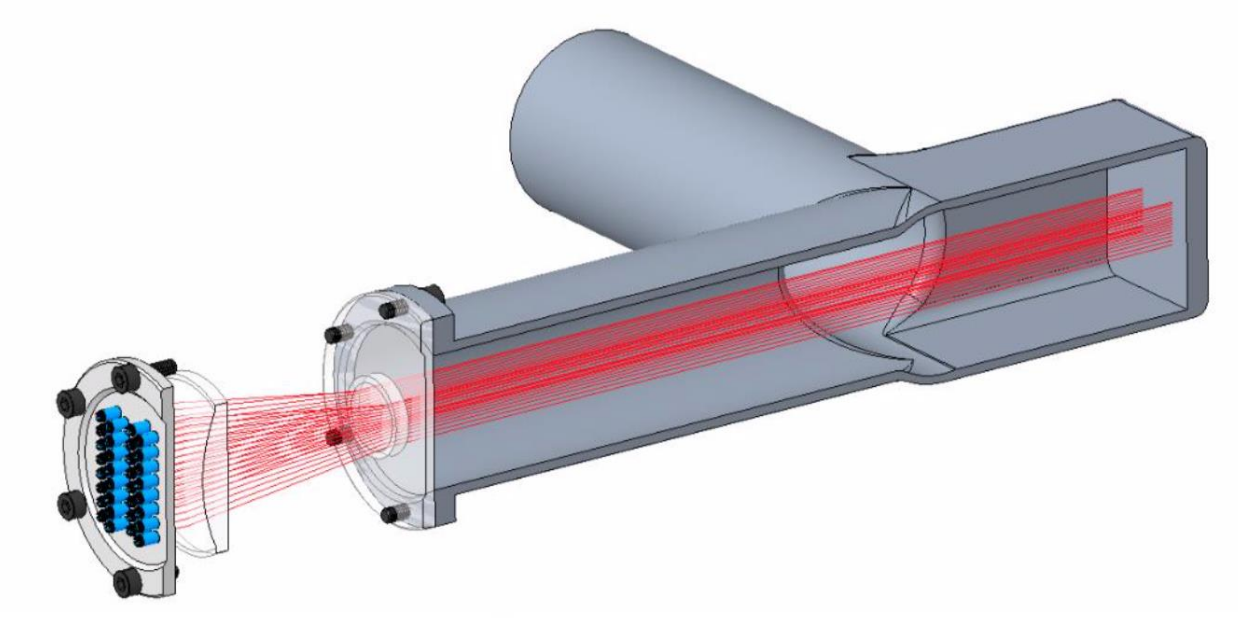
Non-invasive laser-based particulate counter for CEBAF

FRIB-APES Seminar



A. Sy

Friday, January 13, 2023

Acknowledgments

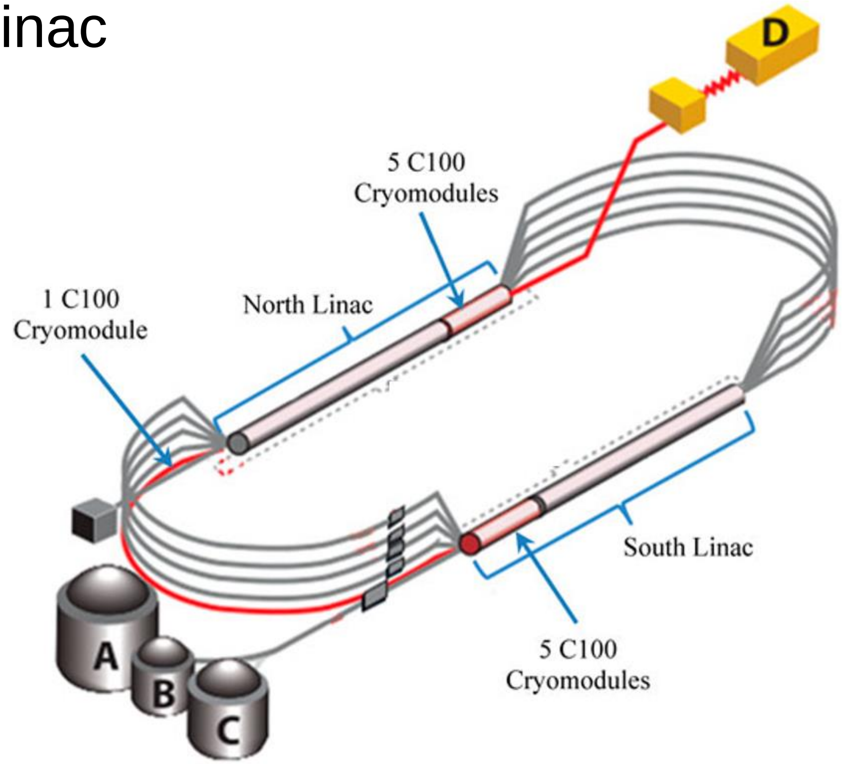
- This work was initiated by Rongli Geng (now at ORNL)
- The system is built by OmniSensing Photonics, LLC (Maryland)
- This is an ongoing effort with contributions from many at JLab: C. Zorn, J. McKisson, W. Xi, D. Weisenberger, M. Spata, K. Jordan, J. Gubeli, H. Zhang

