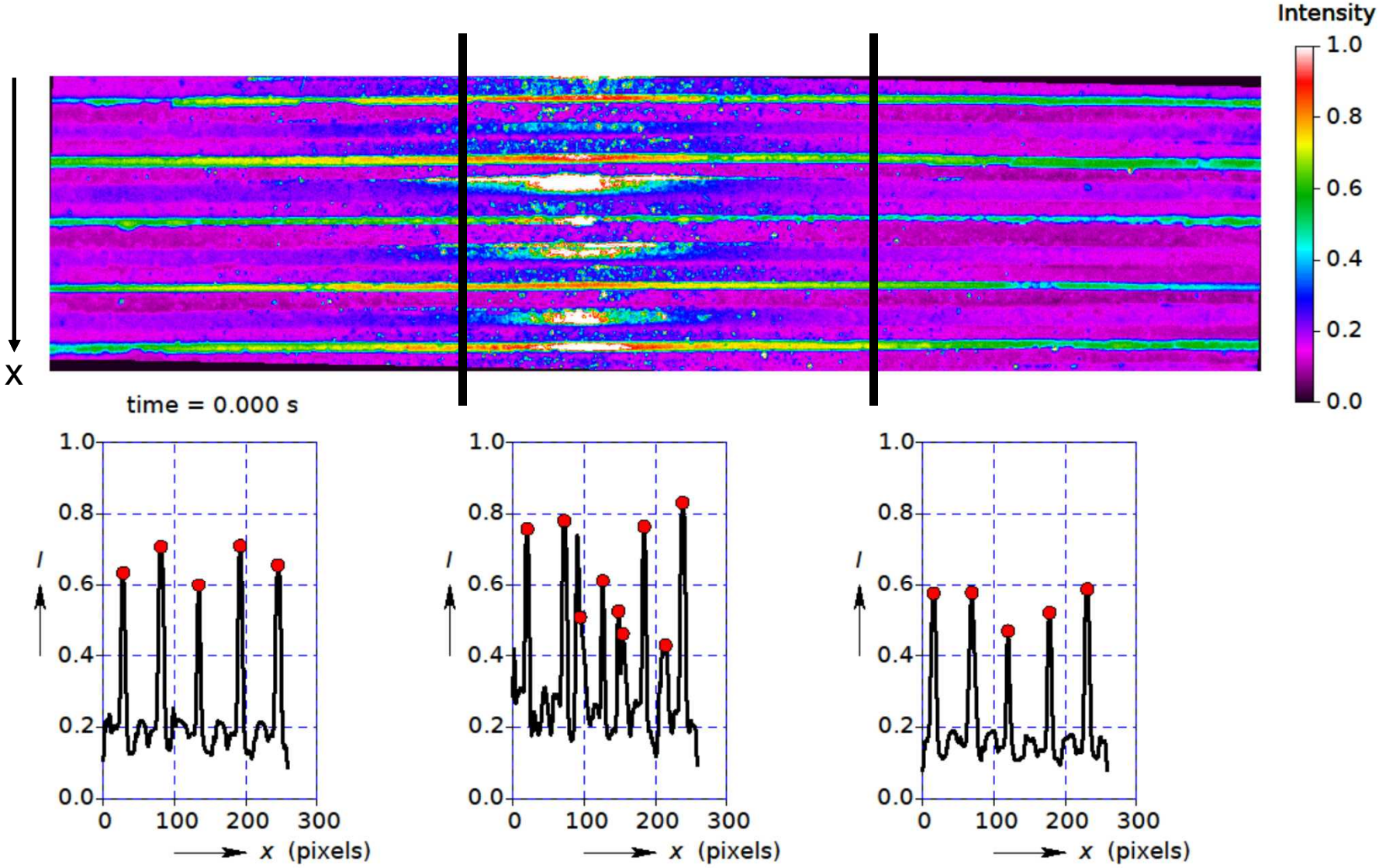
Slide 32

JA10 Interval 0 has no data for peak 0-1 around 150s-end because pretty much can't detect peak 1.
Jang, Amy, 8/3/2015

5 Cell MinK

9_16_5Cell_MinK_2

0th Frame Image with Intensity Plots

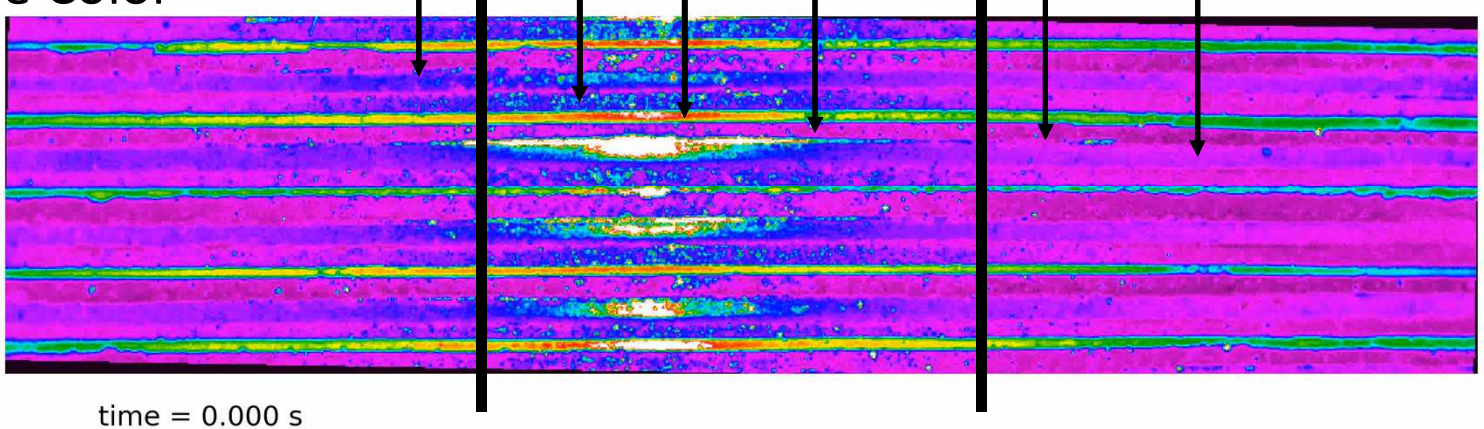


Averaged Intensity vs. Axial Position Video

Sandia National Laboratories

Battery Stack in False Color

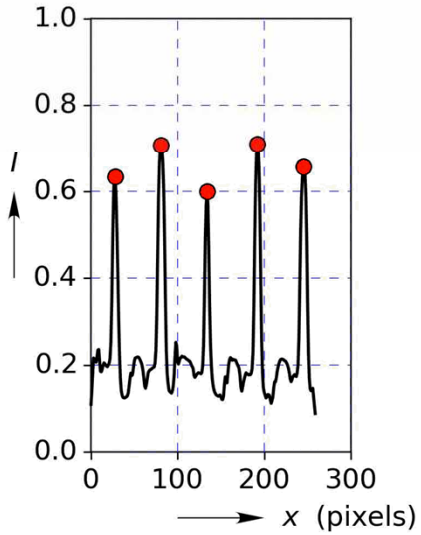
Layers:
Heat Pellet, Cathode, Separator, Anode, Current Collector, Heat Pellet