Motivation

- 12 GeV upgrade to Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab completed in 2017
- Design energy of 1.1 GeV per linac

High duty factor/CW electron beam
1.1 GeV design per linac
Recirculating up to 5 passes (5.5)
4 experimental Halls
Polarized and unpolarized beams

Design energy of 11 GeV to Halls
A, B, C; 12 GeV to Hall D



- Operational challenges with legacy C20/C50 cavities and newer C100 cavities
  - Field emission a challenge in both types

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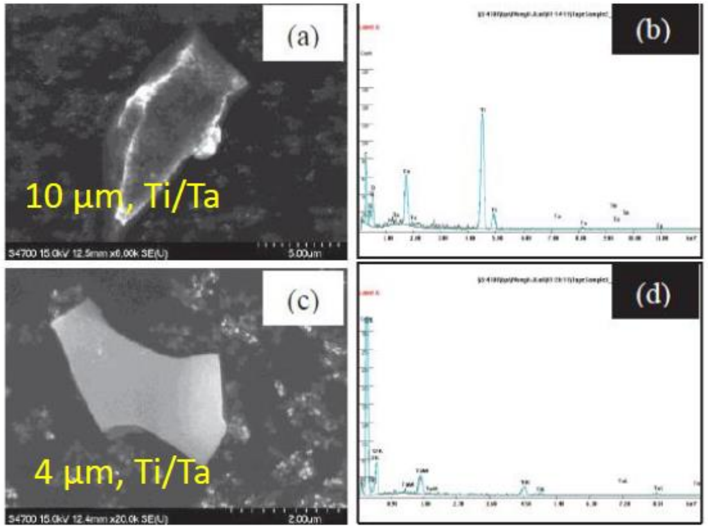
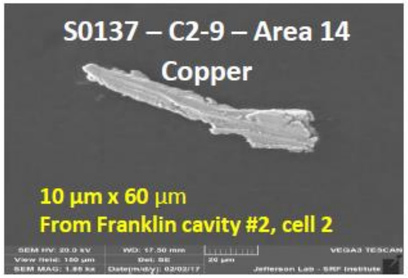
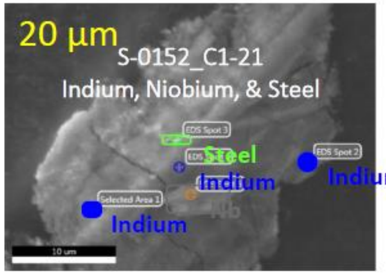
Motivation

- Field emission from particulates in SRF cavities prevents maximum operation efficiency
  - Cavity trips interrupt operation
  - Gradient reduction to reduce FE effects
  - Slow gradient loss over time
  - Prevents full energy reach of the machine



- Root cause studies found particulates on beamline surfaces, in cavities and girders
  - Metallic particulates dominate
  - Evidence of long distance transport of particulates





[Adapted from Geng et al., SRF2015 MOPB035]

Motivation

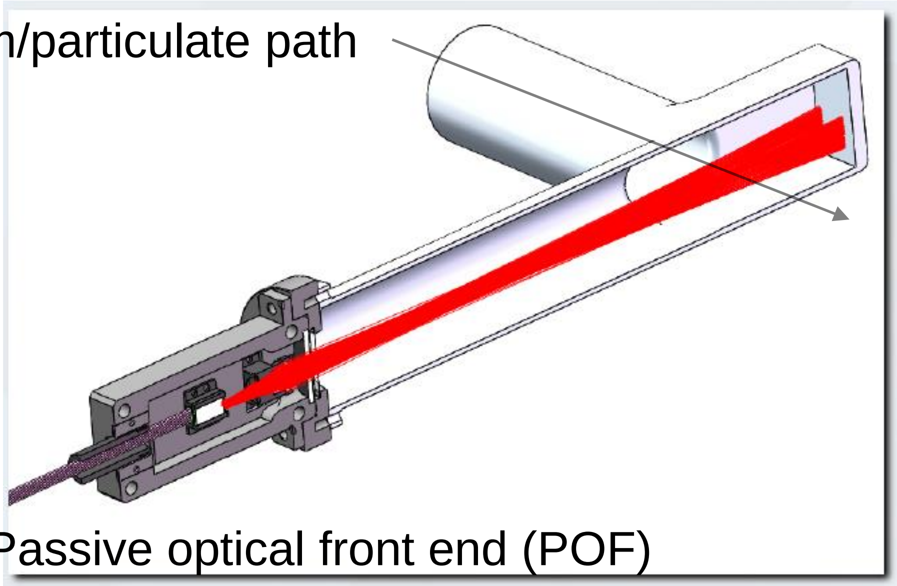
- Understanding particulate transport in the machine will provide better understanding of sources of particulates, inform mitigation techniques