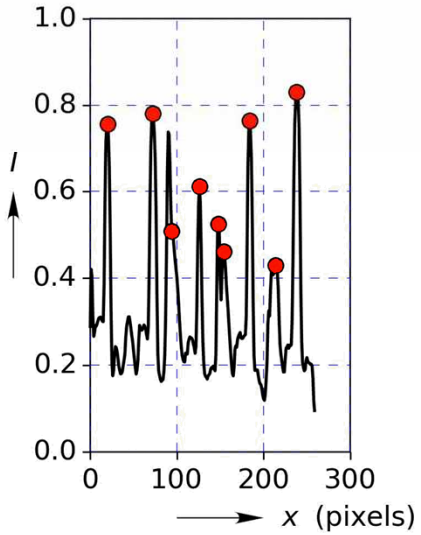


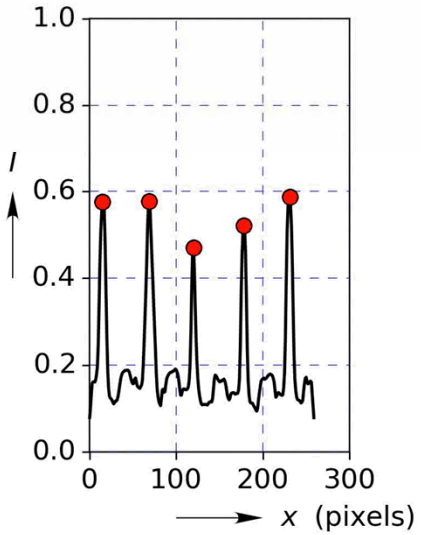
Intensity
1.0
0.8
0.6
0.4
0.2
0.0

x

time = 0.000 s





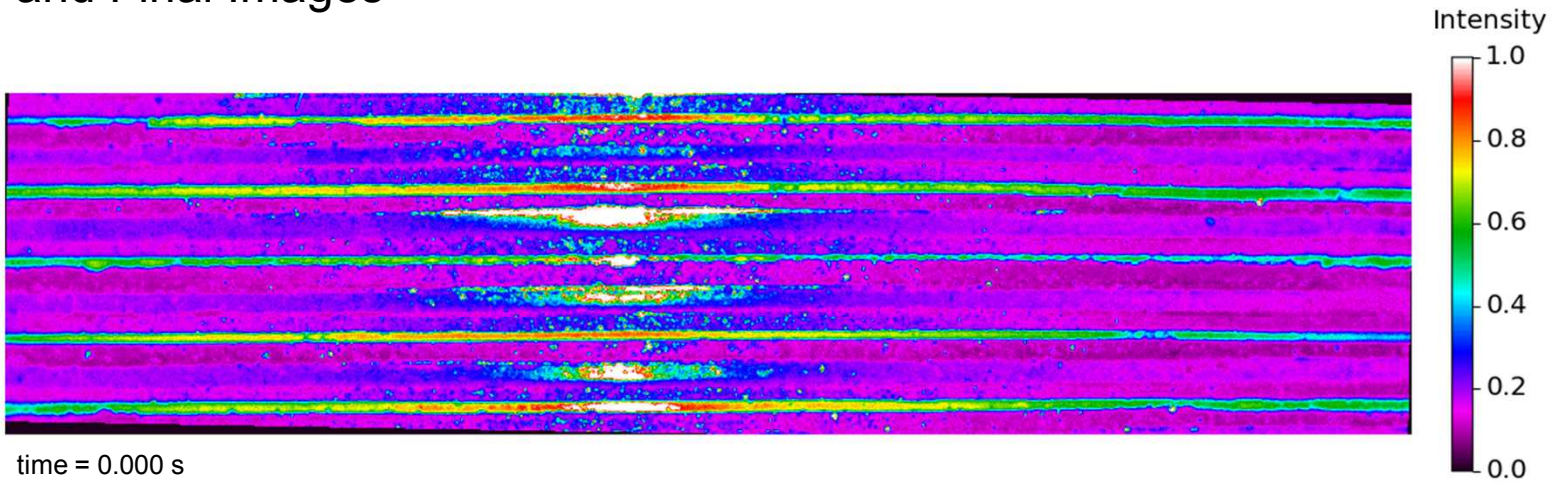


Row-Averaged Intensity Averaged Along the Stack Axis

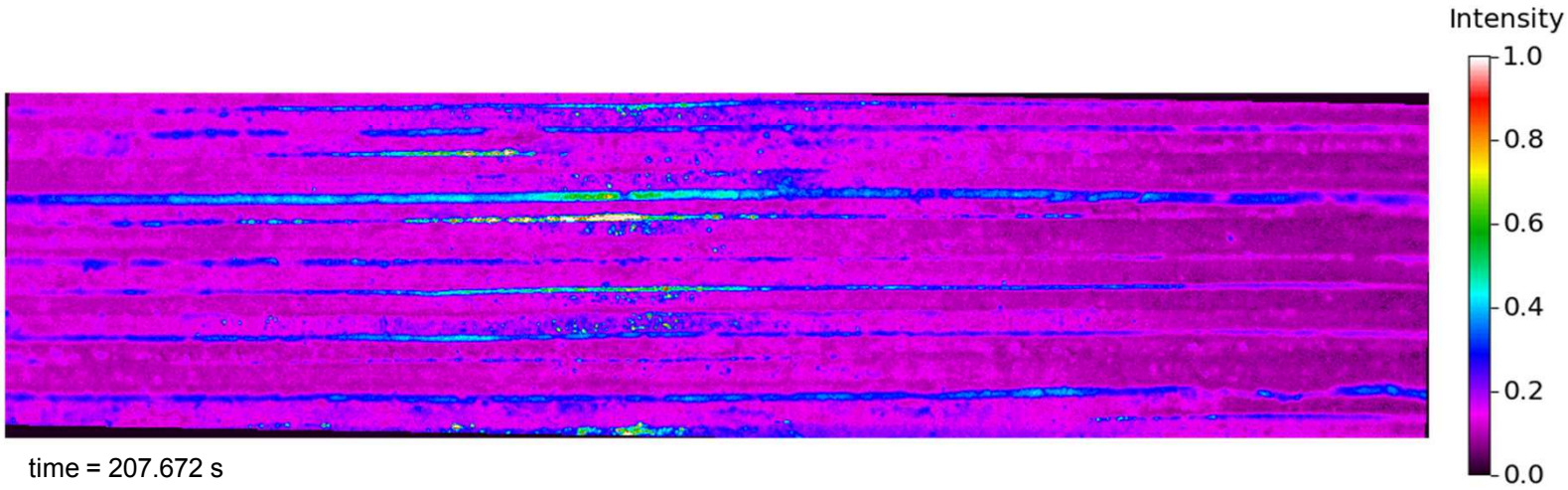
Displacement vs. Time

Sandia National Laboratories

Initial and Final Images



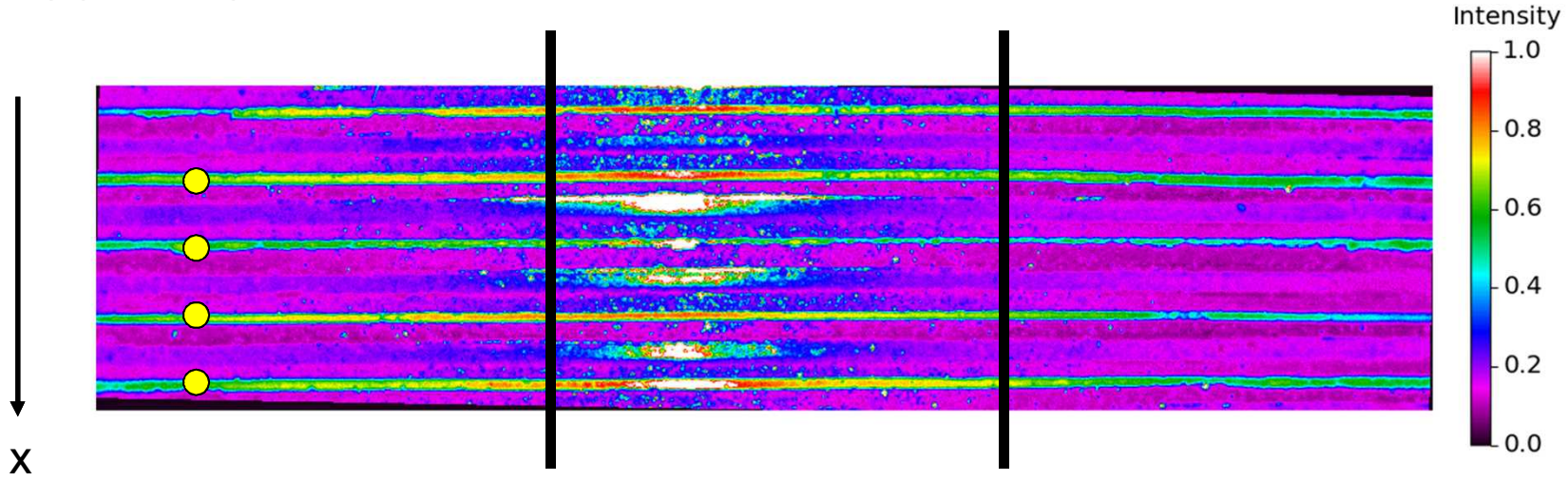
time = 0.000 s

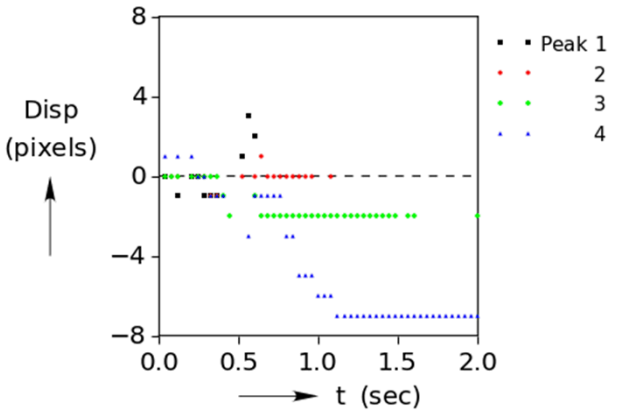


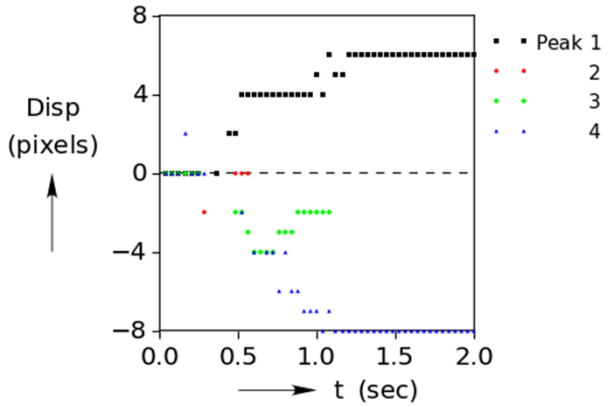
time = 207.672 s

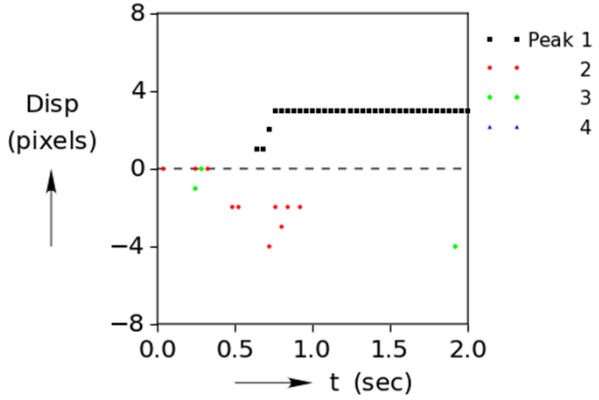
Displacement vs. Time

Rise Time



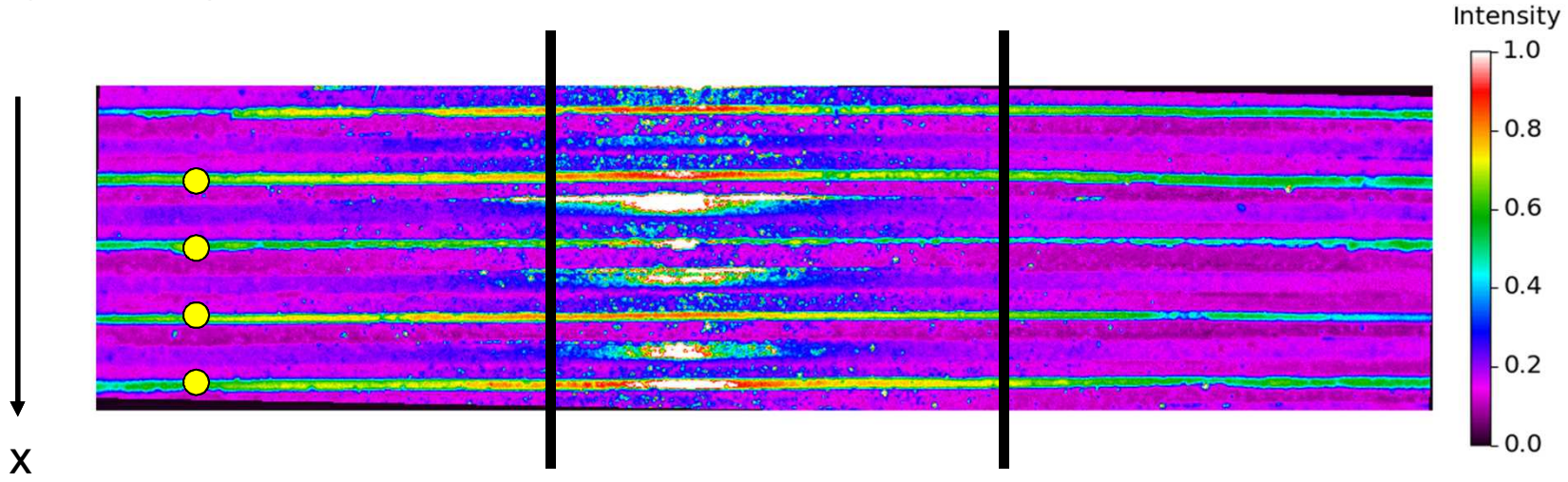


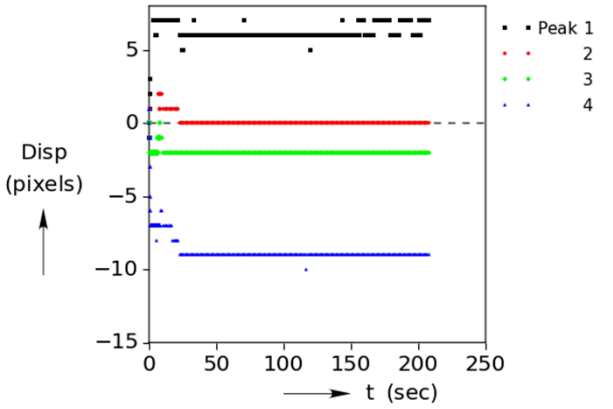


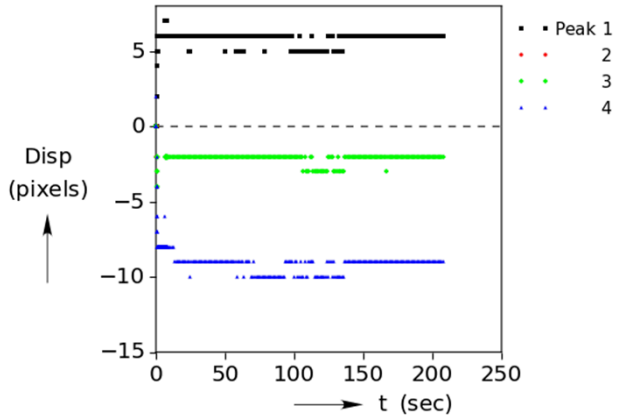


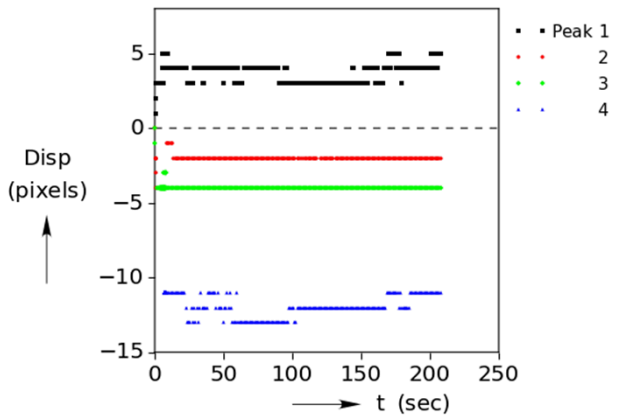
Displacement vs. Time

Full Time





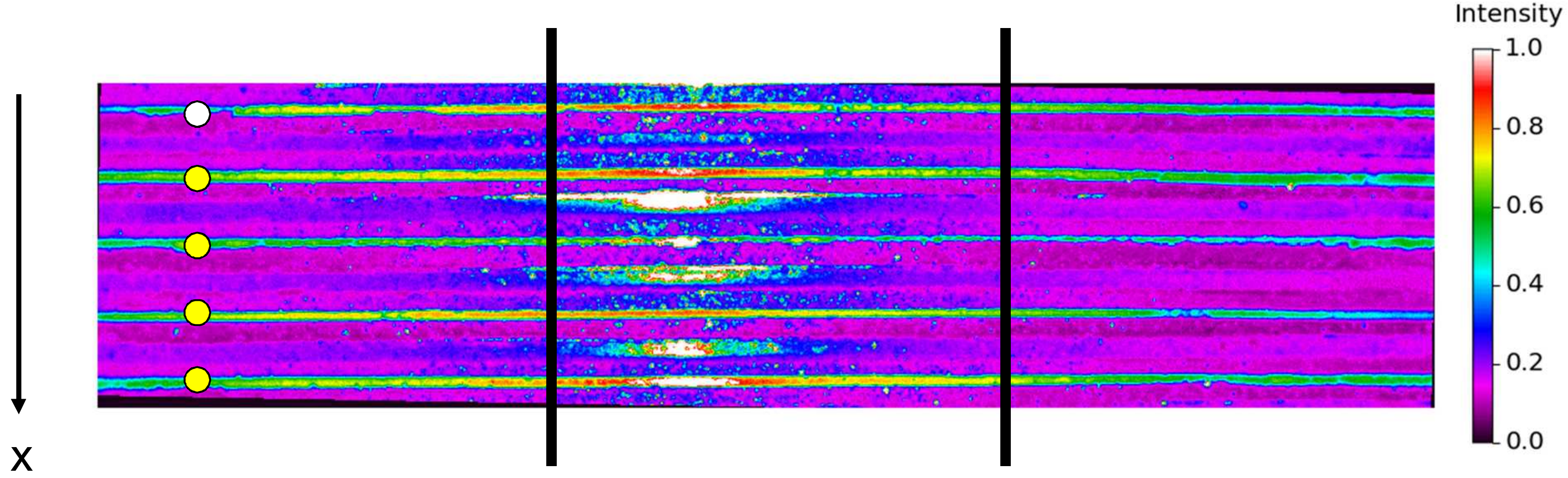


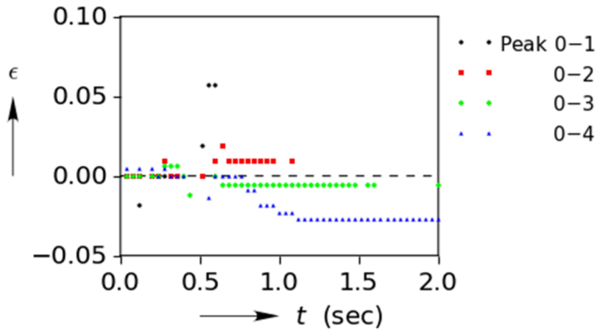


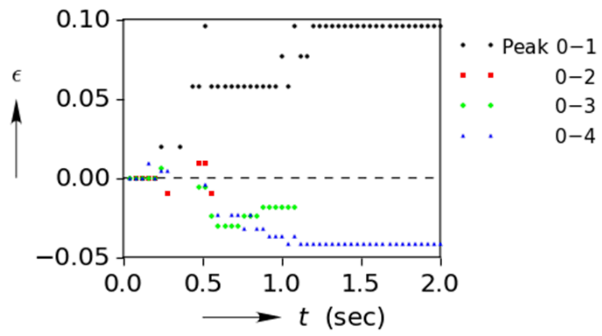
Strain vs. Time

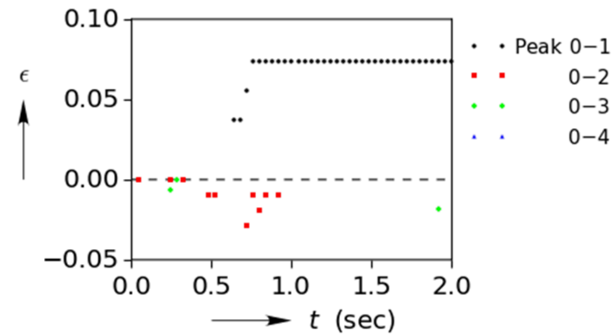
Sandia National Laboratories

Rise Time







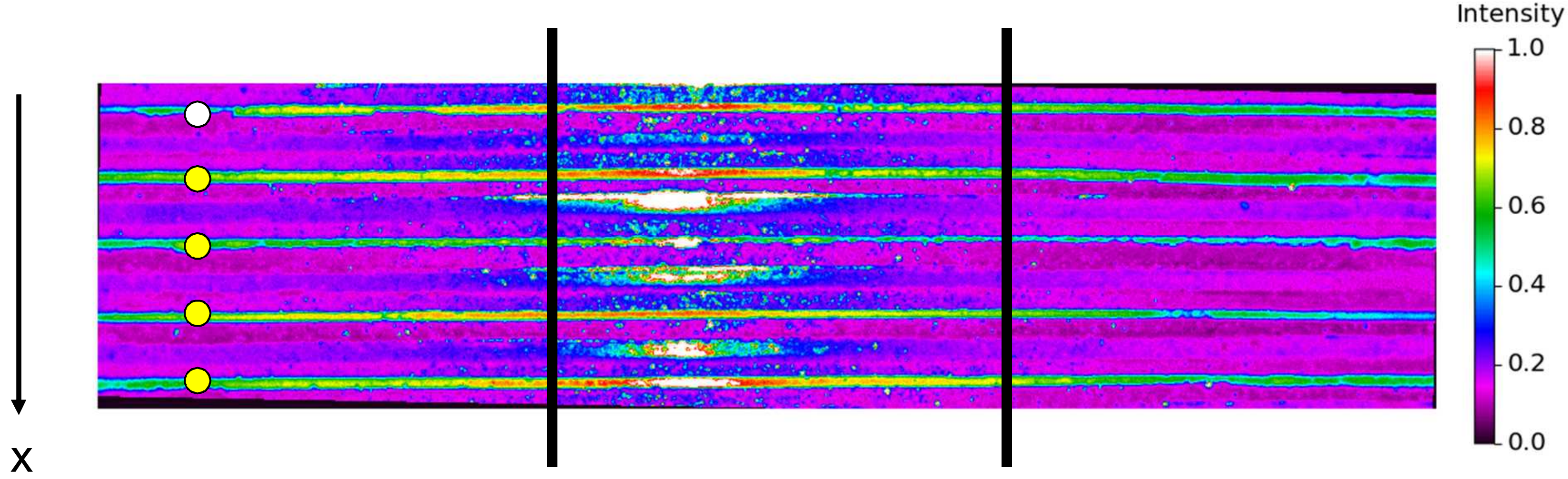


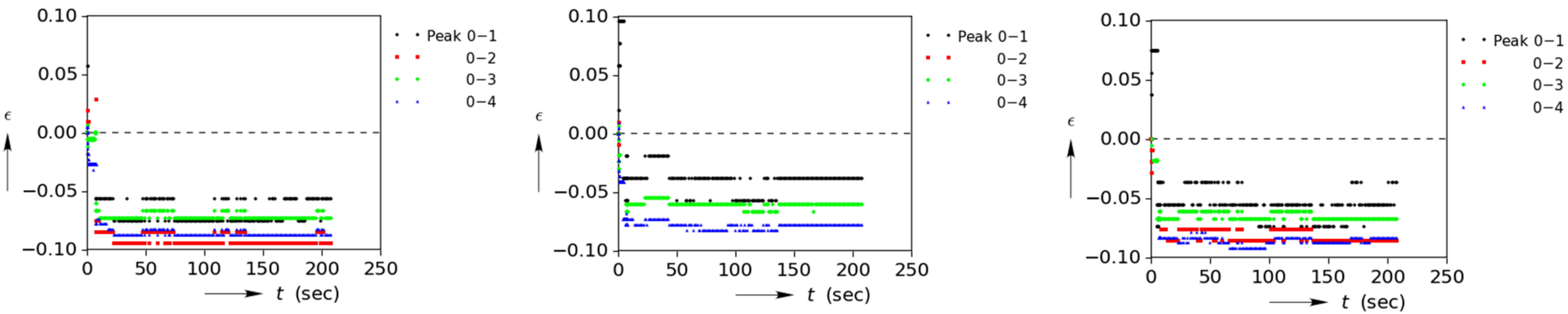
Slide 39

JA2 I cutoff outliers in interval 0 for the strain rise and full time plots. Peak 0-1 had strain approximately equal to 0.15 because the flame was being picked up.
Jang, Amy, 8/3/2015

Strain vs. Time

Full Time

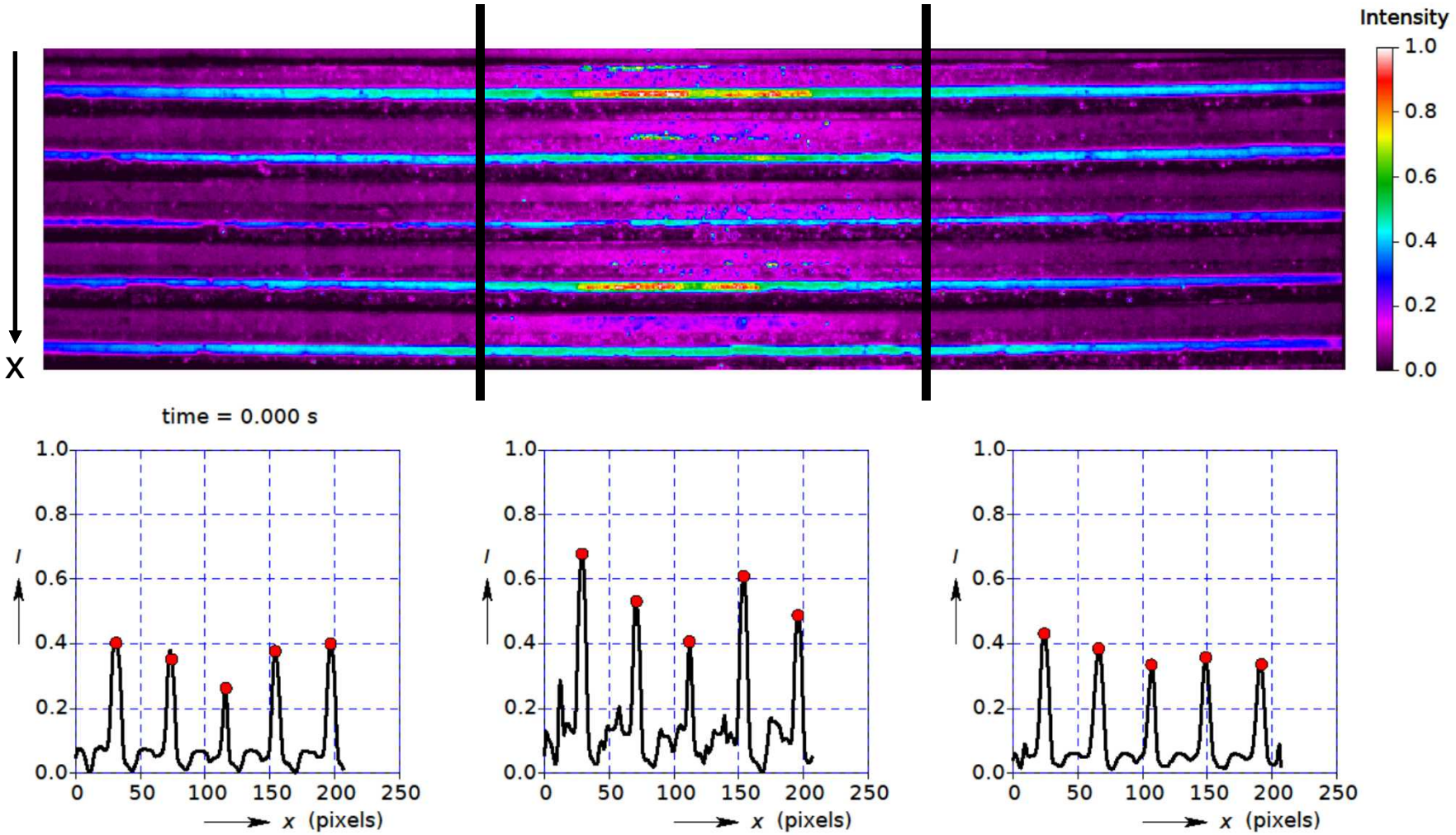




5 Cell FF

9_18_5Cell_FF_2

0th Frame Image with Intensity Plots

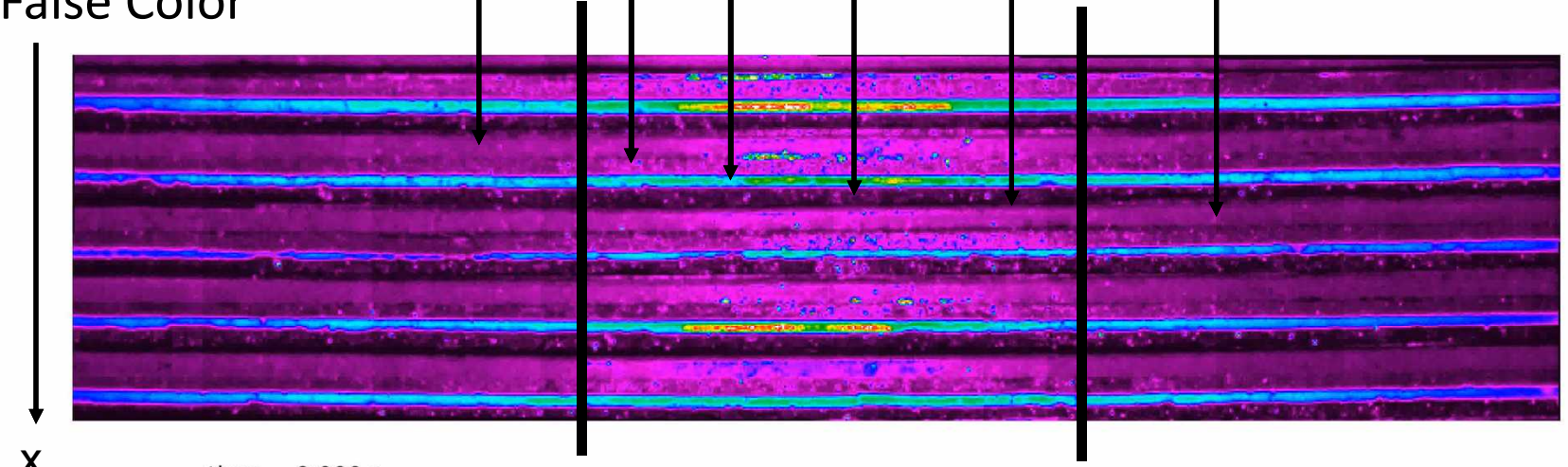


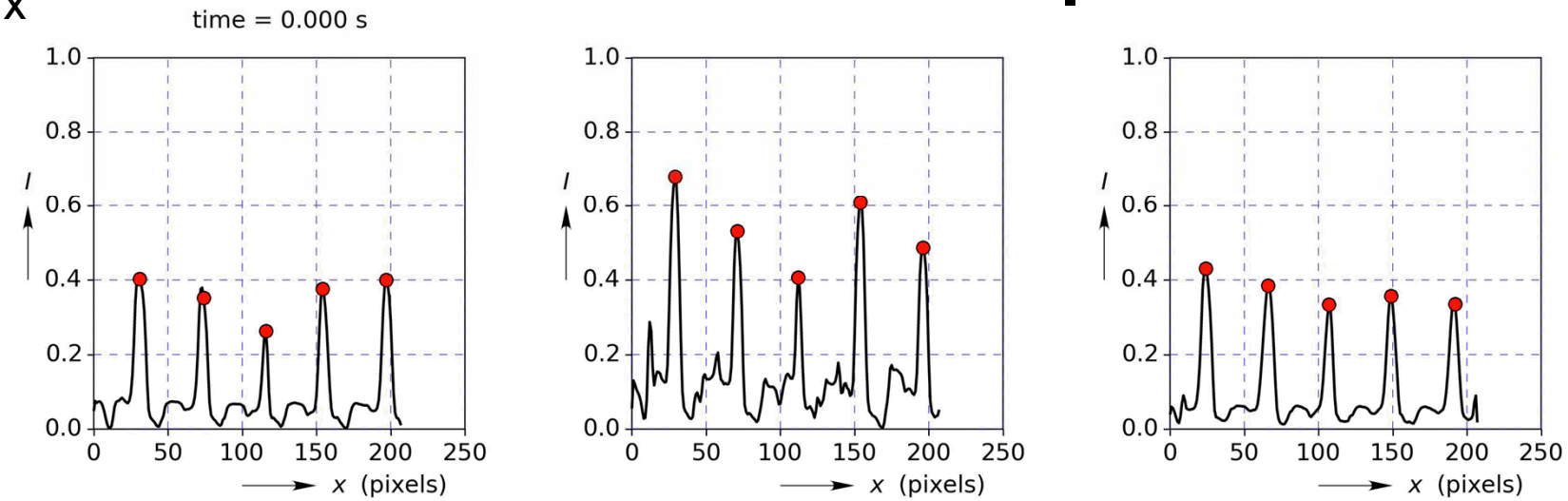
Averaged Intensity vs. Axial Position Video

Sandia National Laboratories

Battery Stack in False Color

Layers:
Heat Pellet, Cathode, Separator, Anode, Current Collector, Heat Pellet



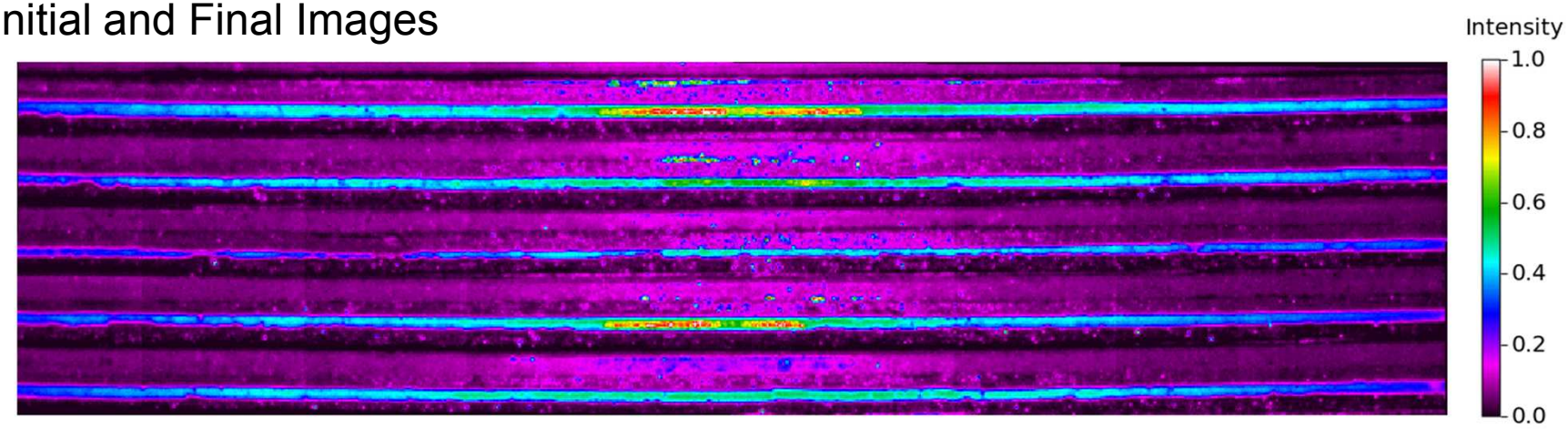


Row-Averaged Intensity Averaged Along the Stack Axis

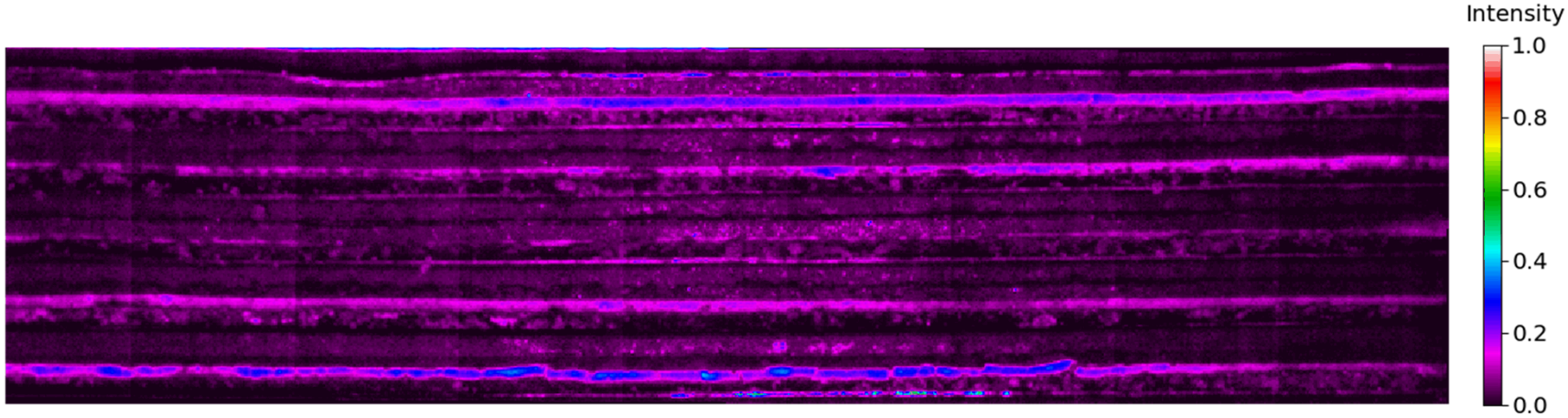
Displacement vs. Time

Sandia National Laboratories

Initial and Final Images



time = 0.000 s

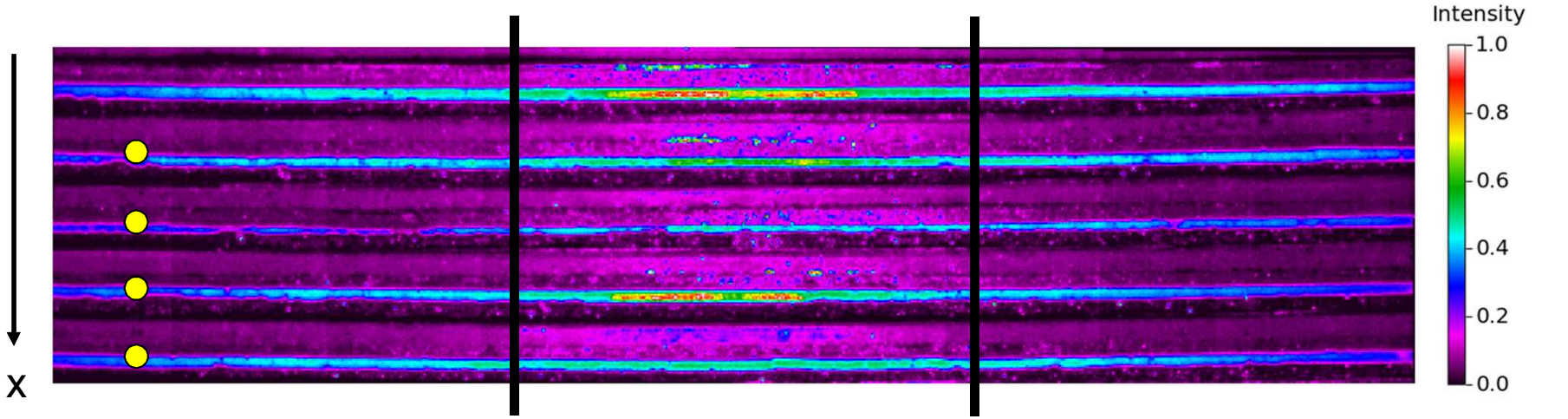


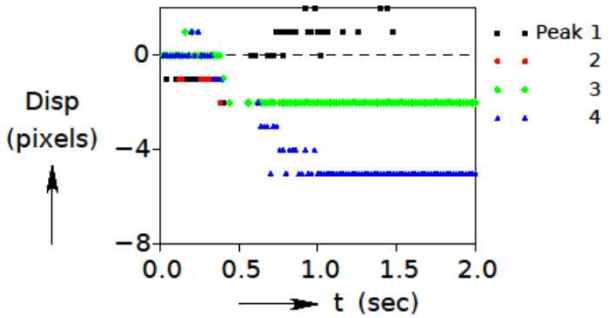
time = 155.804 s

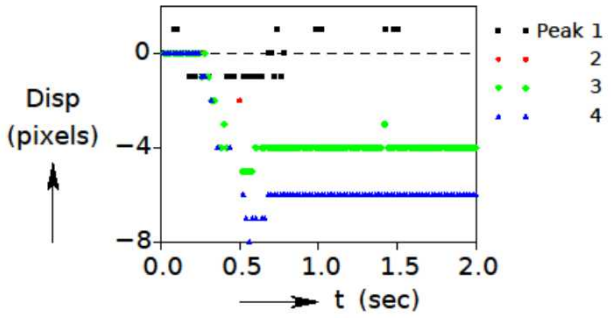
Displacement vs. Time

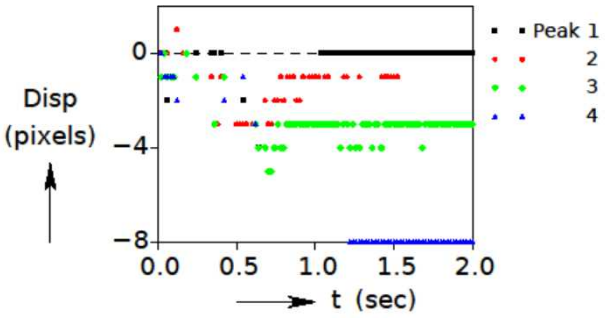
Sandia National Laboratories

Rise Time







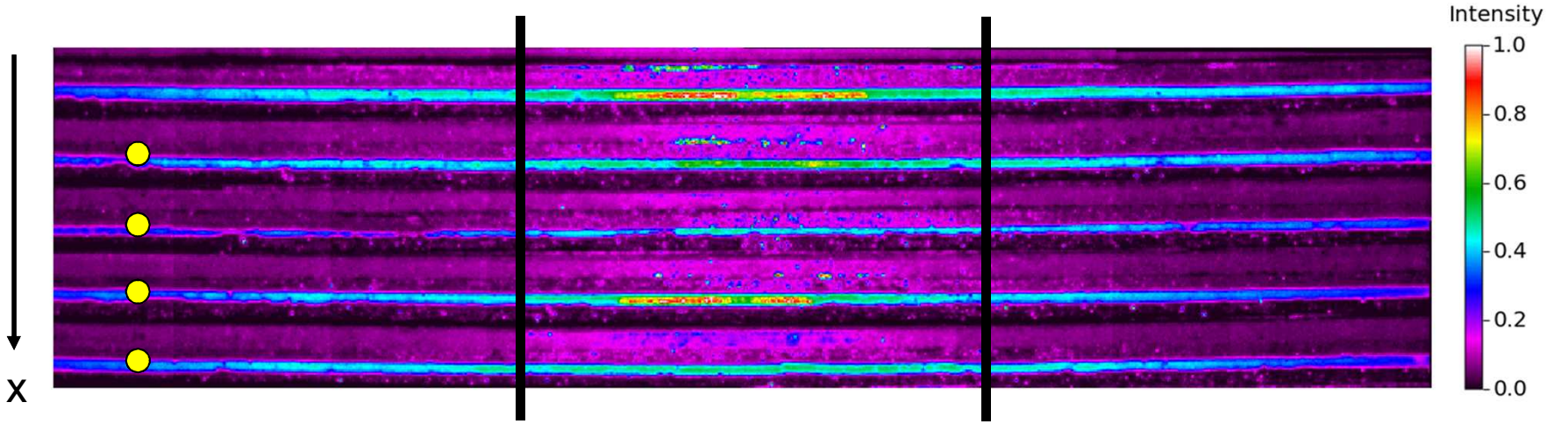


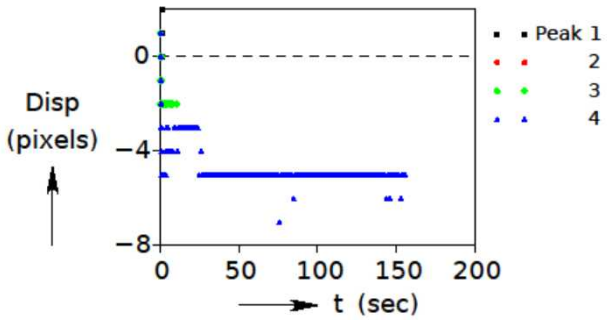
Slide 45

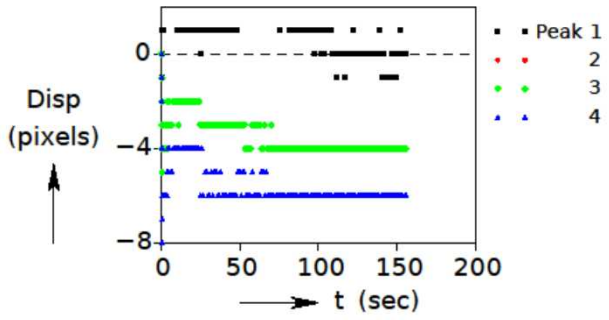
JA17 Data looks weird. But I checked the data, and the correct peaks were being selected.
Jang, Amy, 8/5/2015

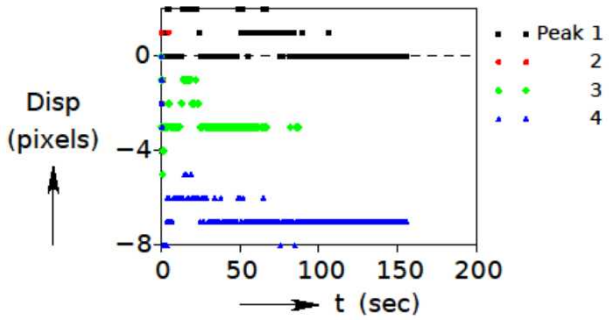
Displacement vs. Time

Full Time









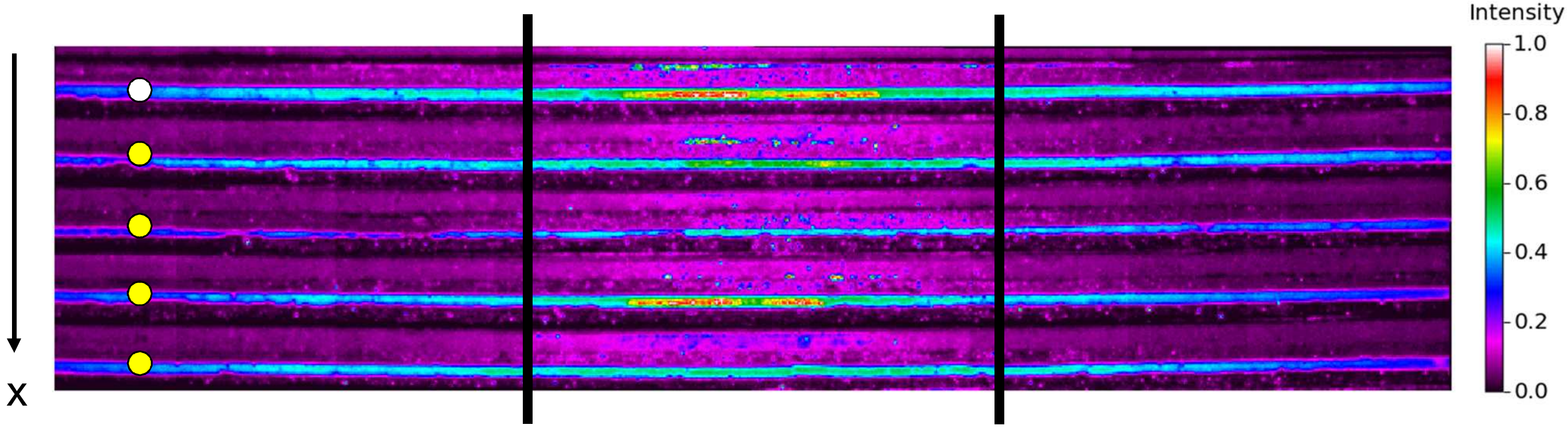
Slide 46

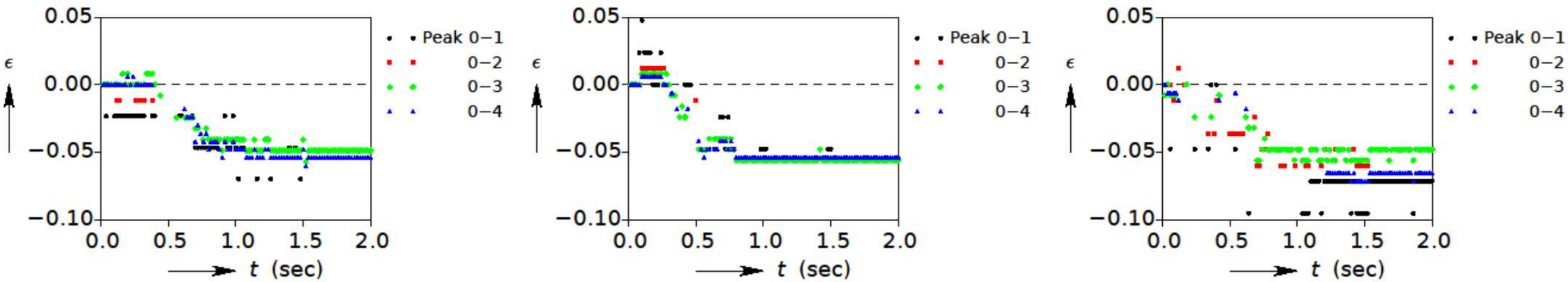
JA18 Data looks weird. But I checked the data, and the correct peaks were being selected.
Jang, Amy, 8/5/2015

JA4

Strain vs. Time

Rise Time



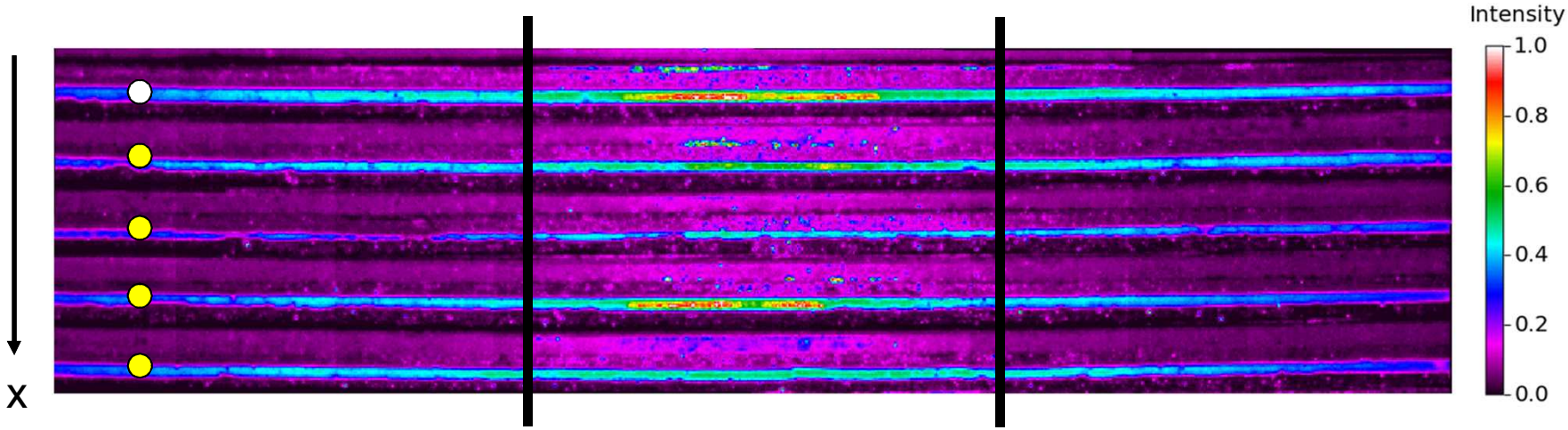


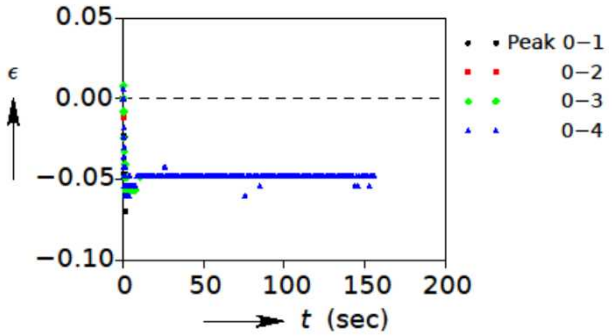
Slide 47

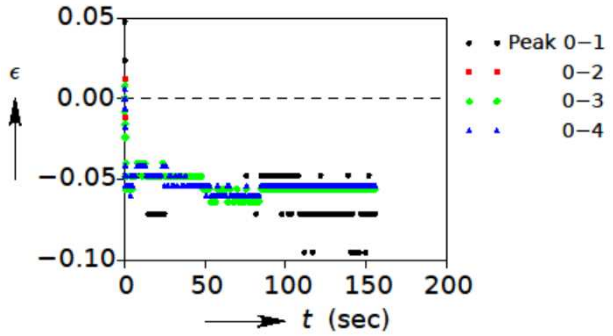
JA4 Interval 1 has a high positive strain for peak 0-1 approximately equal to 0.05 because small inital distance -> large strain.
Jang, Amy, 8/3/2015

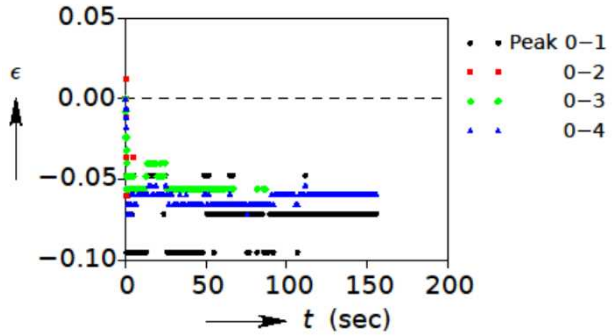
Strain vs. Time

Full Time









Slide 48

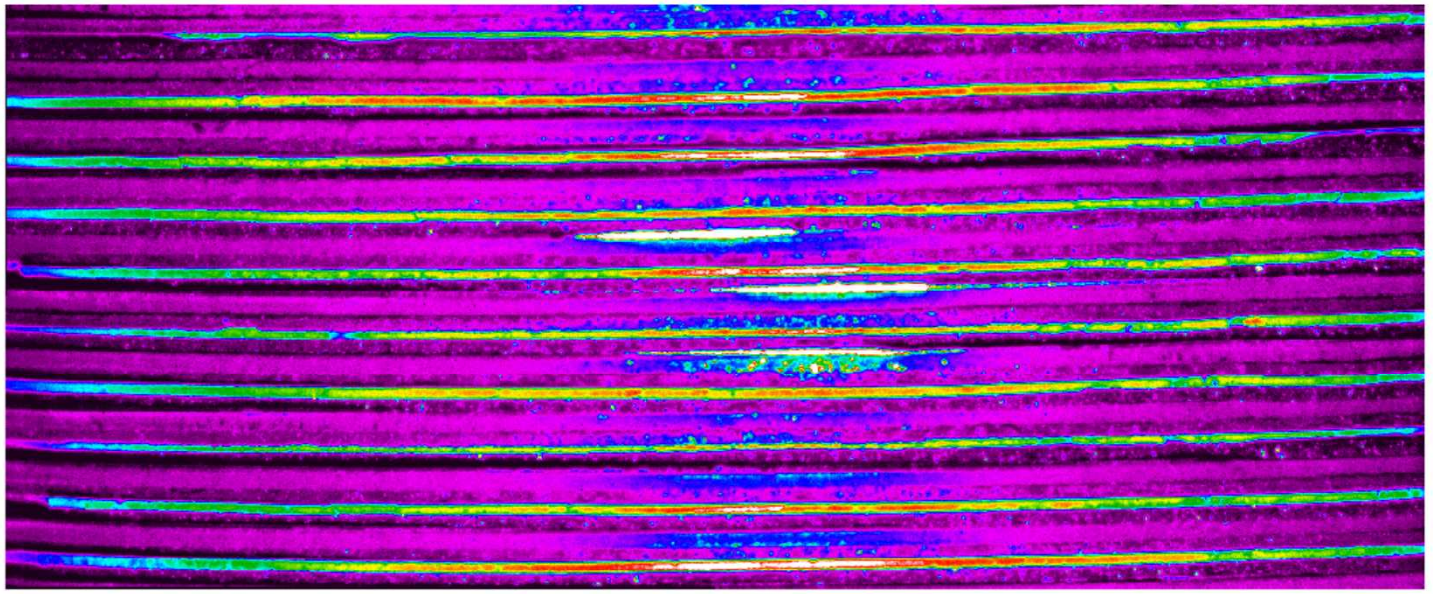
JA3 Missing data for peak 0-1, 0-2, and 0-3 in interval 0 and peak 0-2 for intervals 1 and 2. This agrees with the video: those peaks were difficult to detect.