- Based on root cause studies of particulate generation → want to be able to detect ~micron sized particulates, determine speed and direction of transport
  - Non-invasive technology is ideal

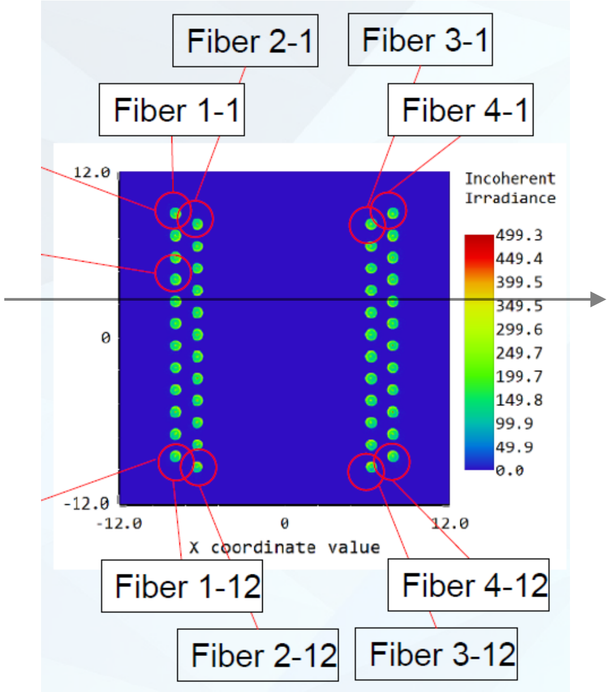
System concept

- Laser arrays for particle detection – detector mounted on a viewport for non-invasive operation
- Goals: detect particulates ~ few um in size at ~ 1 m/s speed
- Particle detection area ~ 420 mm^2 across beam pipe diameter

Beam/particulate path



Passive optical front end (POF)



Laser arrays offset for better coverage across active area

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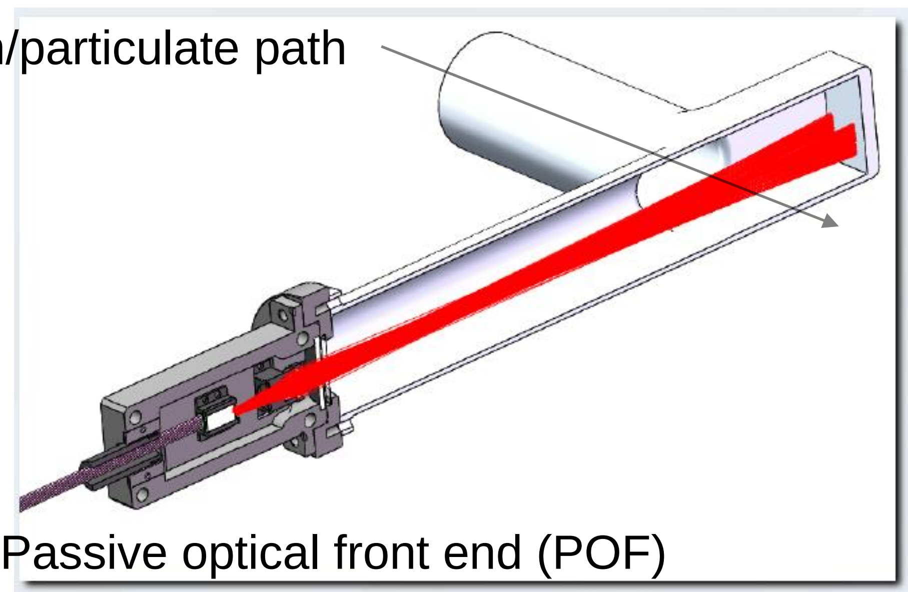
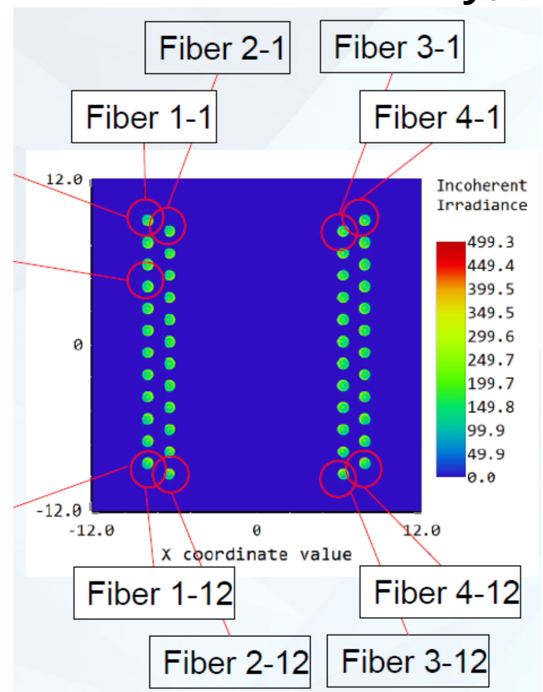
System concept