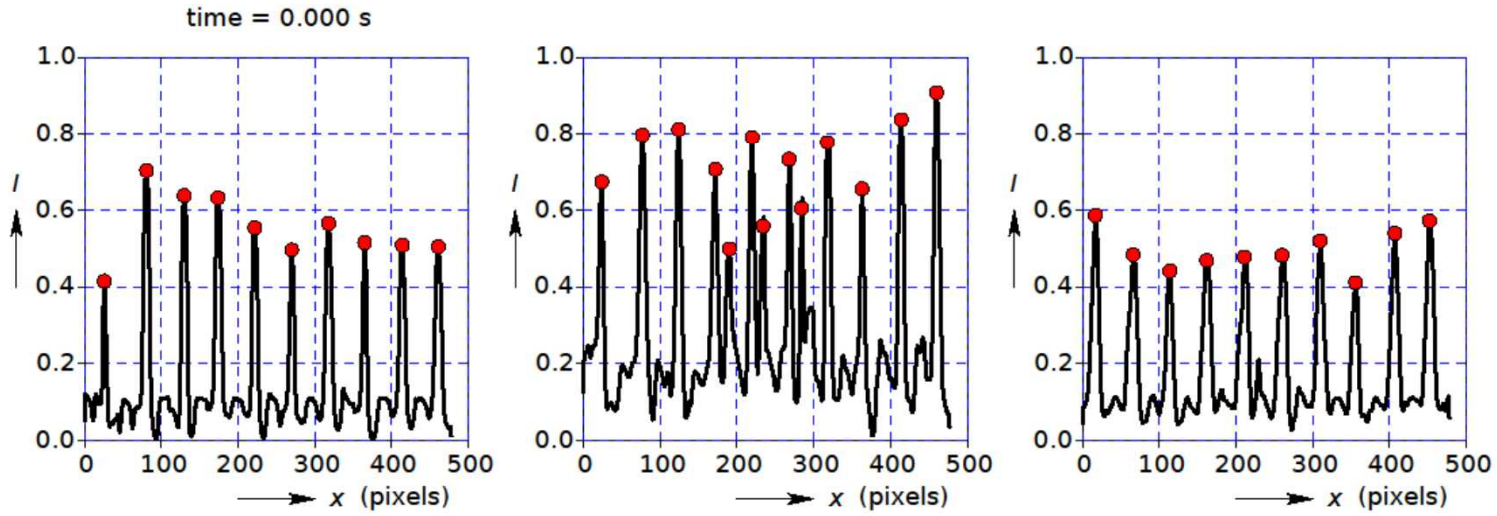
Jang, Amy, 8/3/2015

10 Cell Mink Insulated Battery

9_17_10Cell_MinK_4

0th Frame Image with Intensity Plots

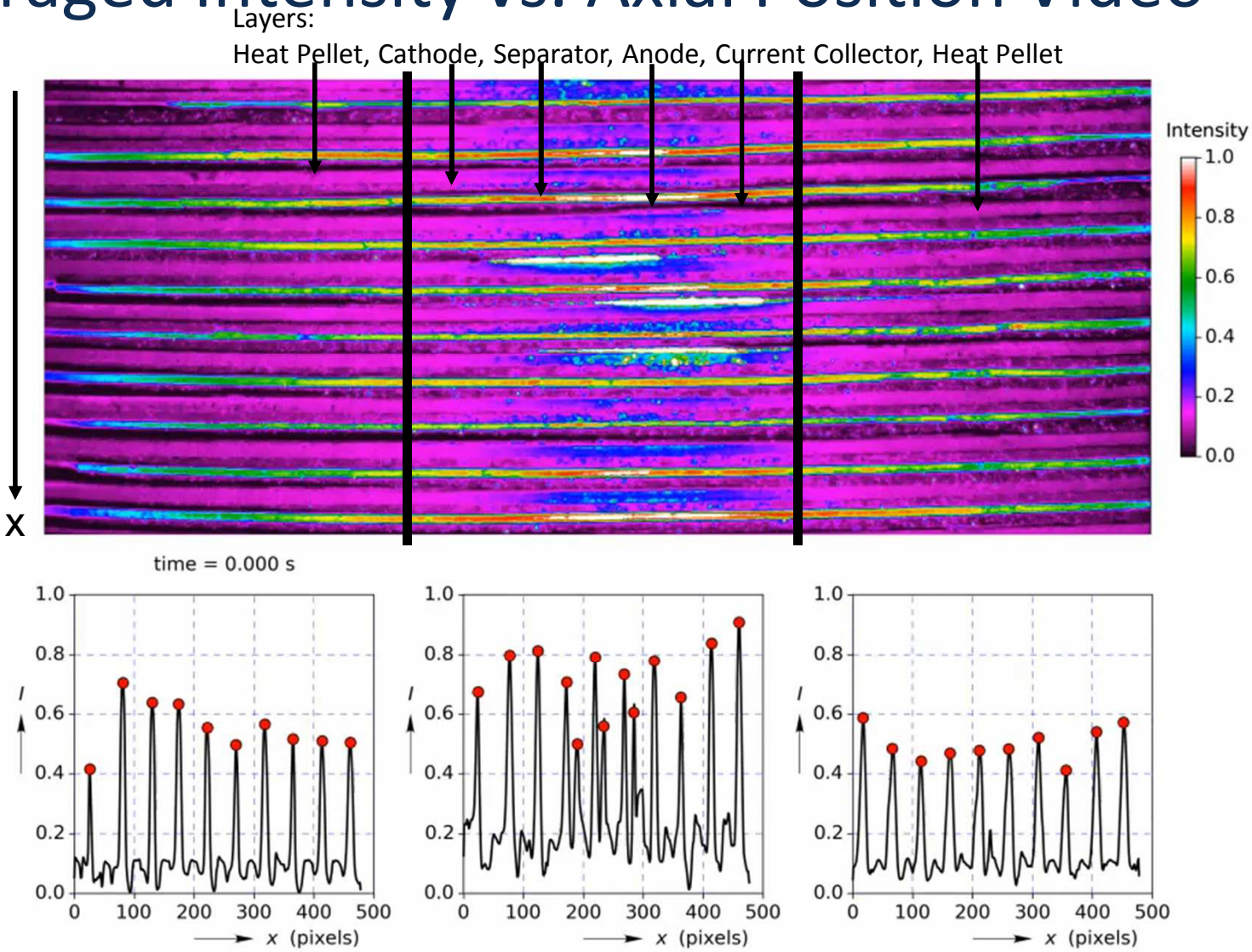




Averaged Intensity vs. Axial Position Video

Sandia National Laboratories

Battery Stack in False Color

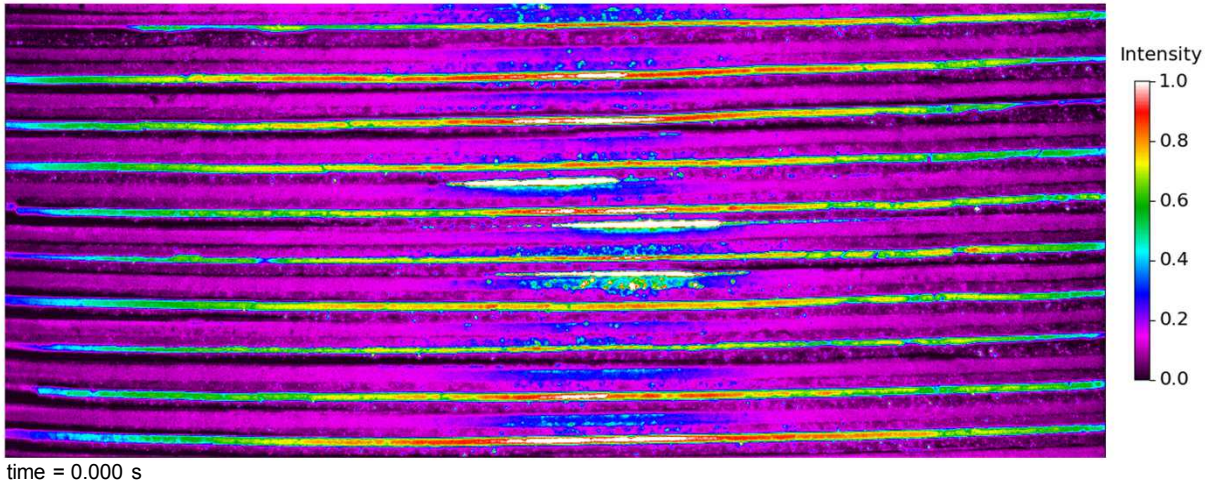


Row-Averaged Intensity Averaged Along the Stack Axis

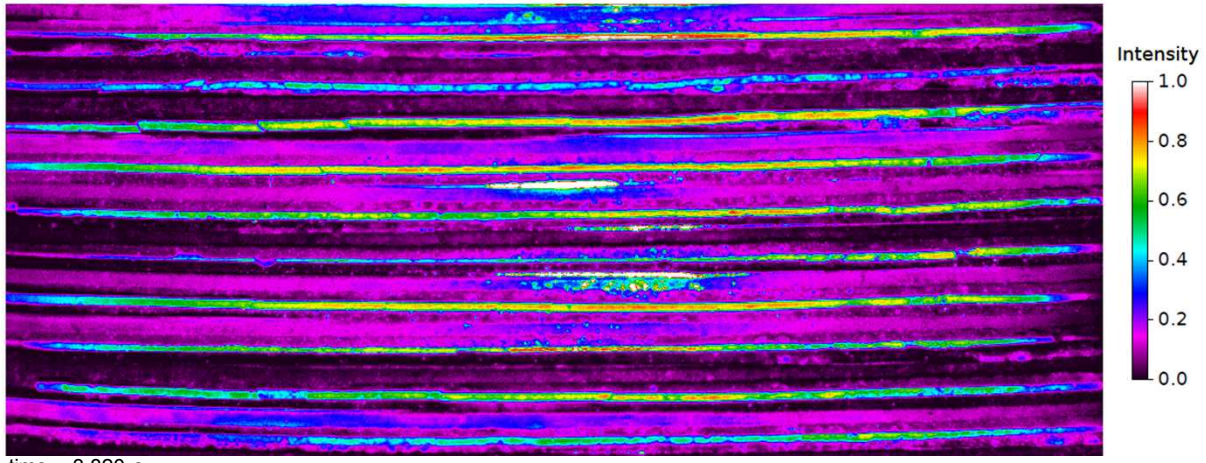
Displacement vs. Time

Sandia National Laboratories

Initial and Final Images



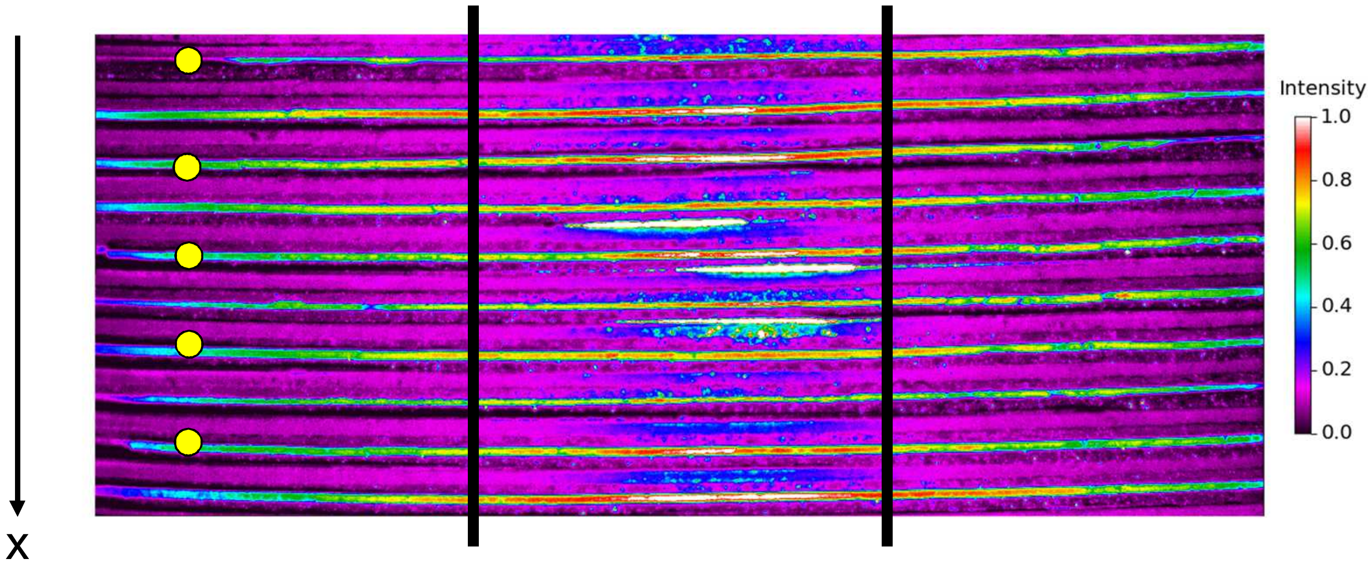
time = 0.000 s

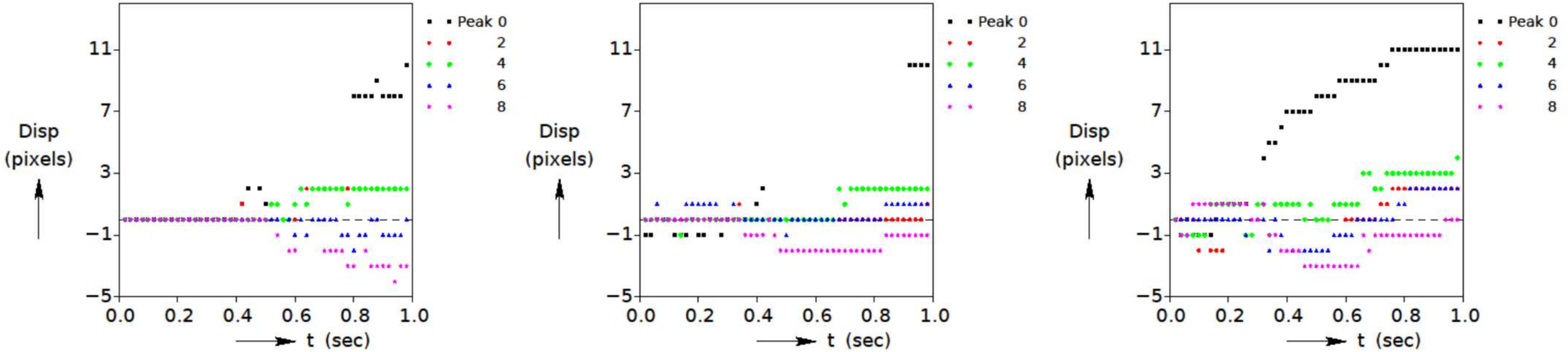


time = 3.820 s

Displacement vs. Time Plots

Rise Time



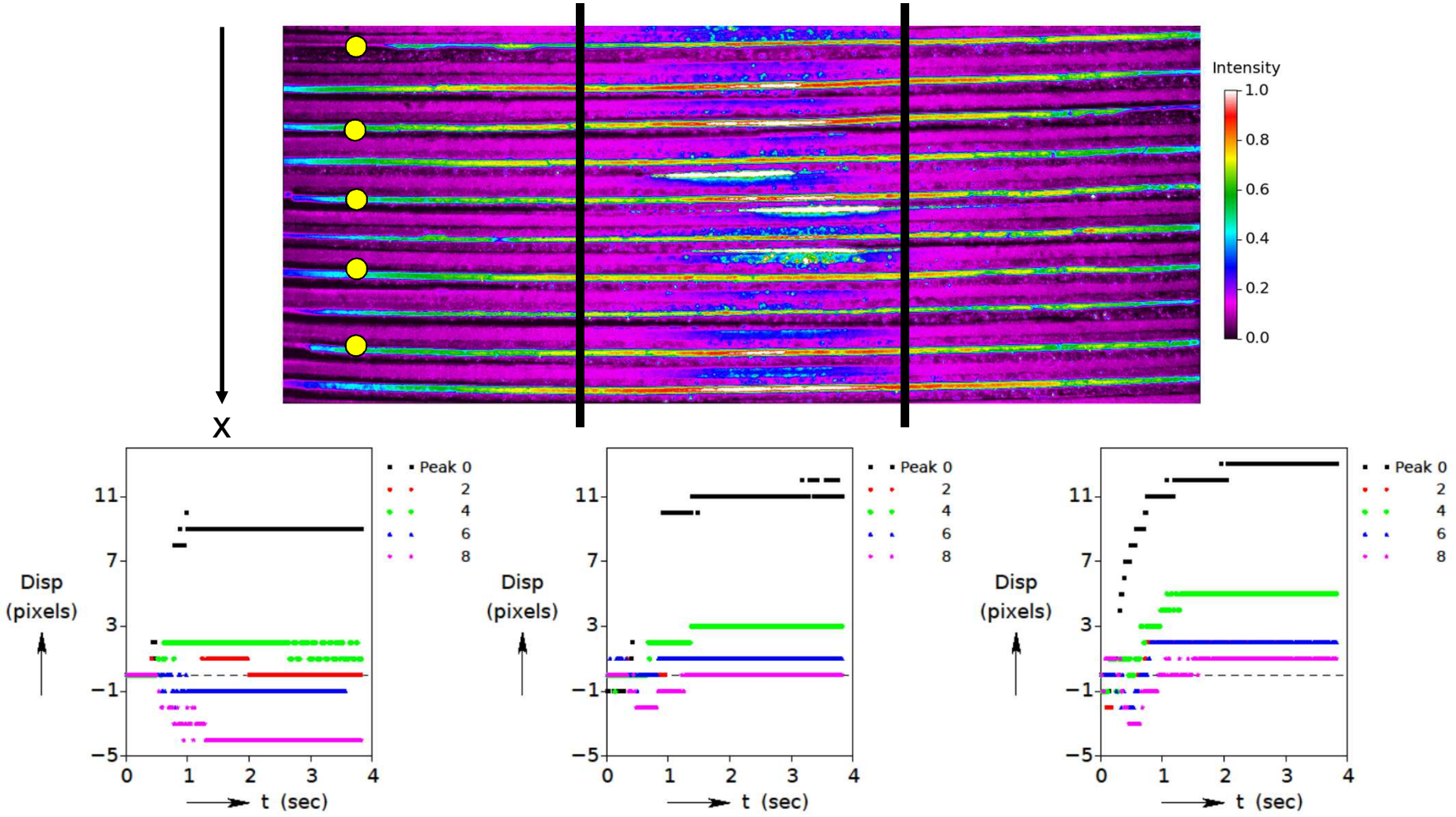


Slide 53

JA15 Missing data for peak 0 in intervals 0 and 1 because it could not be detected.
Jang, Amy, 8/3/2015

Displacement vs. Time Plots

Full Time

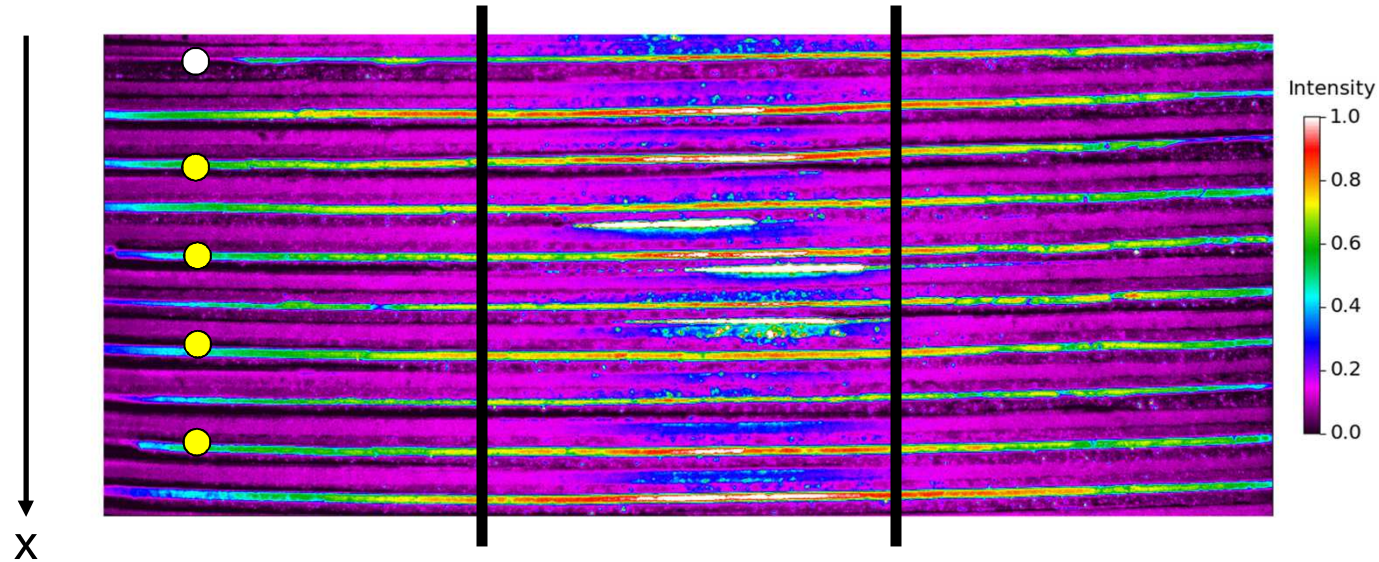


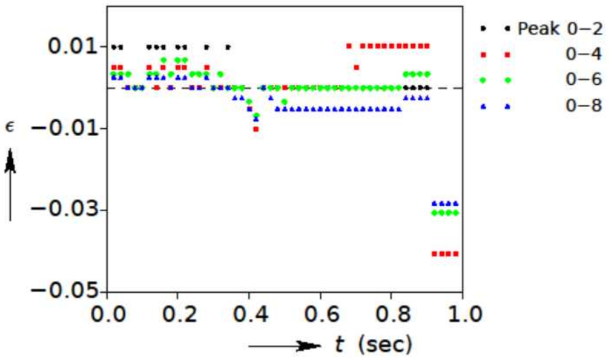
Slide 54

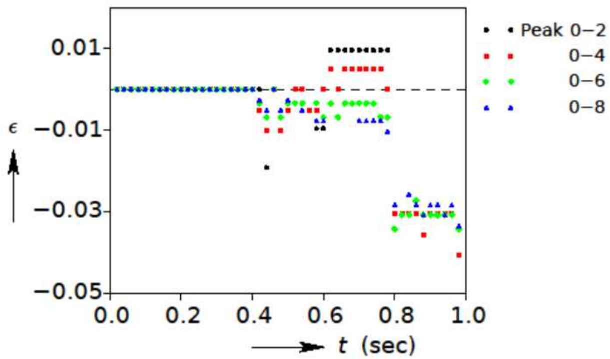
JA14 Missing data for peak 0 in intervals 0 and 1 because it could not be detected.
Jang, Amy, 8/3/2015

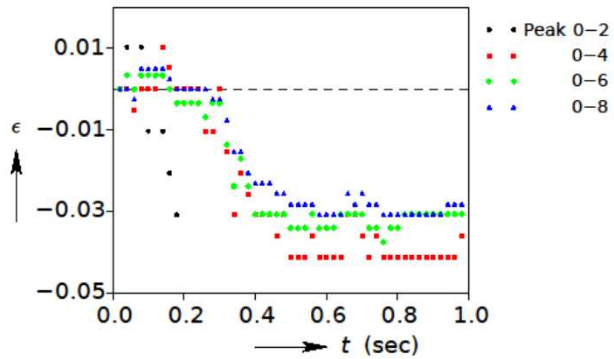
Strain vs. Time Plots

Rise Time







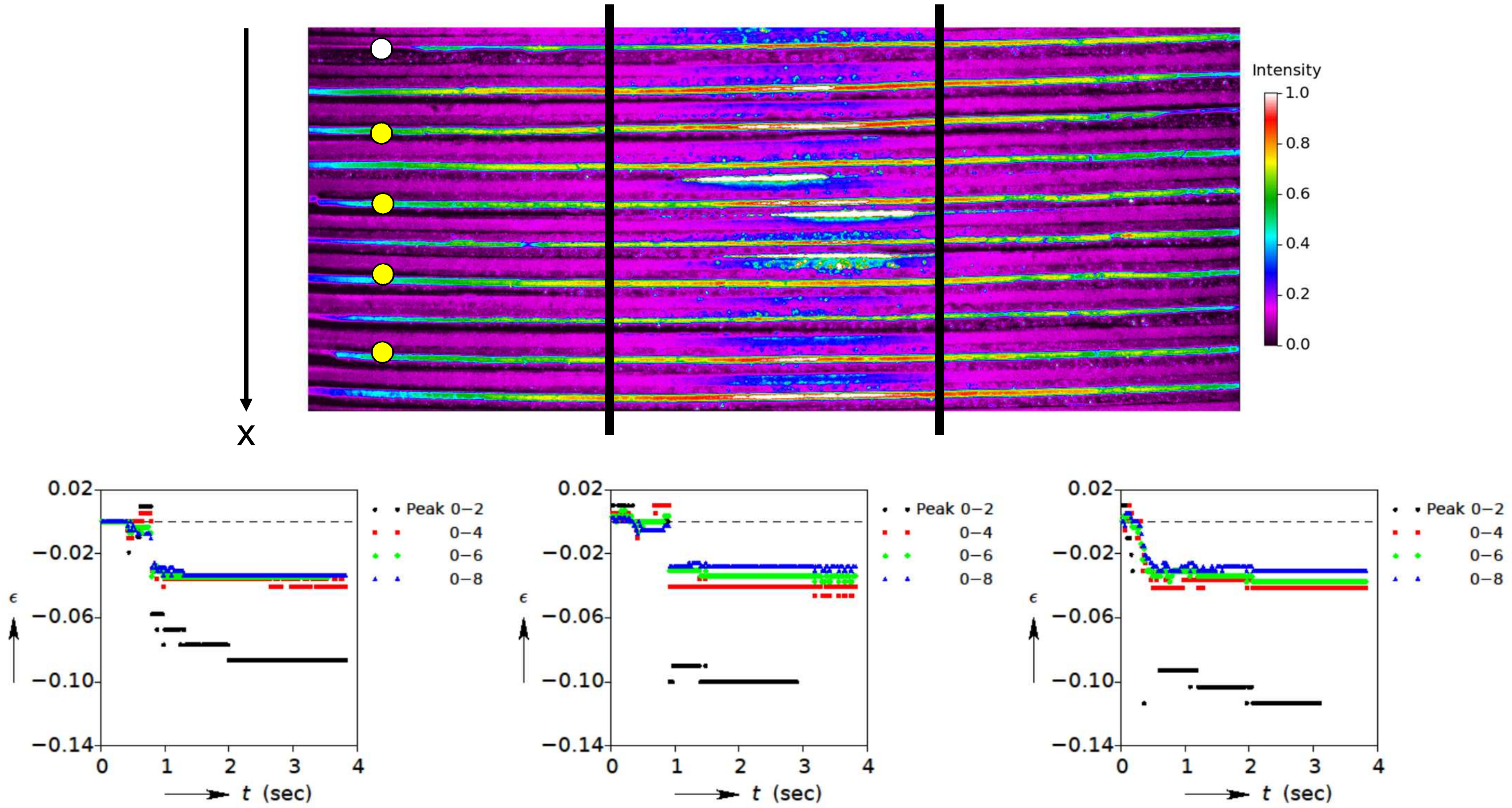


Slide 55

JA13 Look at notes for explanation for why intervals 0 and 1 do not show the expected curve like interval 2.
Jang, Amy, 8/3/2015

Strain vs. Time Plots

Full Time

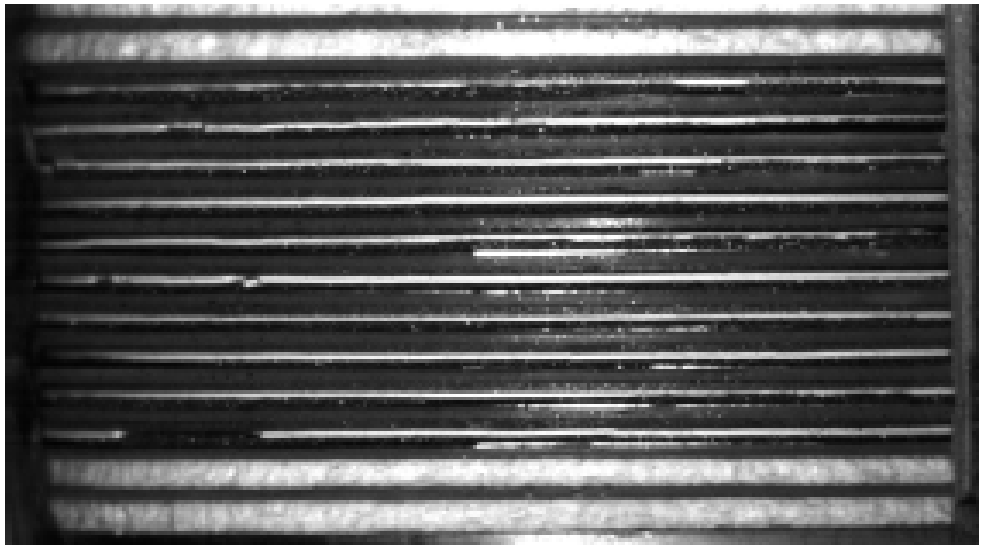


Slide 56

JA12 Look at notes for this slide for explanation for why there is a jump in data for intervals 0 and 1.
Jang, Amy, 8/3/2015

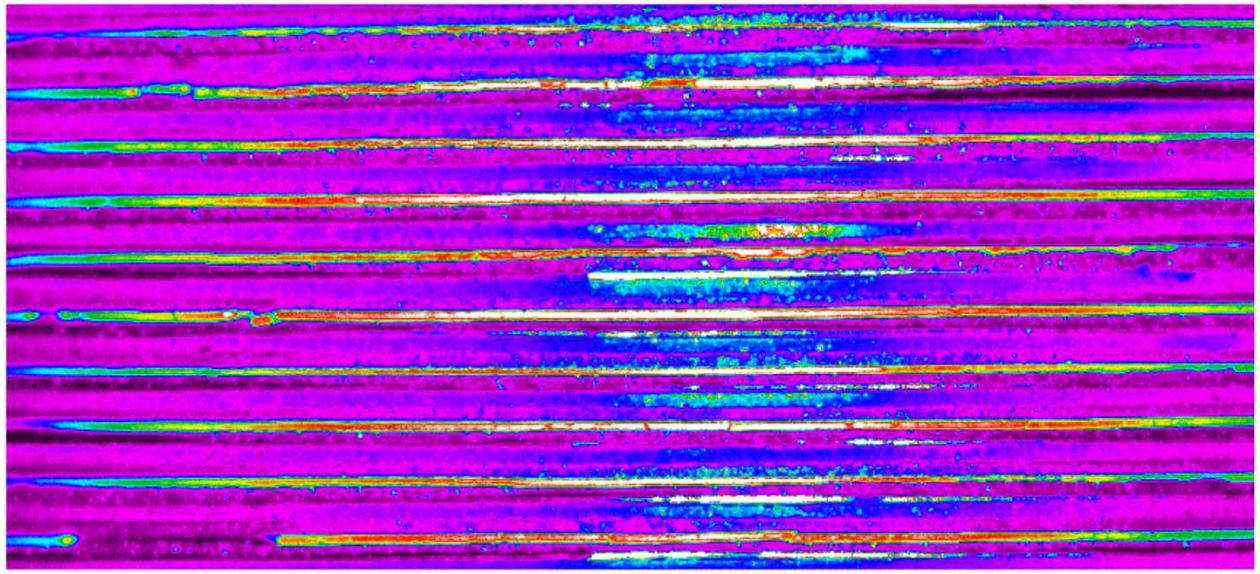
10 Cell Fiberfrax Insulated Battery

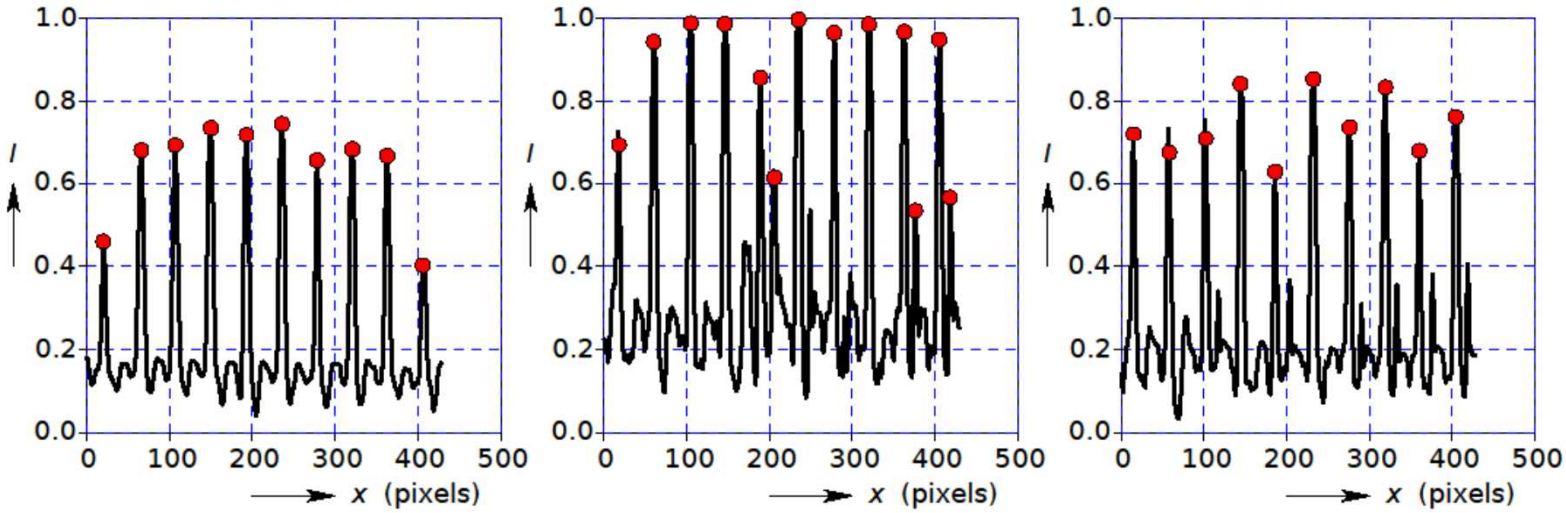
9_18_10Cell_FF_3



0th Frame Image with Intensity Plots

Sandia National Laboratories

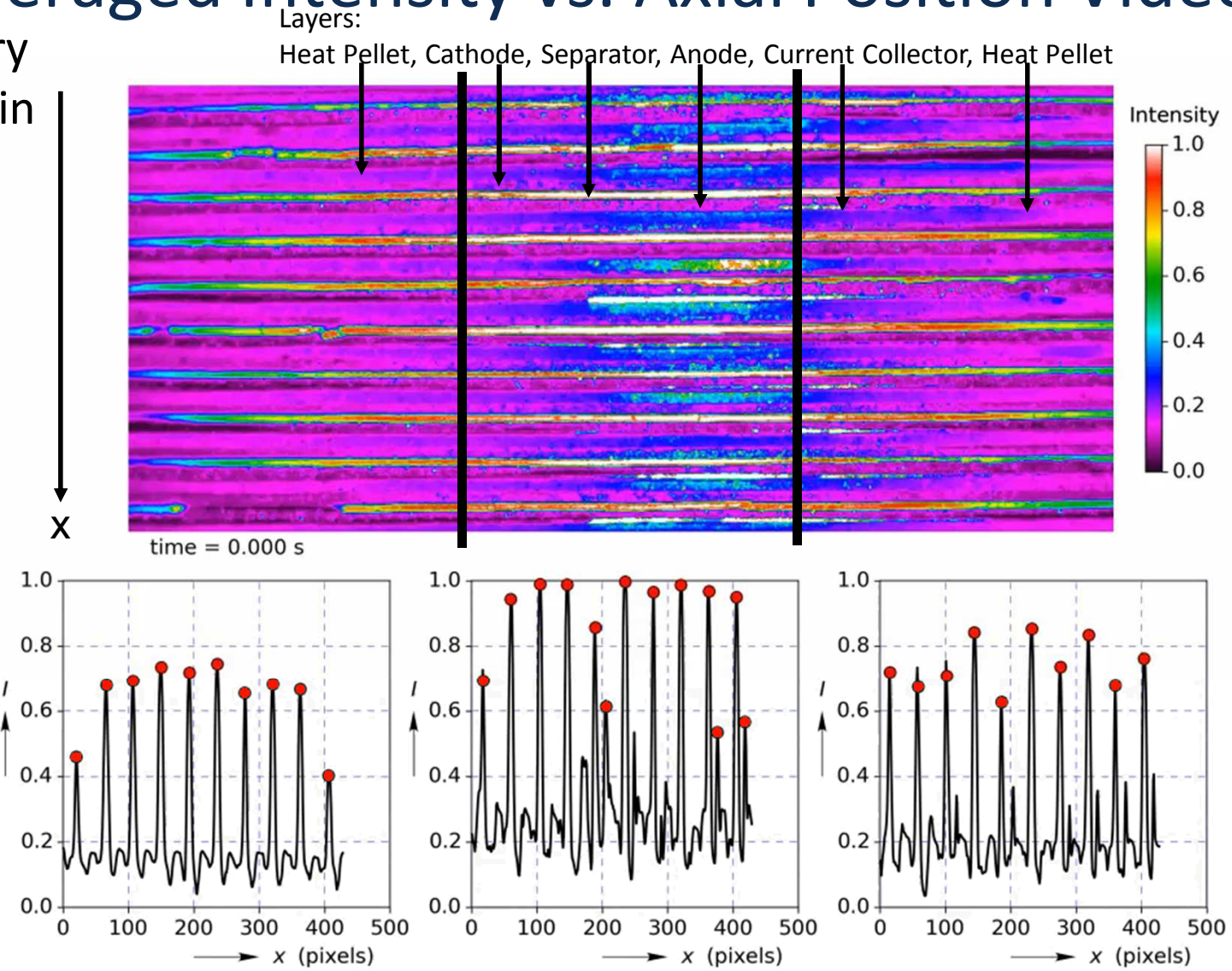




Averaged Intensity vs. Axial Position Video

Sandia National Laboratories

Battery Stack in False Color

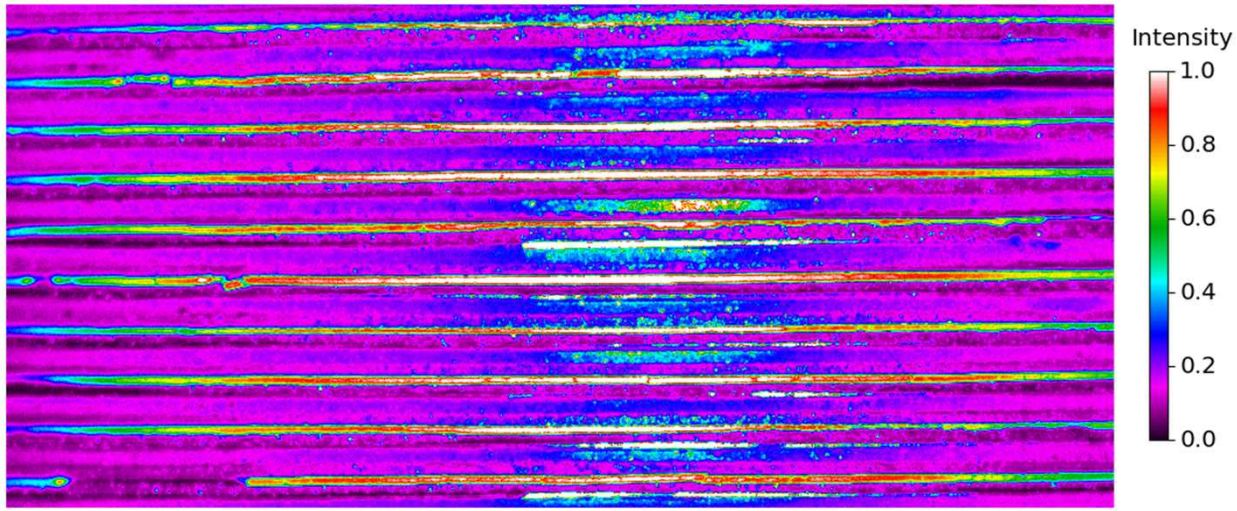


Row-Averaged Intensity Averaged Along the Stack Axis

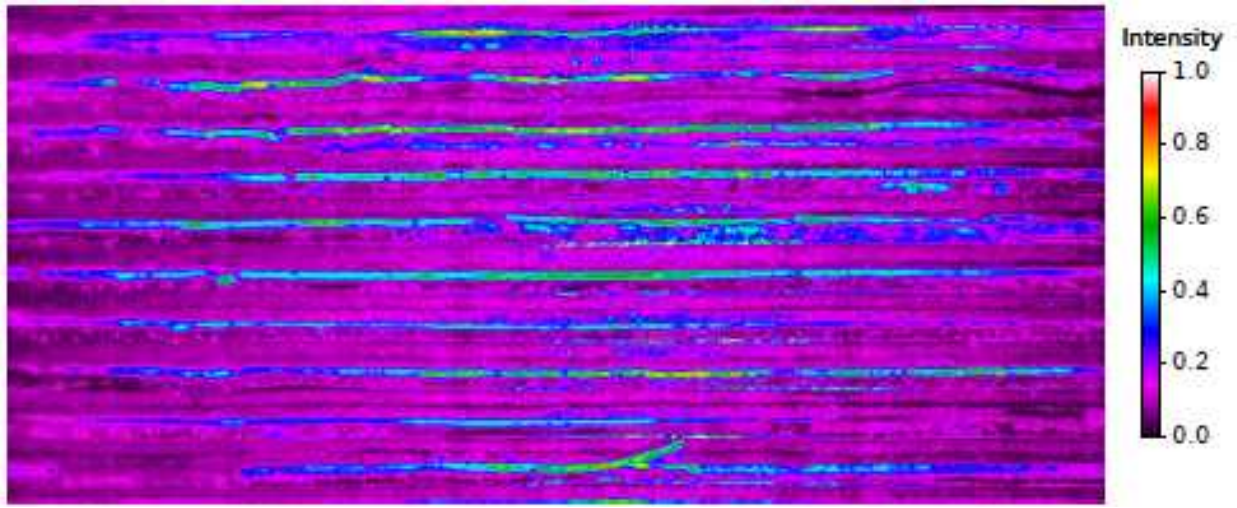
Displacement vs. Time

Sandia National Laboratories

Initial and Final Images



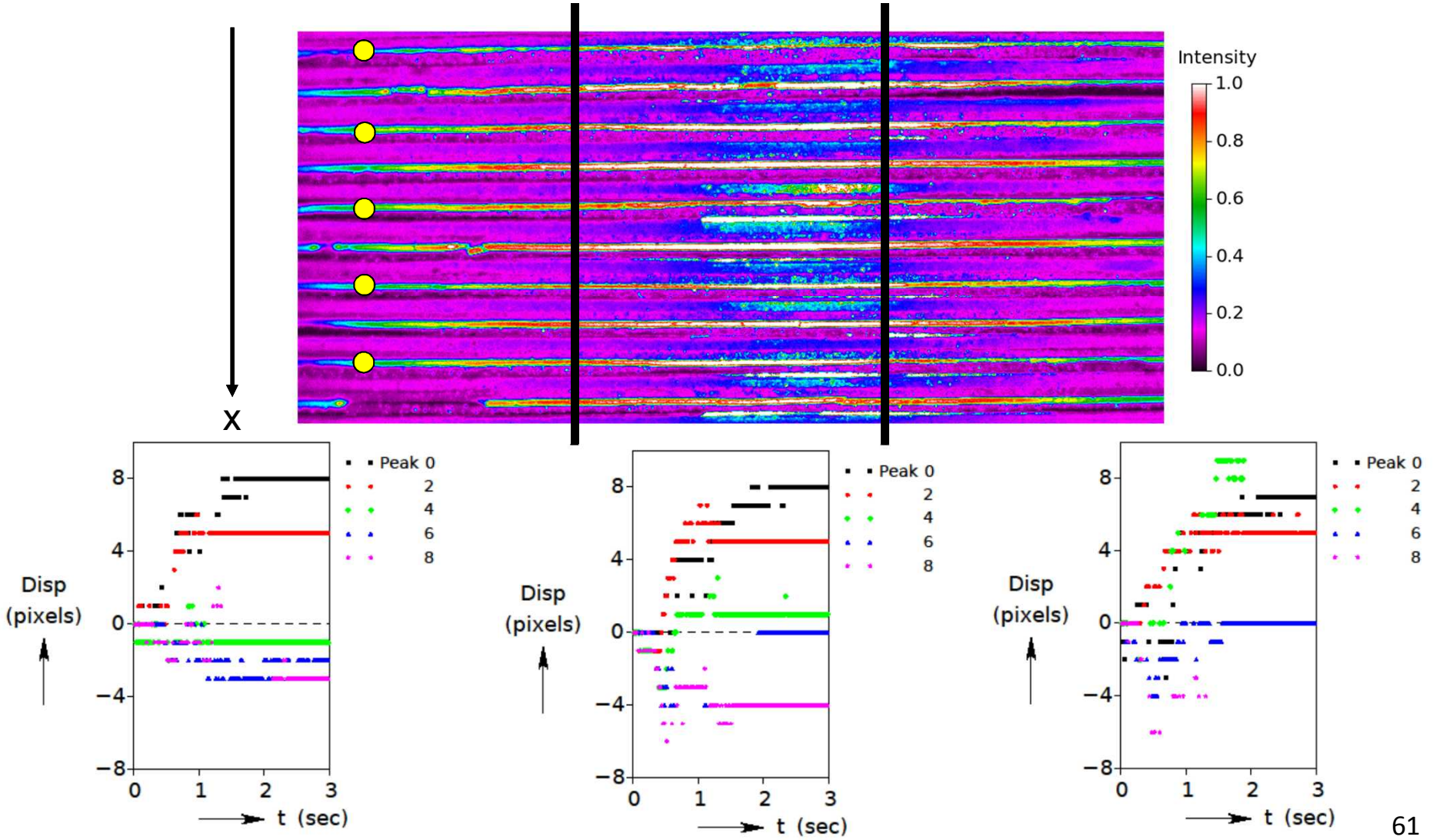
time = 0.000 s



time = 200.804 s

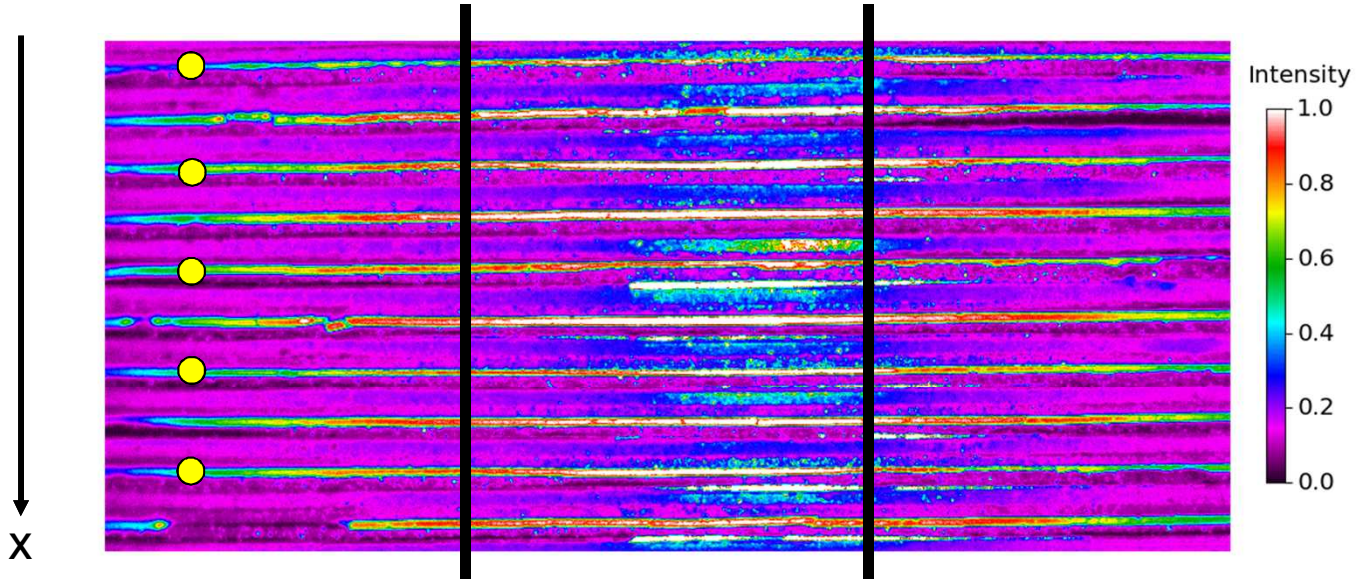
Displacement vs. Time

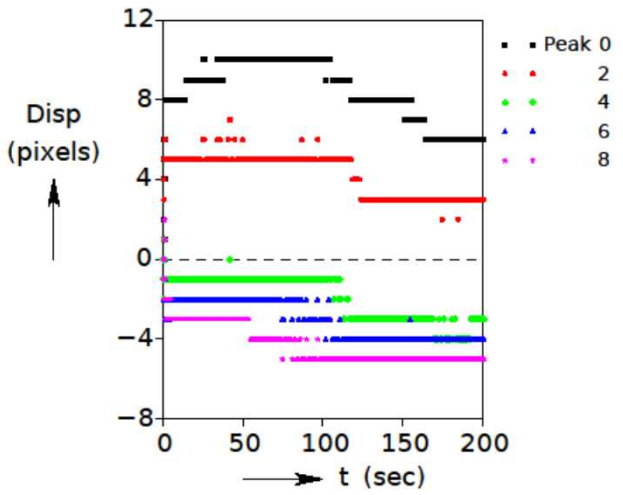
Rise Time

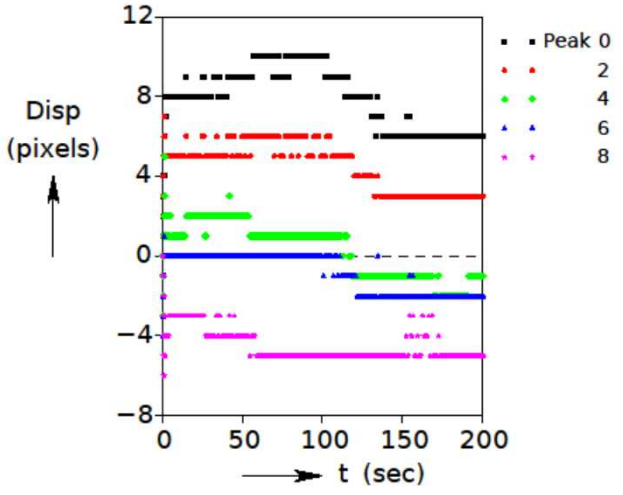


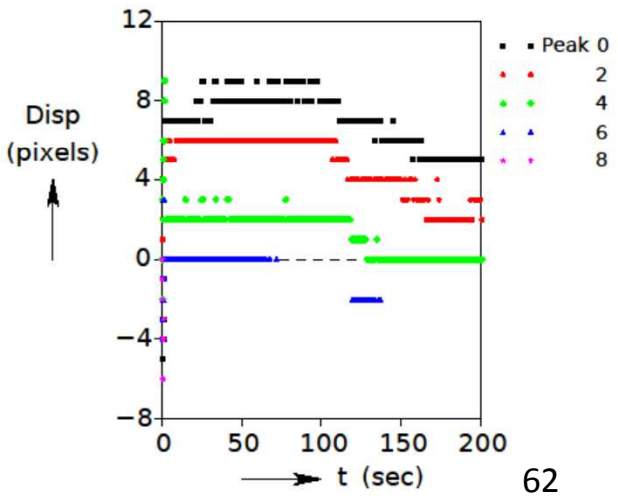
Displacement vs. Time

Full Time









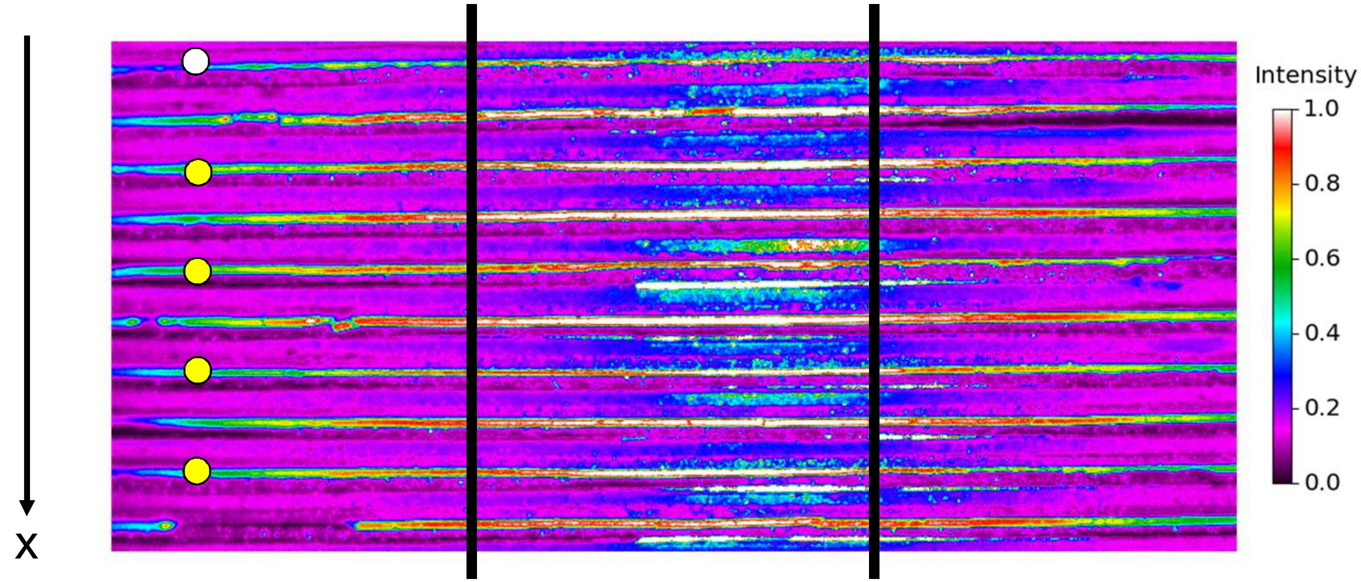
Slide 62

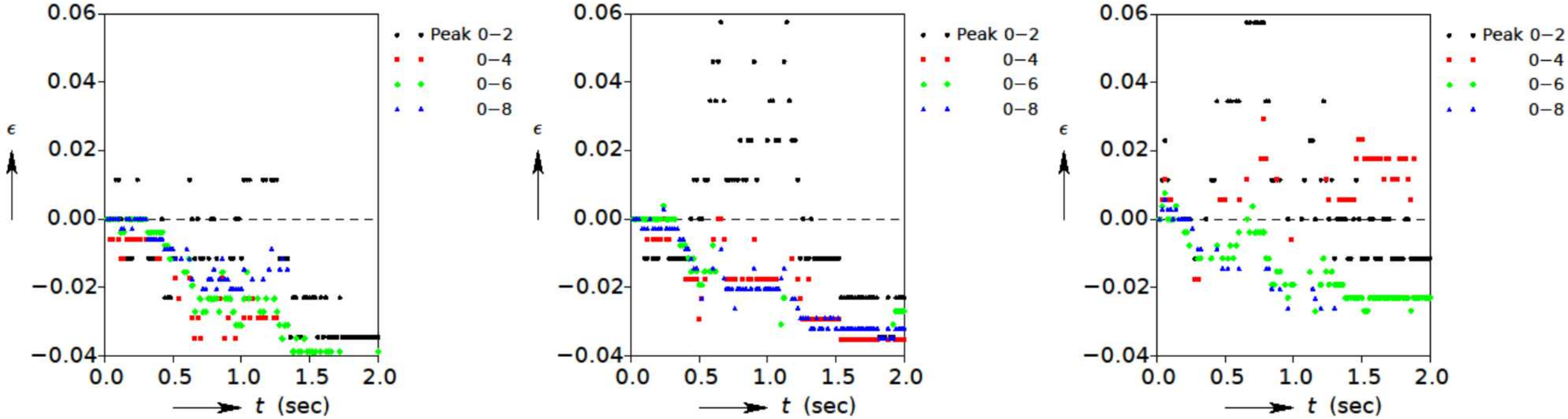
JA16 Interval 2 has almost no data for peak 8 because it could not be detected after the beginning.
Jang, Amy, 8/3/2015

JA1

Strain vs. Time

Rise Time





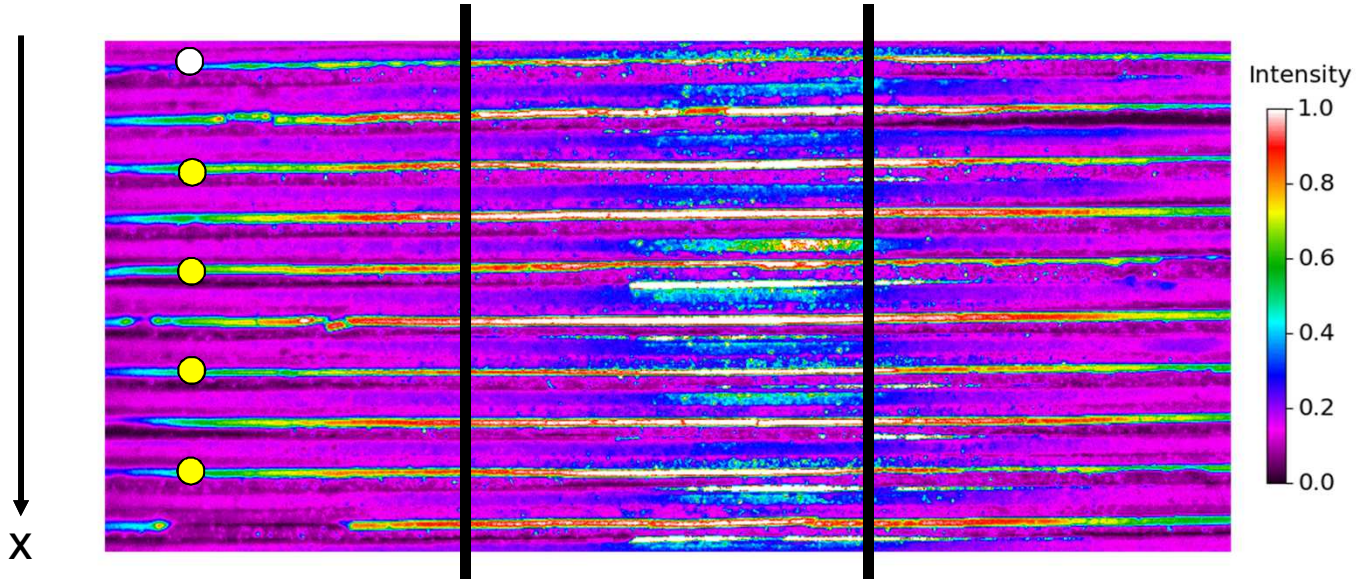
Slide 63

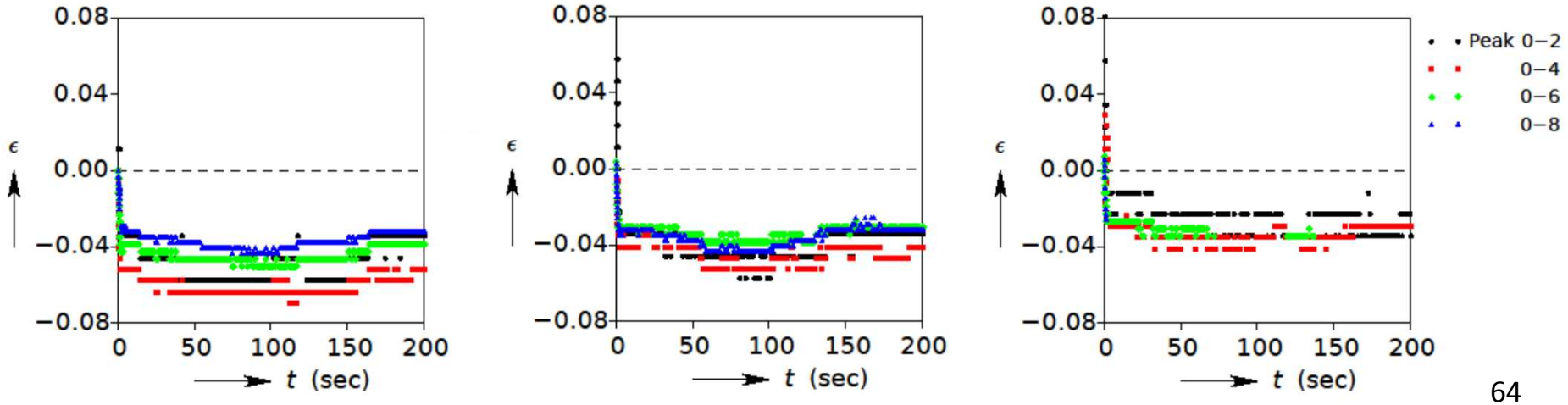
JA1 The scatter for peak 0-2 and 0-4 in intervals 1 and 2 are correct. I checked the data and the correct peaks are being selected. I believe there is positive strain for those two peaks because peak 0 remains pretty stationary while peak 2 and 4 displace downward during this time period.

Jang, Amy, 8/3/2015

Strain vs. Time

Full Time





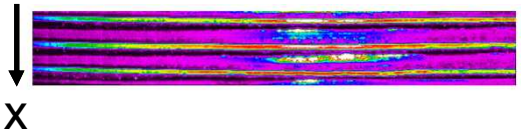
3 Cell Battery Comparison

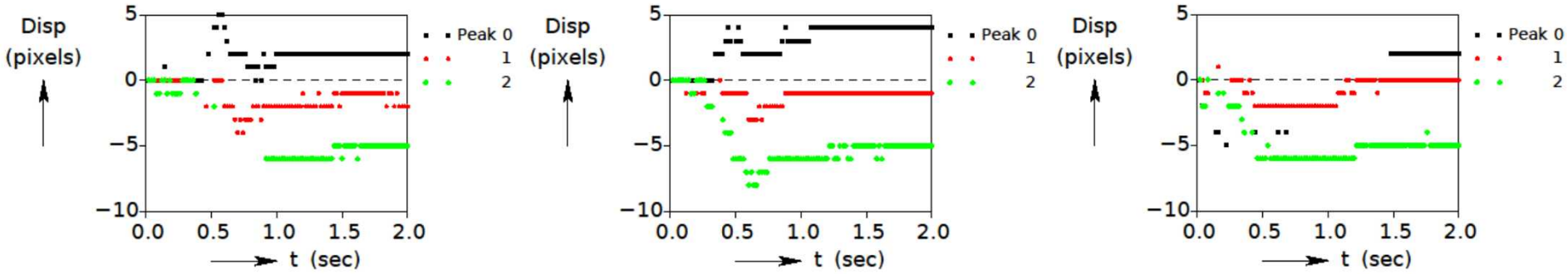
9_18_3Cell_MinK_1 vs. 9_18_3Cell_FF_4

Displacement vs. Time Comparison

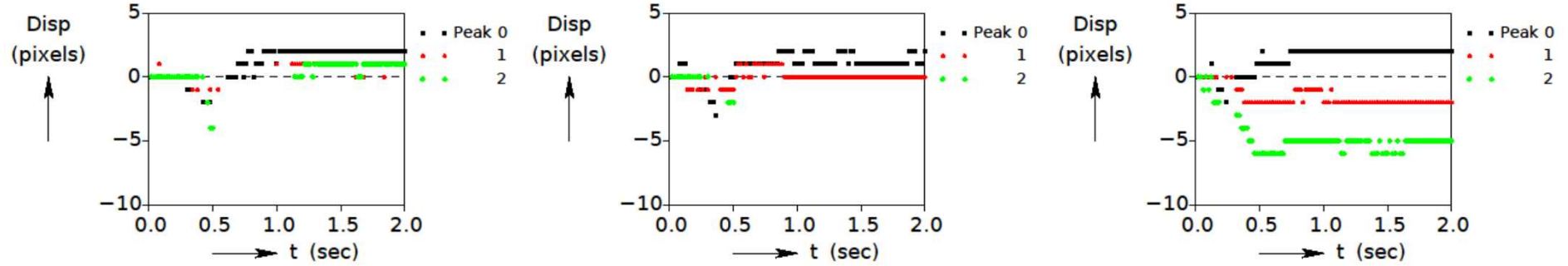
Sandia National Laboratories

Rise Time





MinK Insulation (9_18_3Cell_MinK_1)

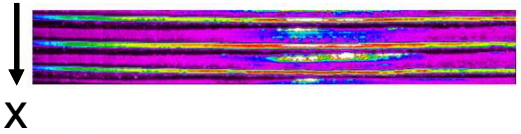


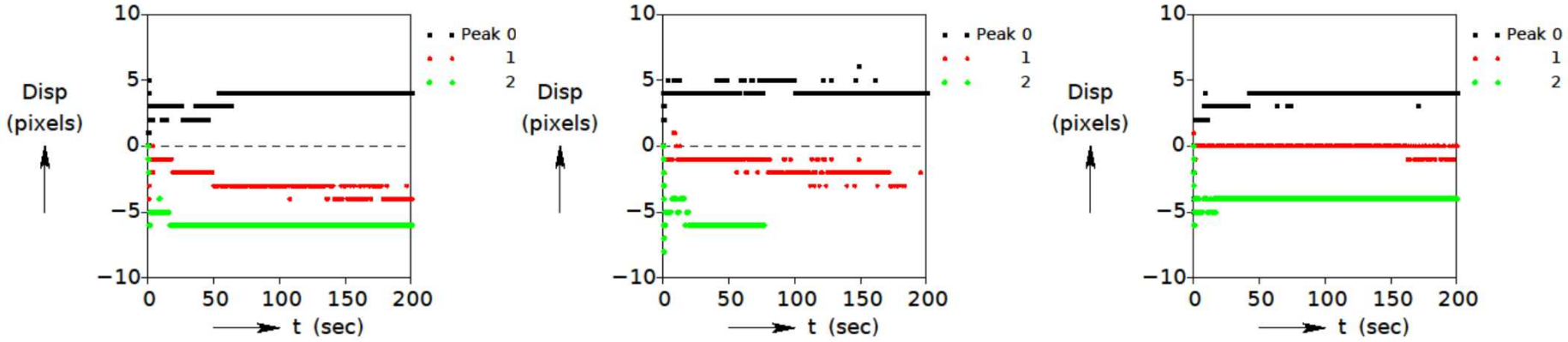
Fiberfrax Insulation (9_18_3Cell_FF_4)