- Optical interference of two coherent laser beams created by splitting each individual laser
- Reference laser is phase modulated – detector laser enters vacuum side toward reflection surface
- Particulates crossing detector laser beams induce intensity, phase changes in interference signal

Beam/particulate path





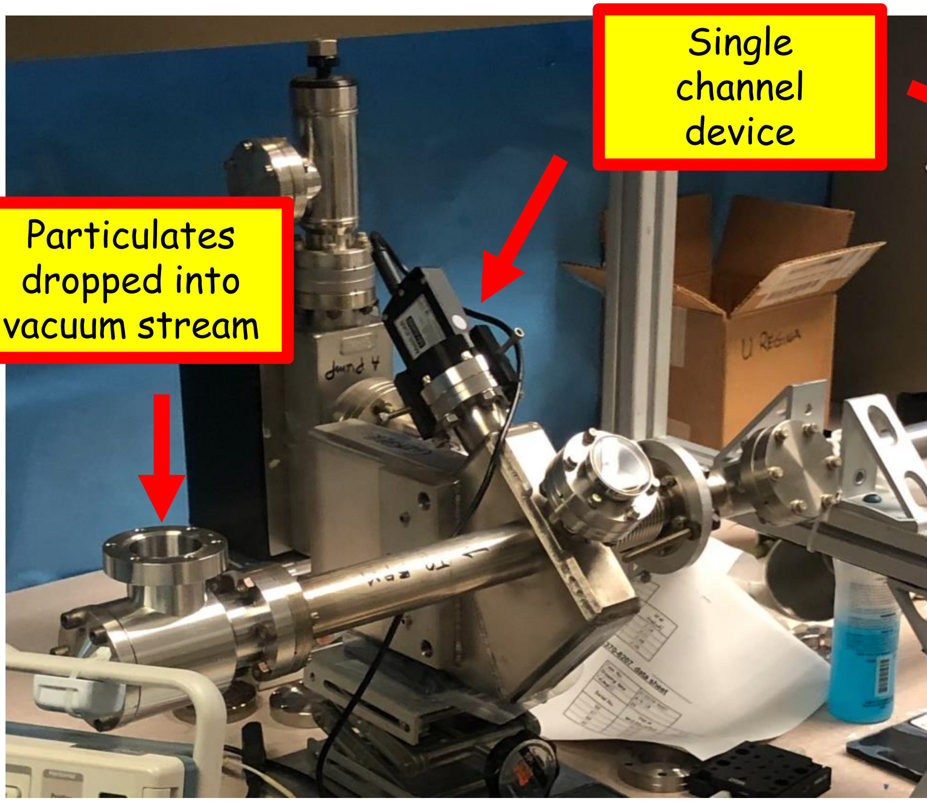
Groups separated by ~10 mm
Laser beam sizes ~ 800 um