Displacement vs. Time Comparison

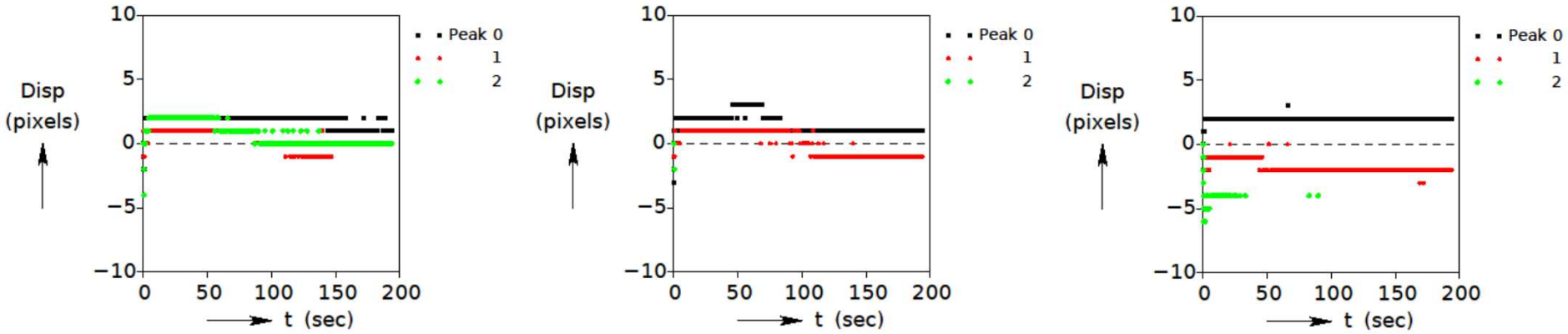
Sandia National Laboratories

Full Time





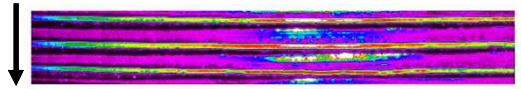
MinK Insulation (9_18_3Cell_MinK)



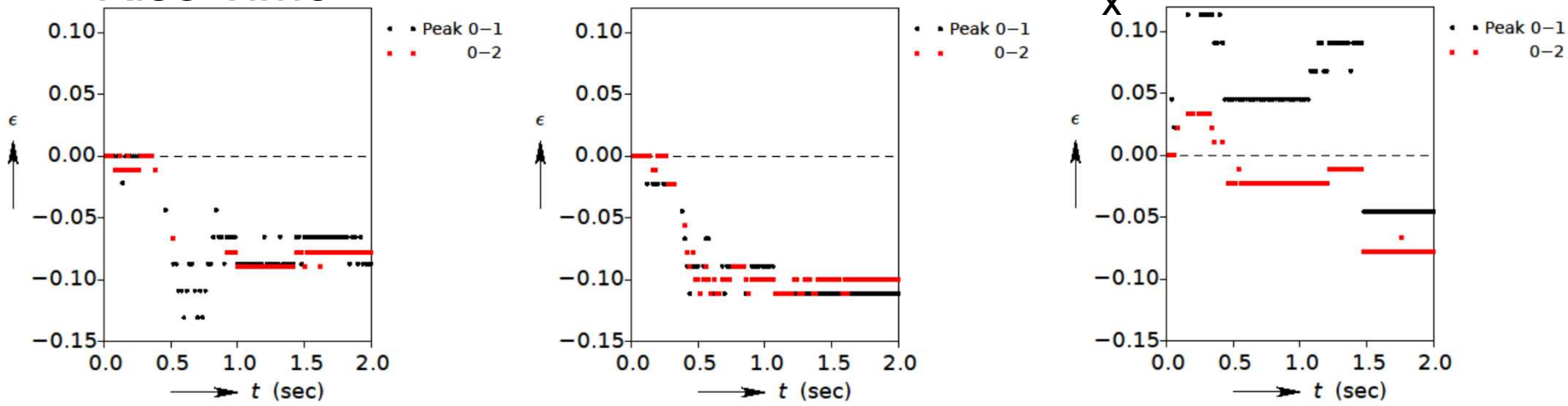
Fiberfrax Insulation (9_18_3Cell_FF)

Strain vs. Time Comparison

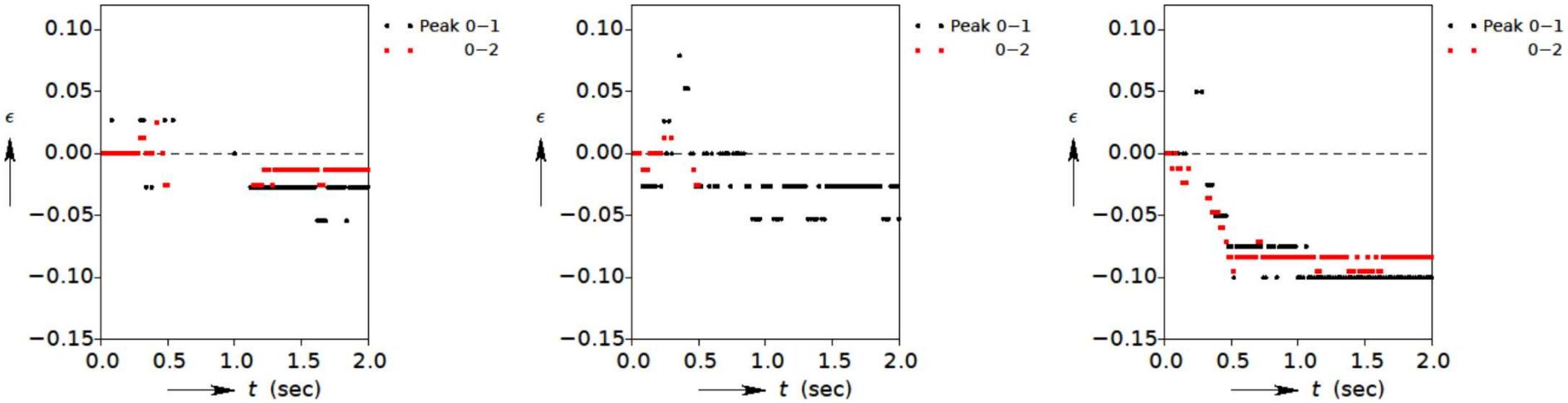
Sandia National Laboratories



Rise Time



MinK Insulation (9_18_3Cell_MinK_1)

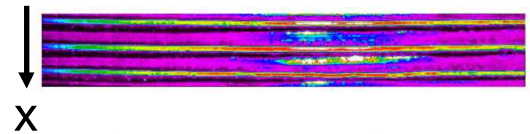


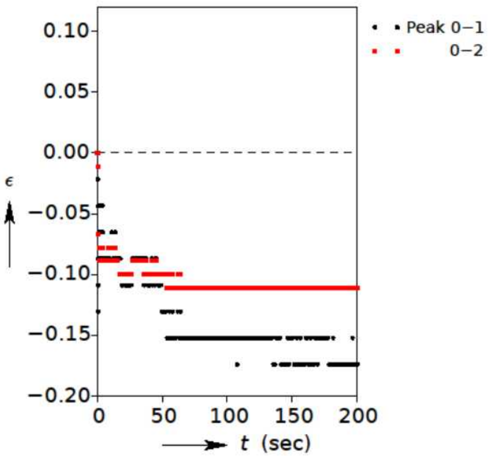
Fiberfrax Insulation (9_18_3Cell_FF_4)

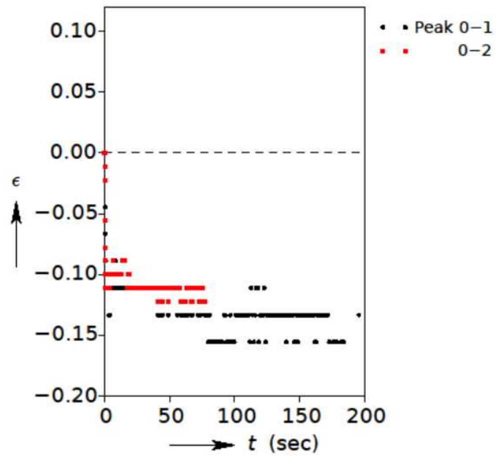
Strain vs. Time Comparison

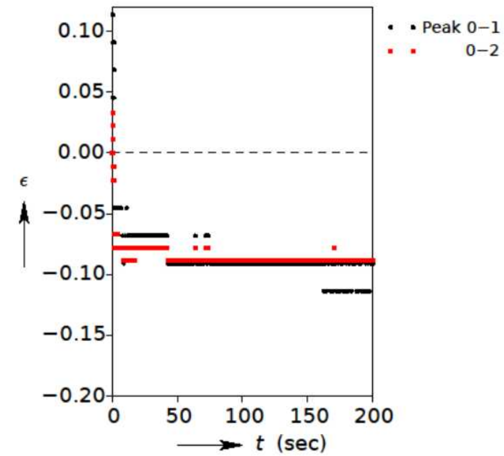
Sandia National Laboratories

Full Time

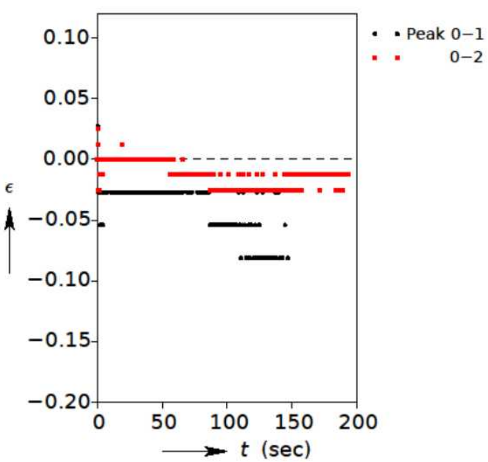


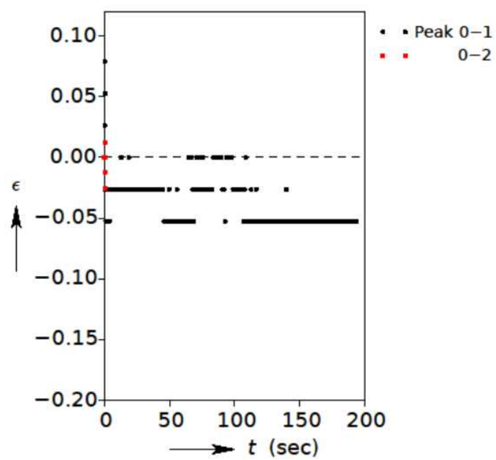


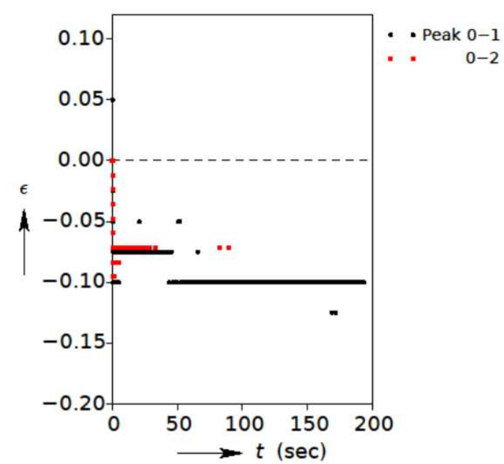




MinK Insulation (9_18_3Cell_MinK_1)







Fiberfrax Insulation (9_18_3Cell_FF_4)

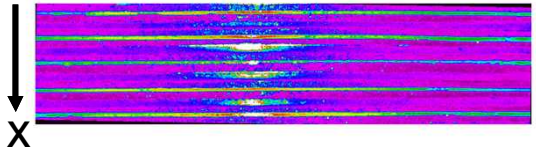
5 Cell Battery Comparison

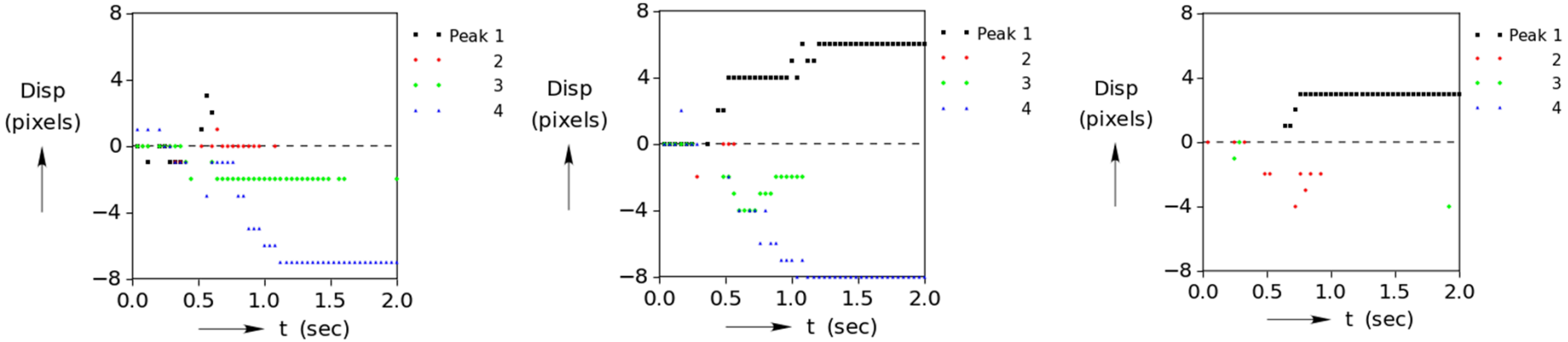
Sandia National Laboratories

9_16_5Cell_MinK_2 vs. 9_18_5Cell_FF_2

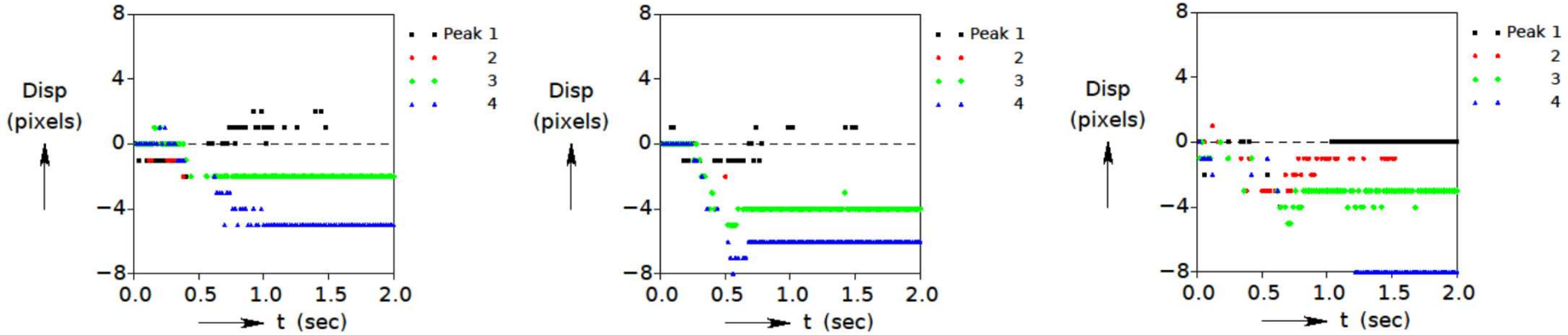
Displacement vs. Time Comparison

Rise Time





MinK Insulation (9_16_5Cell_MinK_2)

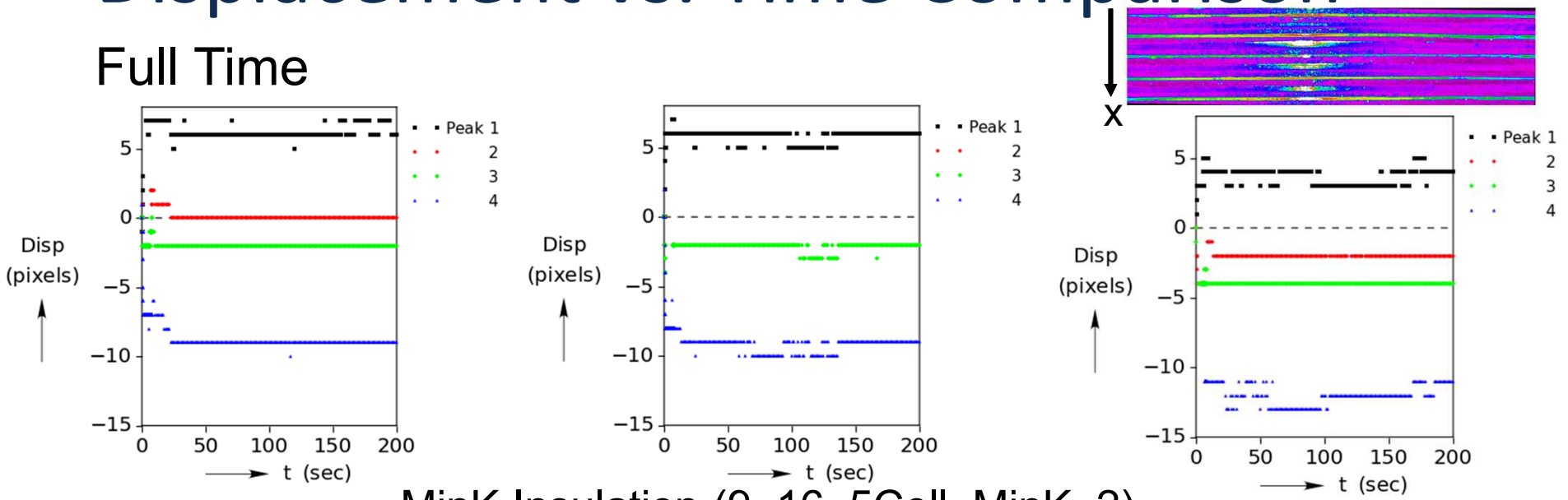


Fiberfrax Insulation (9_18_5Cell_FF_2)

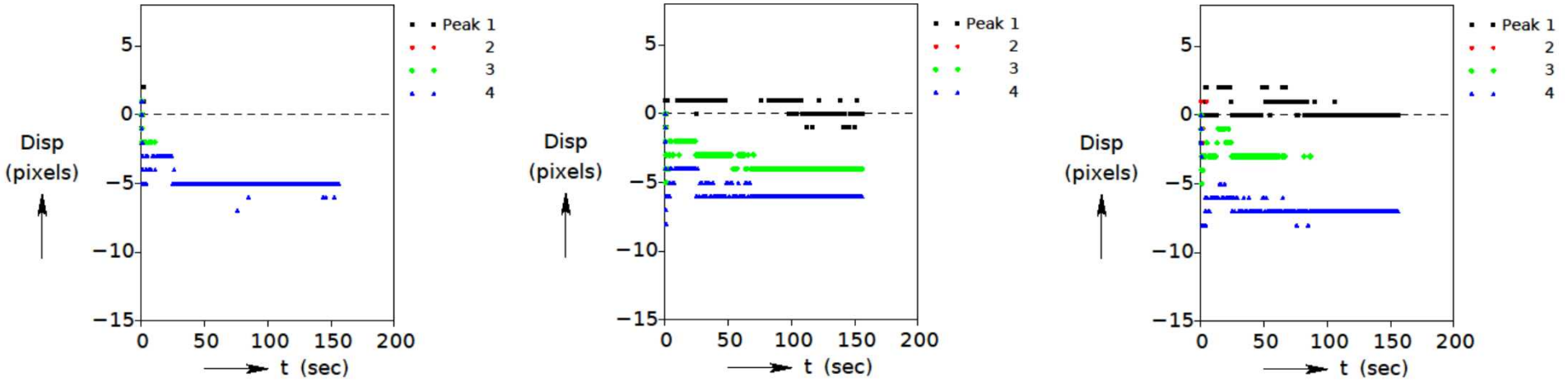
Displacement vs. Time Comparison

Sandia National Laboratories

Full Time



MinK Insulation (9_16_5Cell_MinK_2)

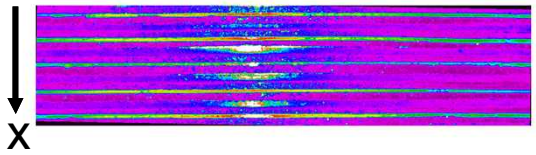


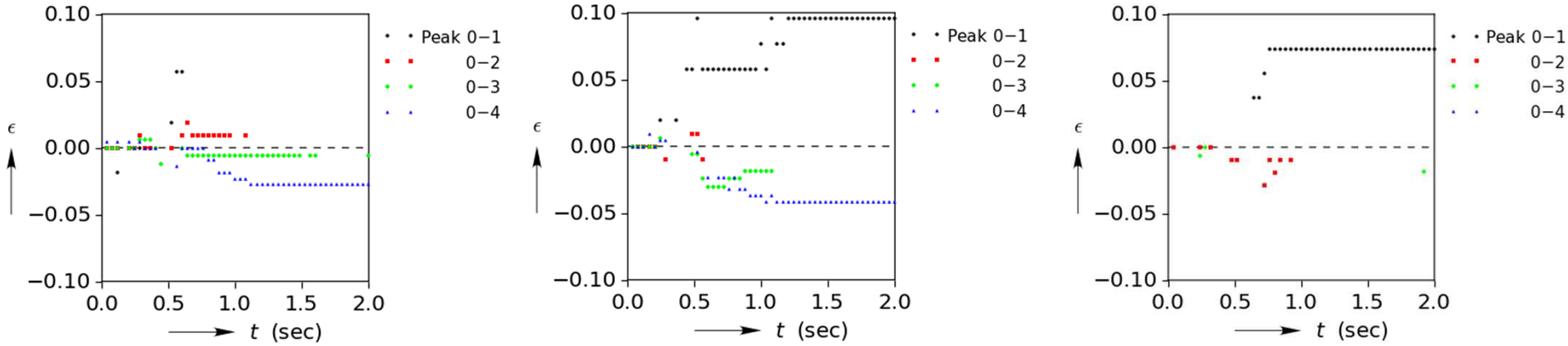
Fiberfrax Insulation (9_18_5Cell_FF_2)

Strain vs. Time Comparison

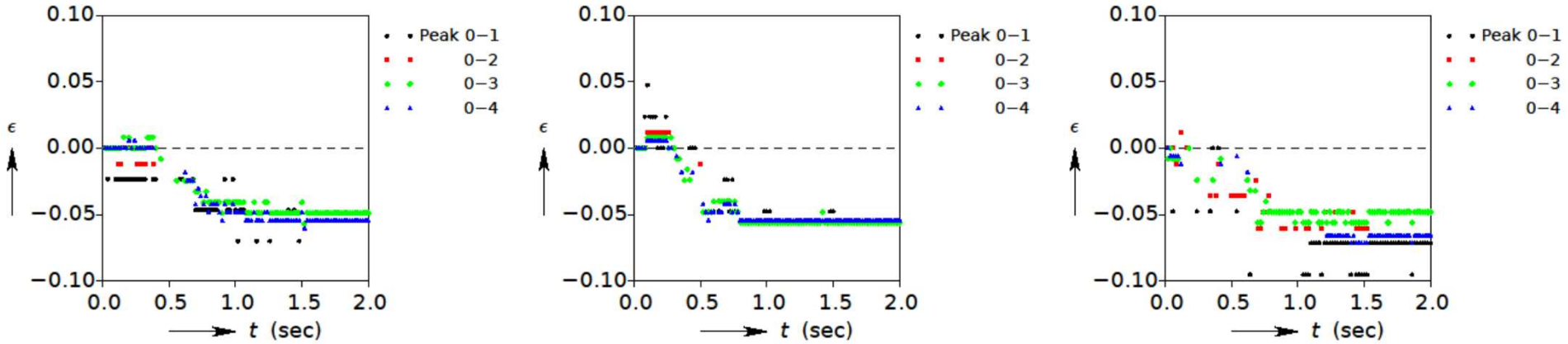
Sandia National Laboratories

Rise Time





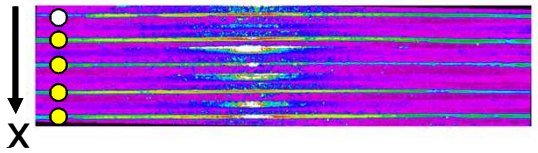
MinK Insulation (9_16_5Cell_MinK_2)

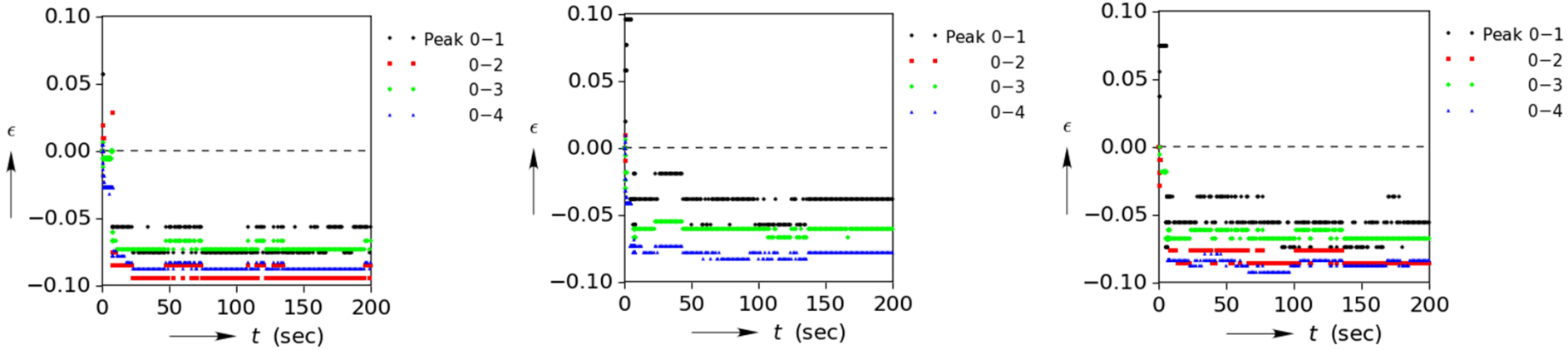


Fiberfrax Insulation (9_18_5Cell_FF_2)

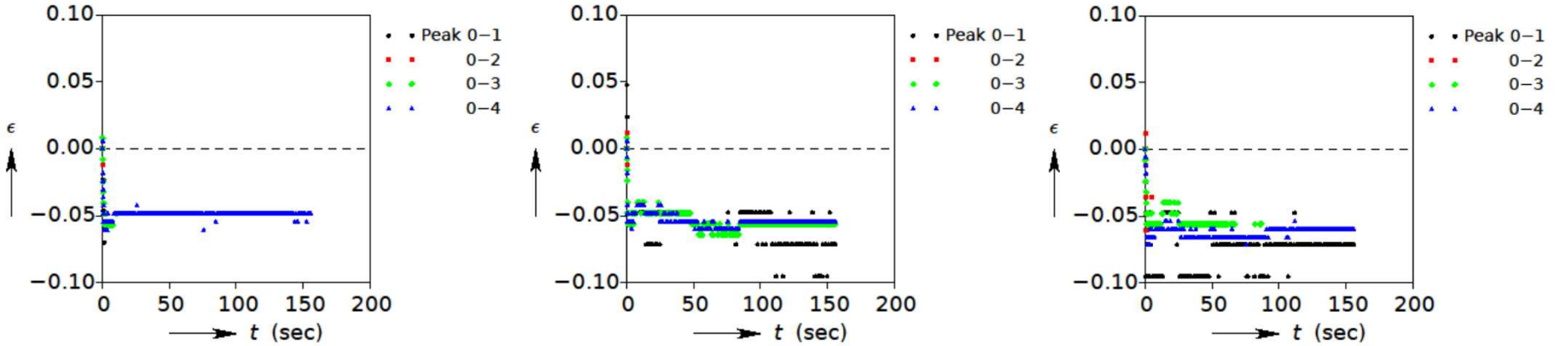
Strain vs. Time Comparison

Full Time





MinK Insulation (9_16_5Cell_MinK_2)



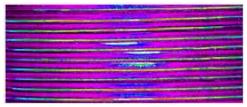
Fiberfrax Insulation (9_18_5Cell_FF_2)

10 Cell Battery Comparison

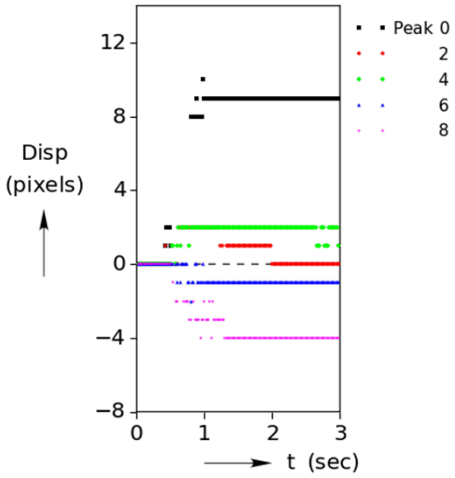
9_17_10Cell_MinK_4 vs. 9_18_10Cell_FF_3

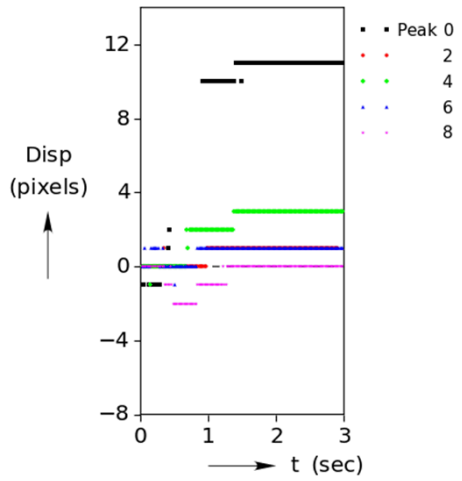
Displacement vs. Time Comparison

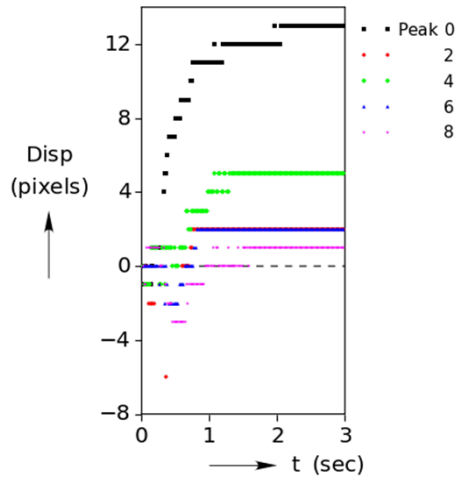
Sandia National Laboratories



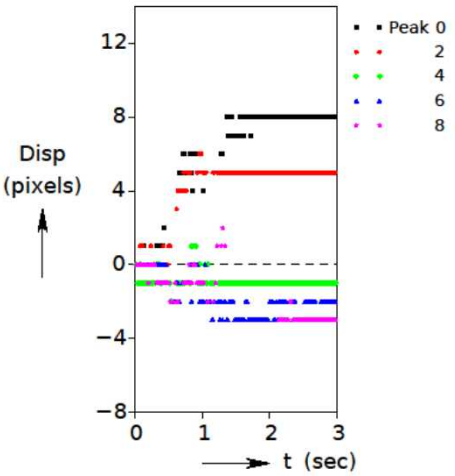
Rise Time

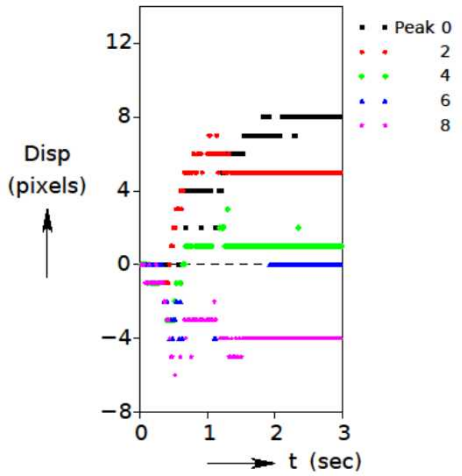


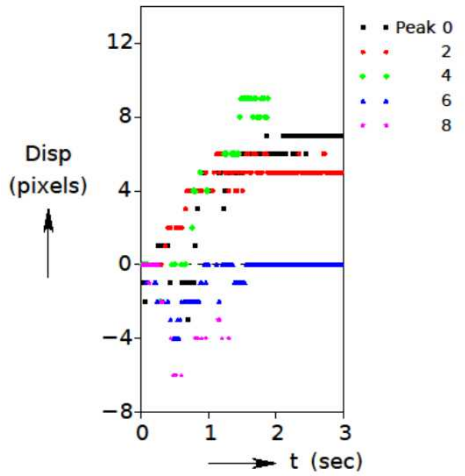




MinK Insulation







Fiberfrax Insulation

Strain vs. Time Comparison

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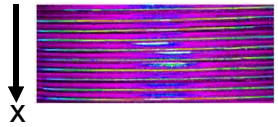
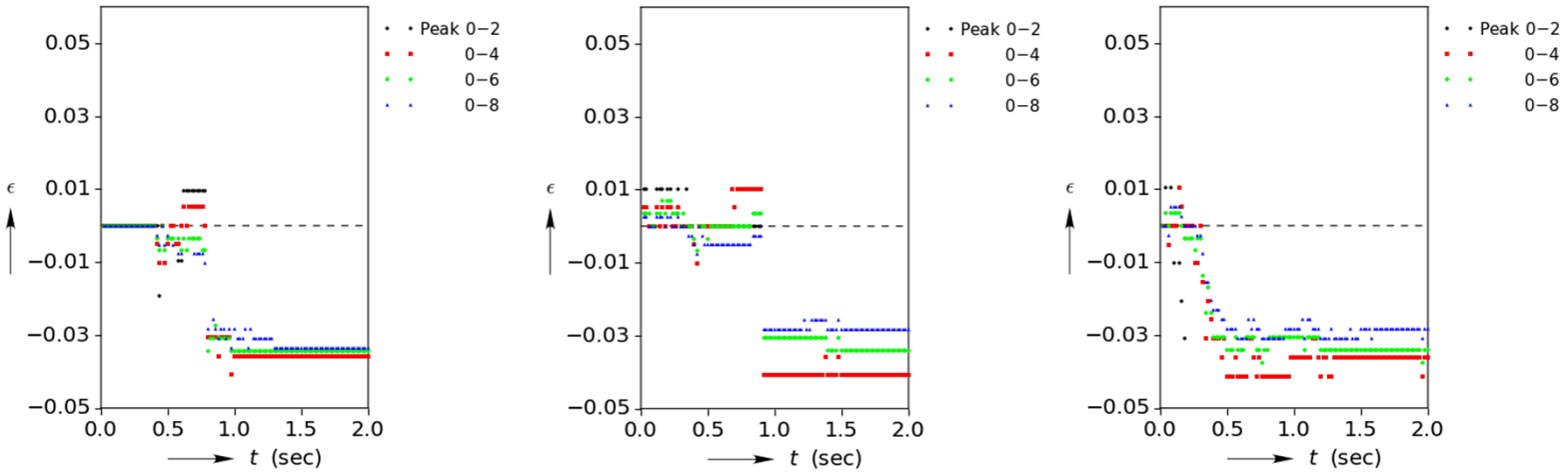
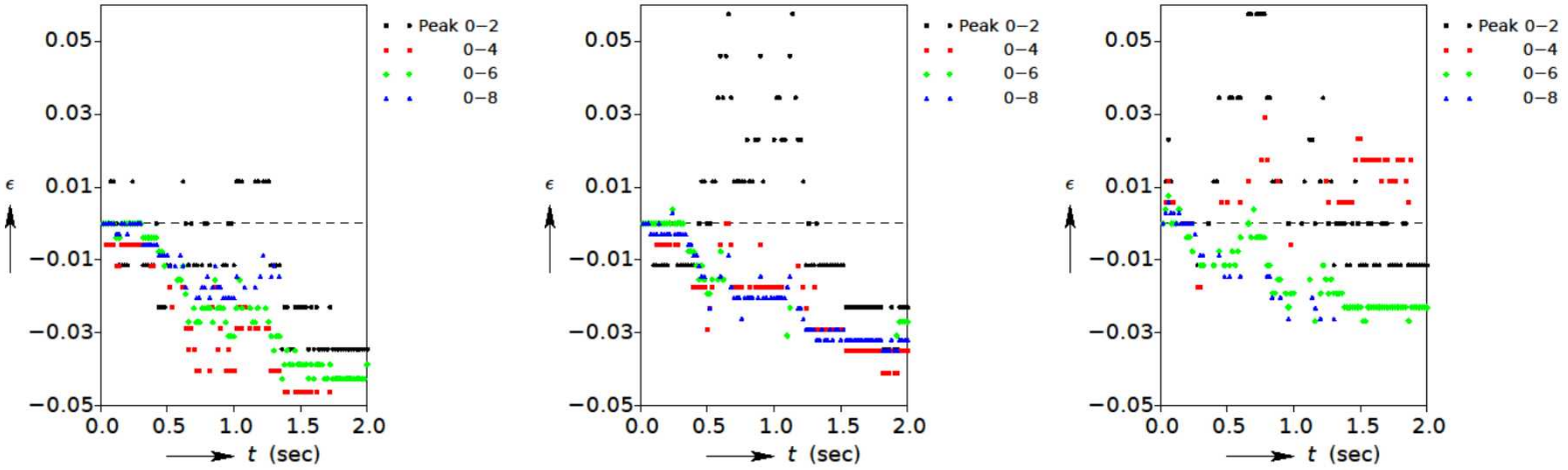


Rise Time



MinK Insulation



Fiberfrax Insulation

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Extra Slides

Strain vs. Time

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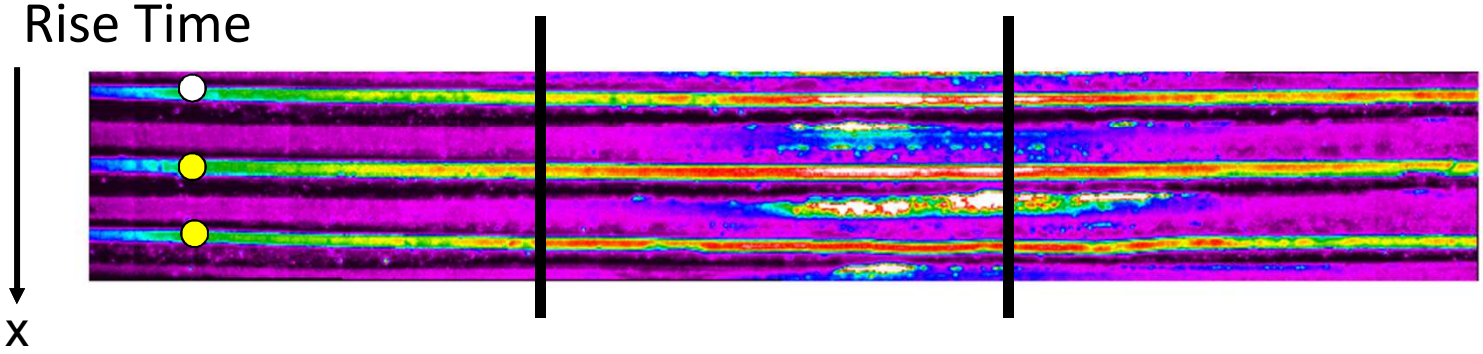
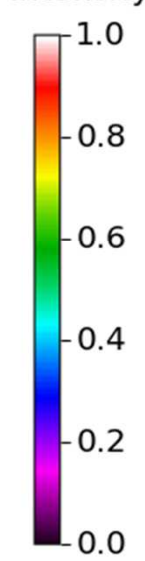
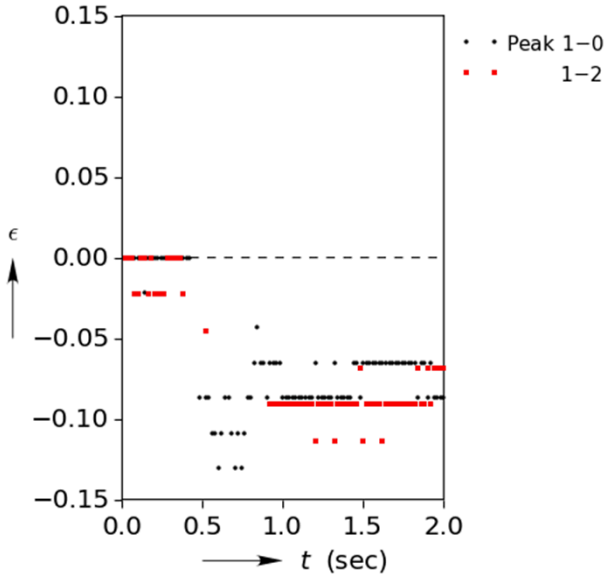
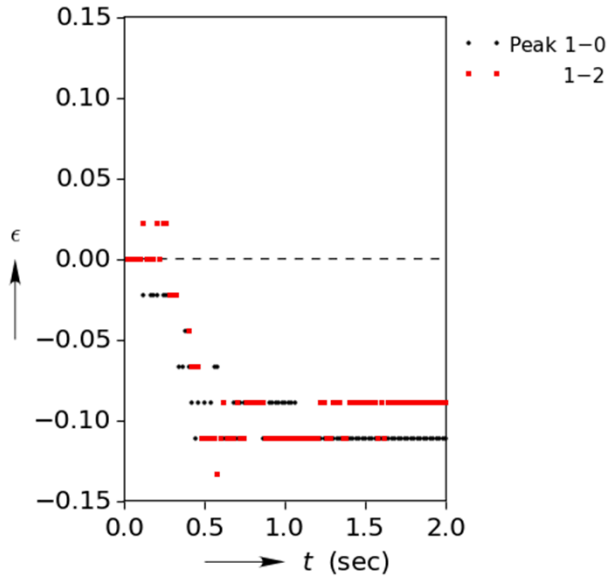
3 Cell MinK Relative to Peak 1

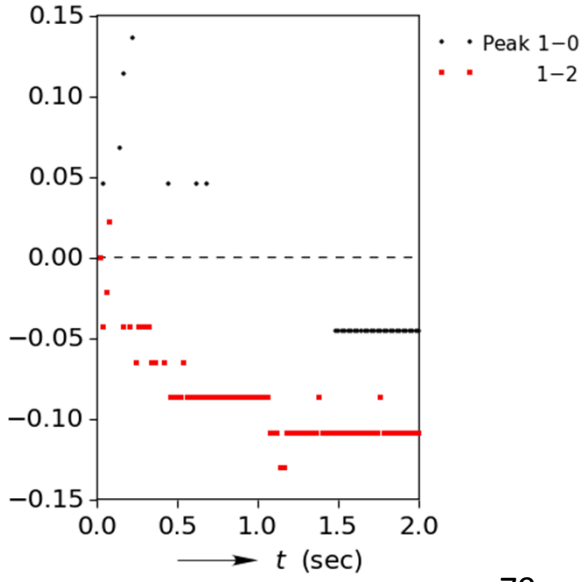
Rise Time











Slide 79

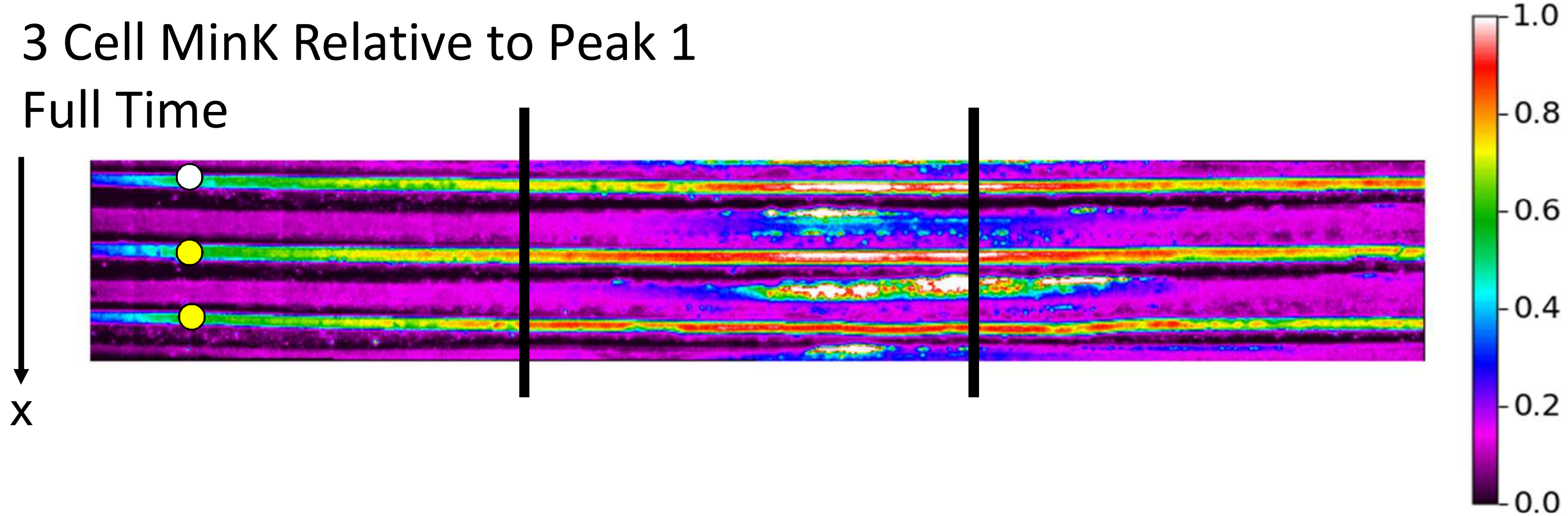
JA5 I think interval 2's jumping data is correct.
Jang, Amy, 8/3/2015

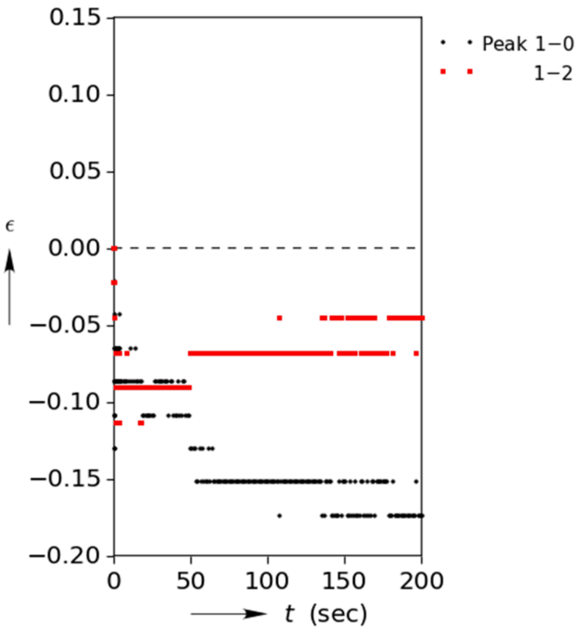
JA6

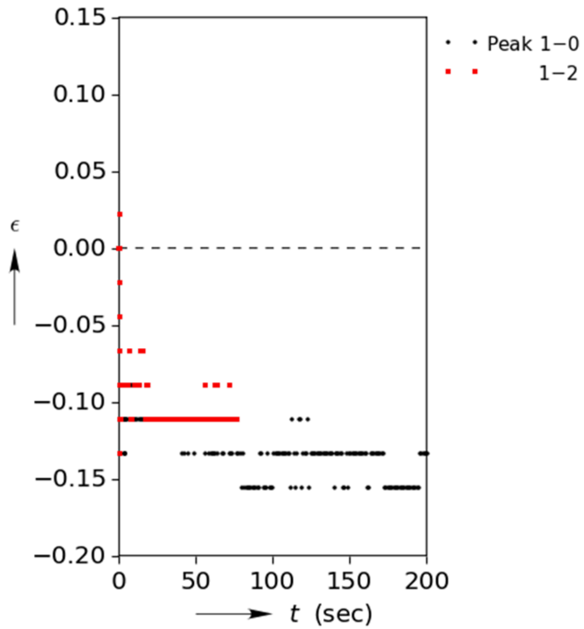
Strain vs. Time

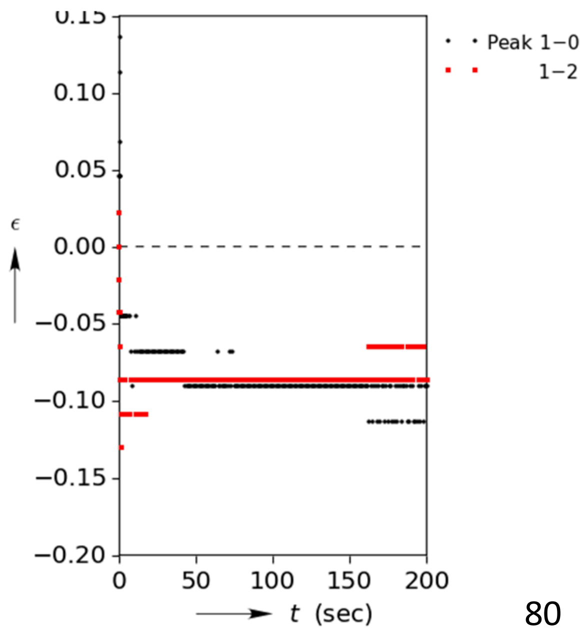
3 Cell MinK Relative to Peak 1

Full Time









Slide 80

JA6 Interval 1 missing peak 0-2 data because peak 2 is hard to detect.
Jang, Amy, 8/3/2015

3 Cell FF – 9_9_3Cell_FF_3

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No strain plots relative to a middle peak because only 2 peaks visible.

Strain vs. Time

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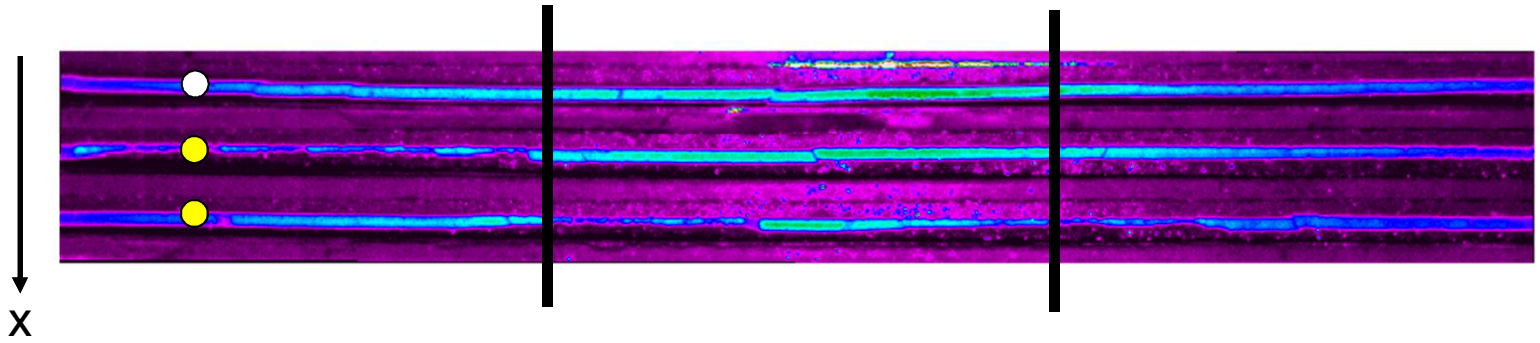
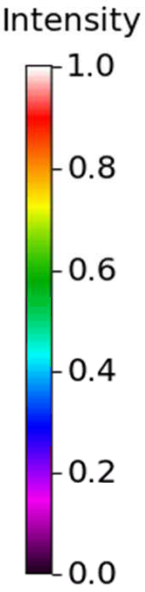
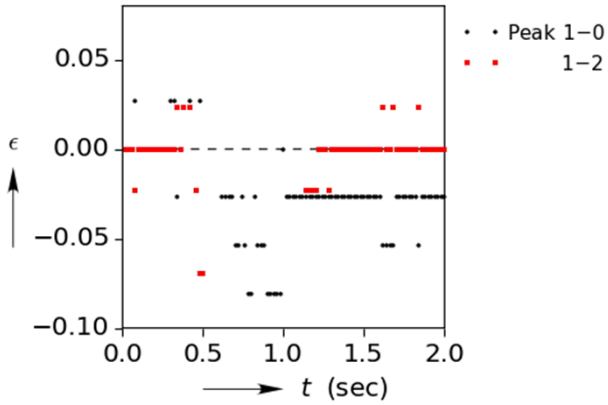
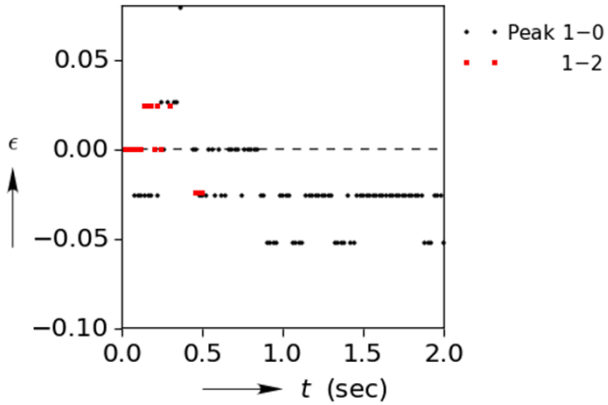
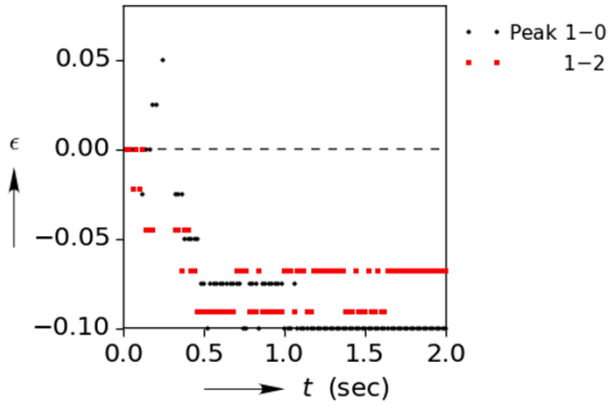
3 Cell FF (9_18_3Cell_FF_4) Relative to Peak 1 Rise Time











Strain vs. Time

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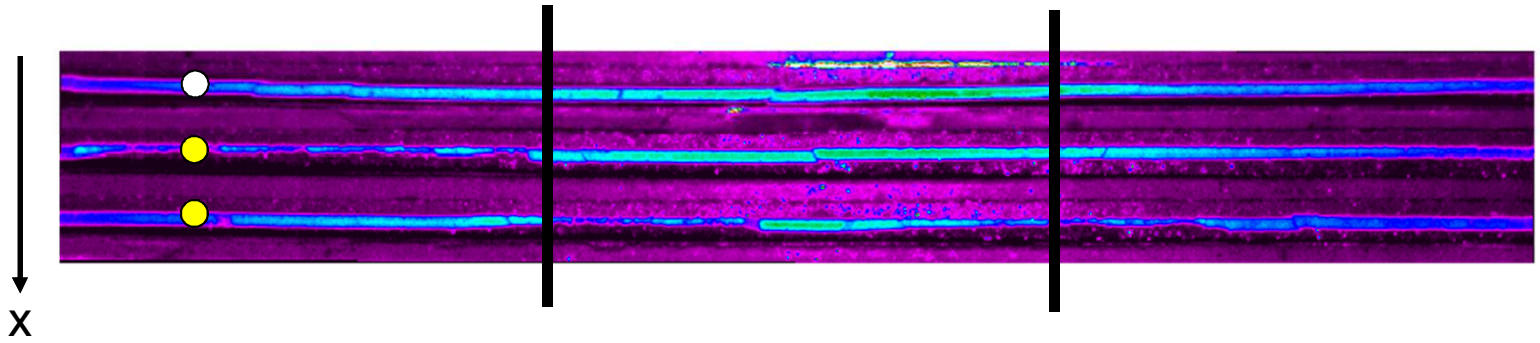
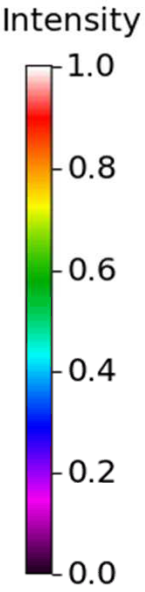
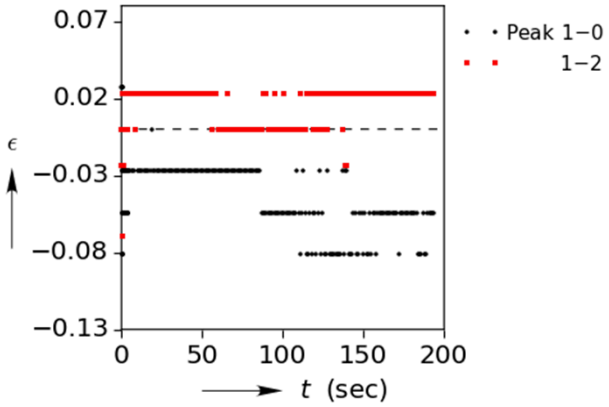
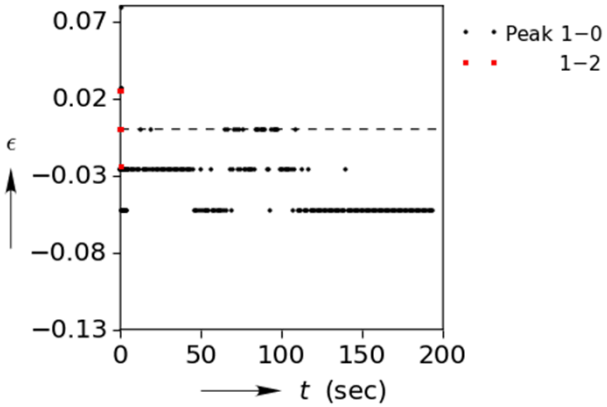
3 Cell FF (9_18_3Cell_FF_4) Relative to Peak 1

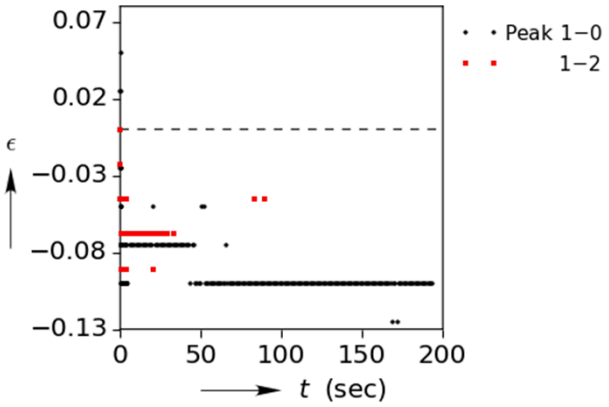
Full Time







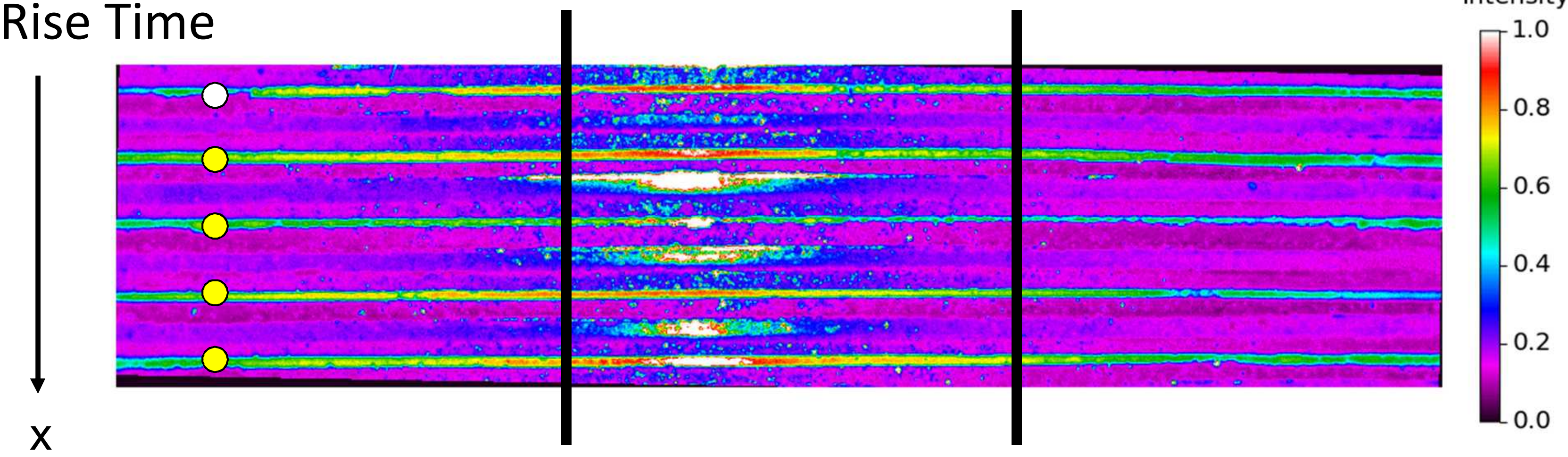


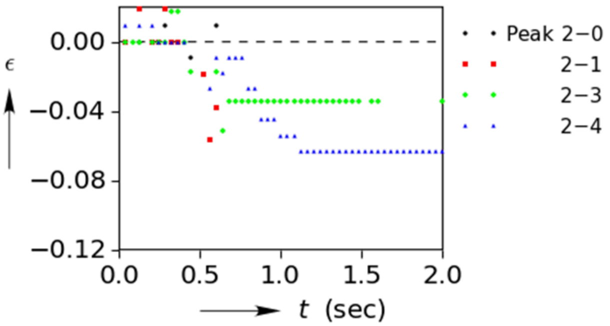


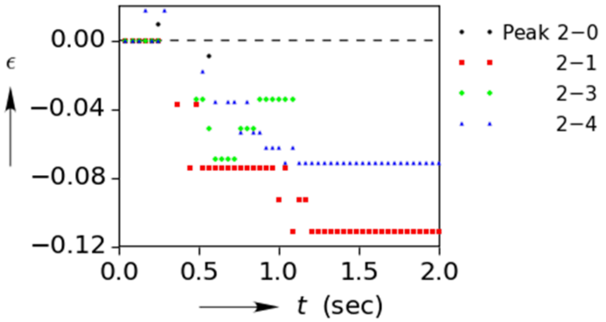
Strain vs. Time

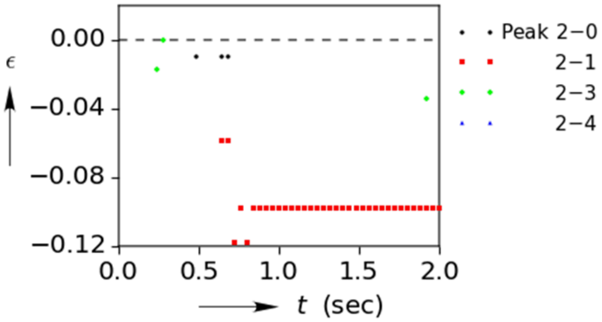
5 Cell MinK Relative to Peak 2

Rise Time





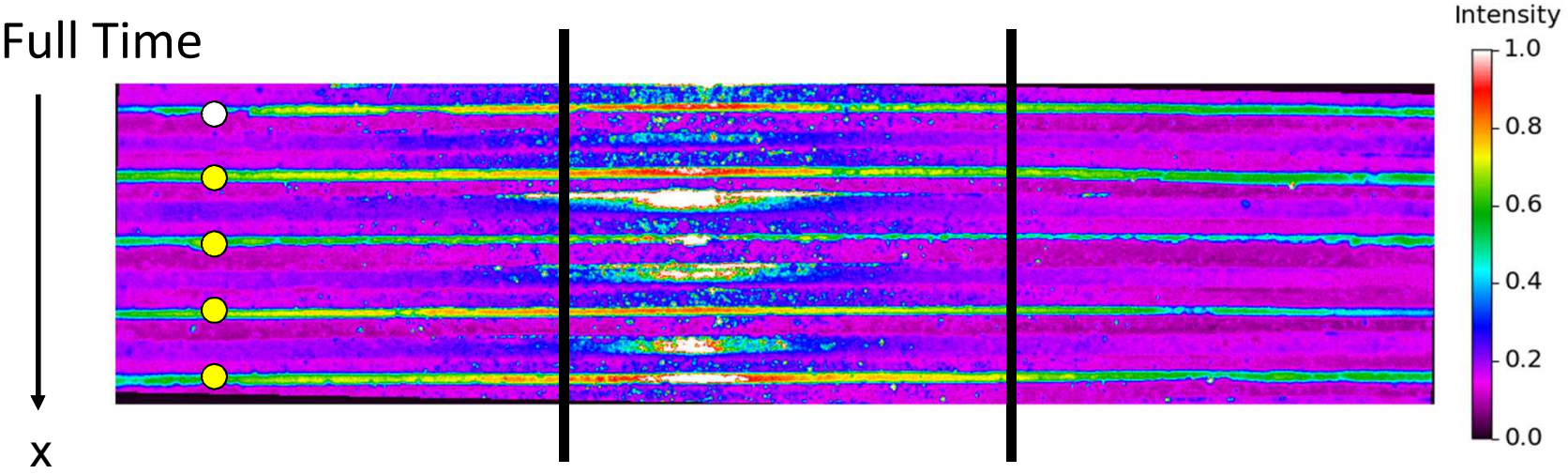


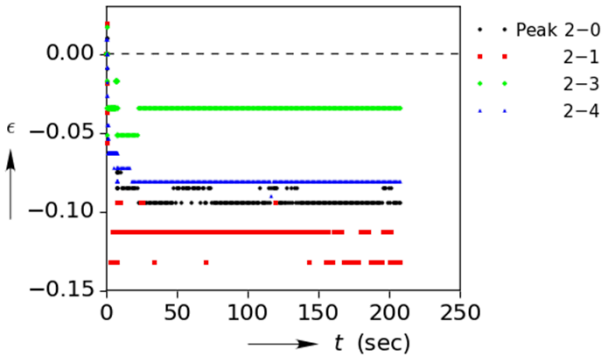


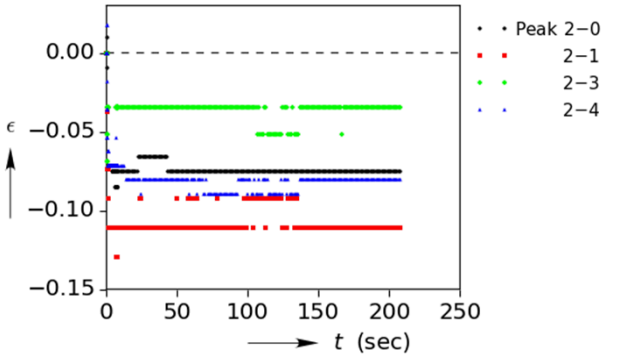
Strain vs. Time

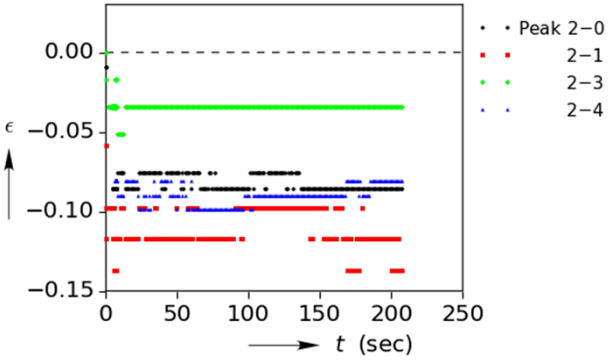
5 Cell MinK Relative to Peak 2

Full Time





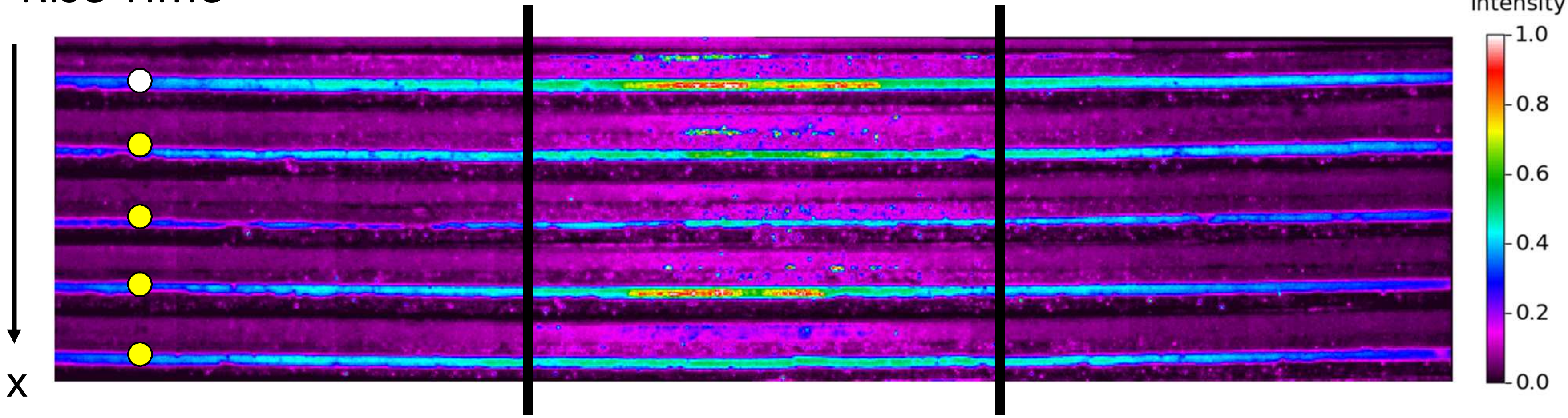


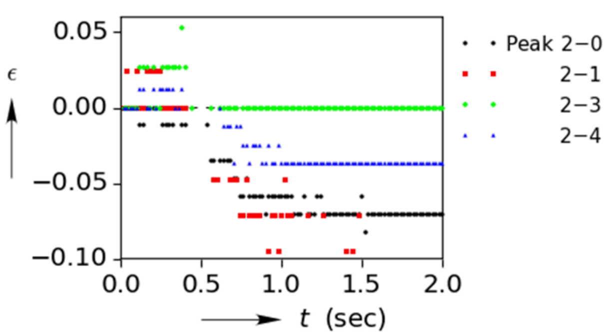


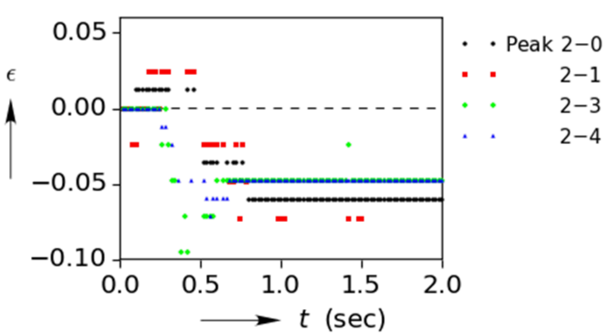
Strain vs. Time

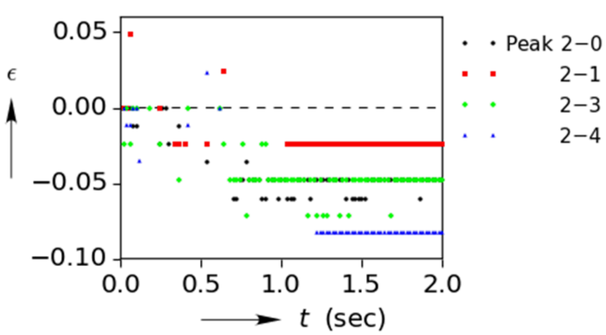
5 Cell FF Relative to Peak 2

Rise Time









Strain vs. Time

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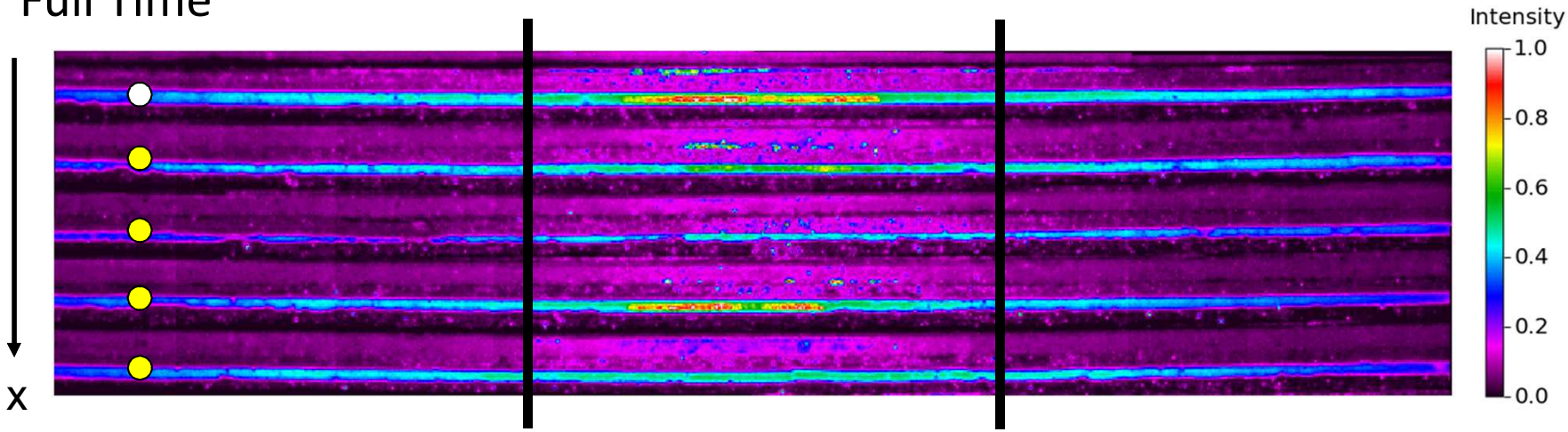
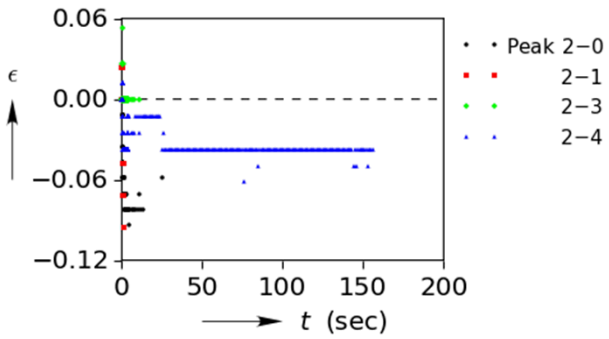
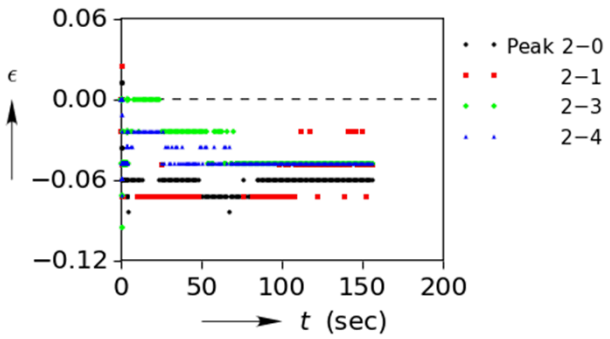
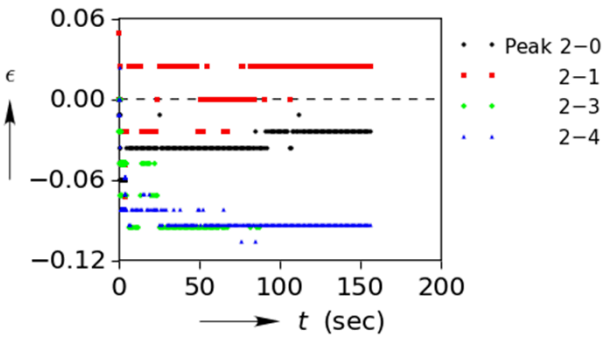
5 Cell FF Relative to Peak 2

Full Time



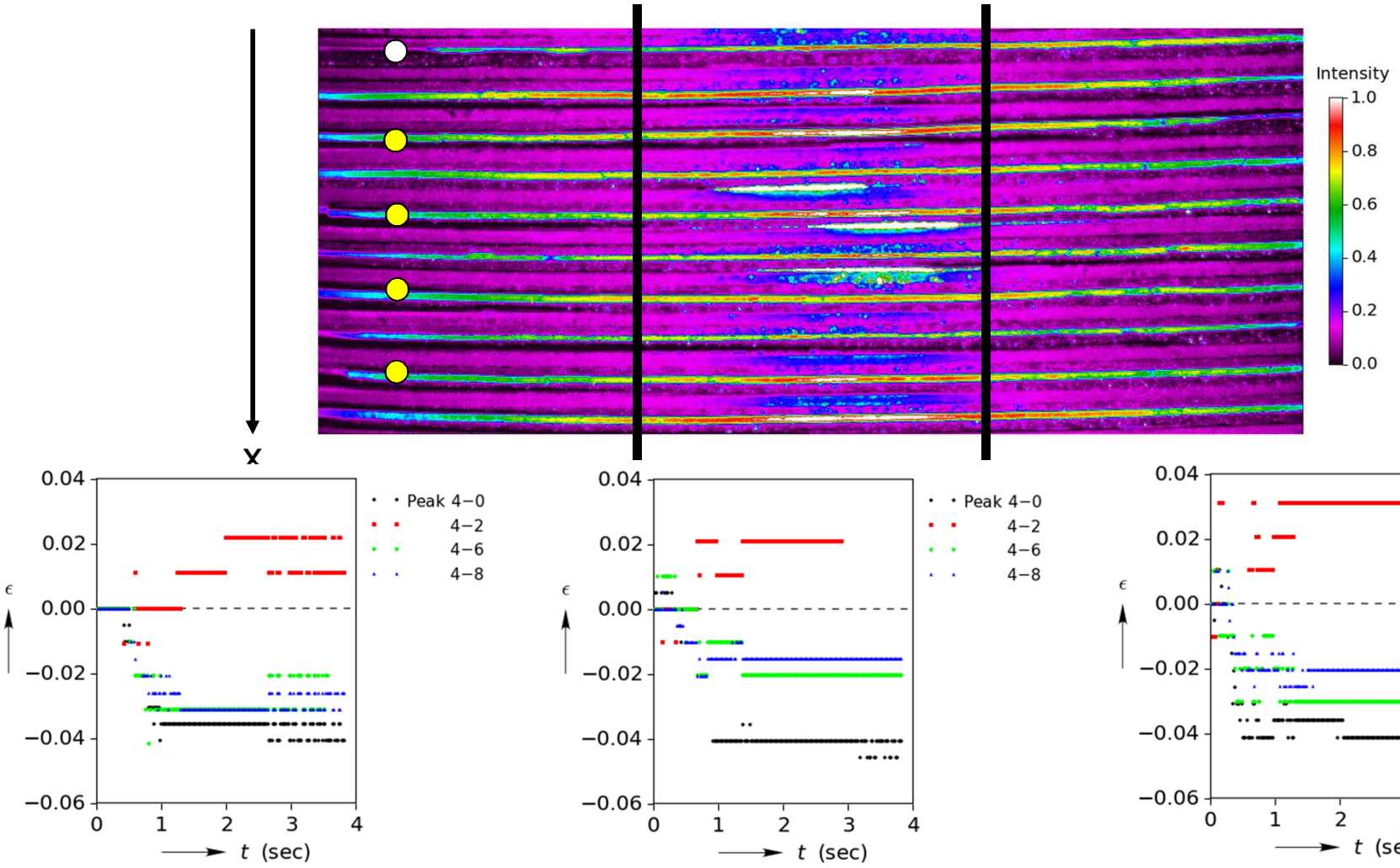






Strain vs. Time

10 cell MinK Relative to Peak 4
Full Time



Strain vs. Time

10 cell Fiberfrax Relative to Peak 4

Full Time