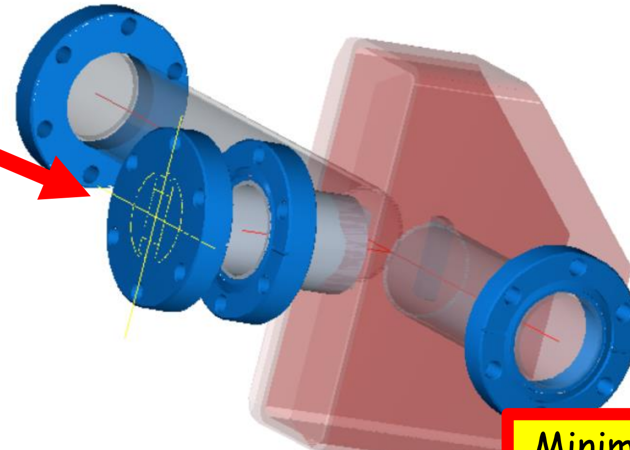
First prototype – testing late 2018

- System built by OmniSensing Photonics, LLC

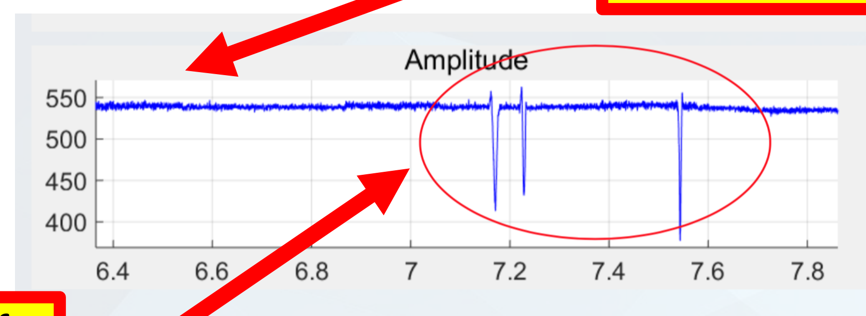
Particulates dropped into vacuum stream

Single channel device





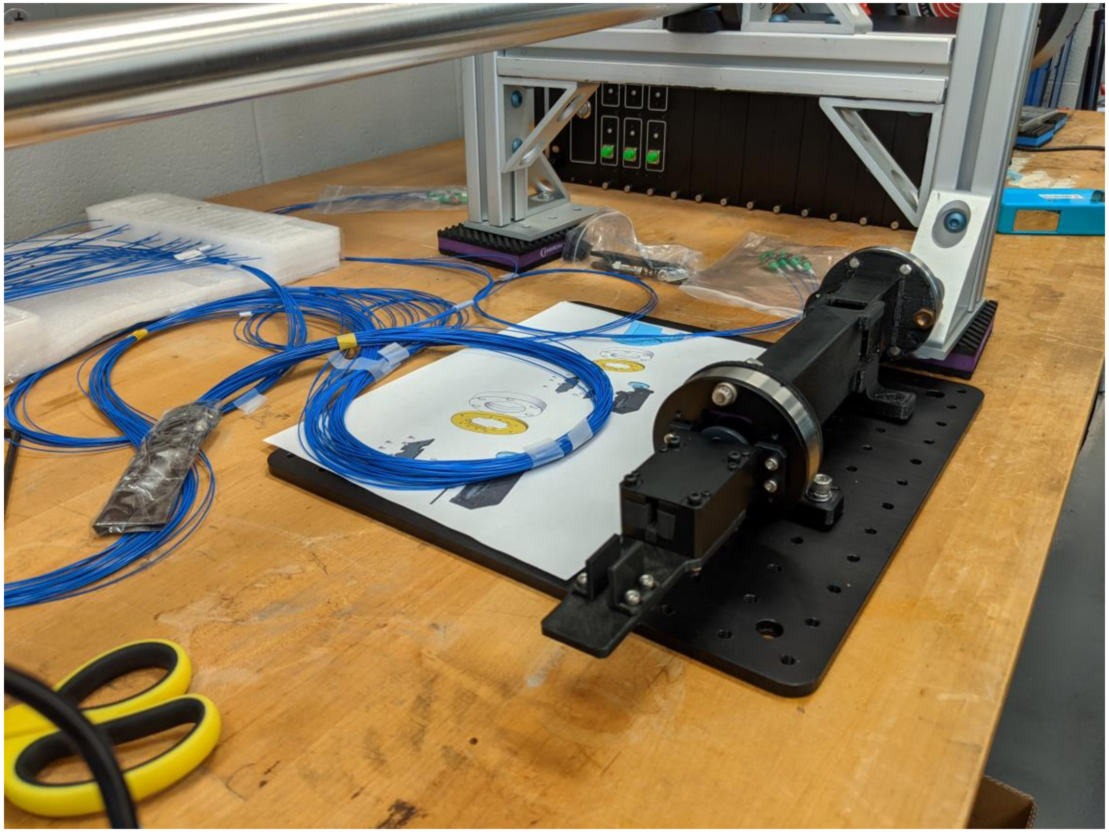
Minimization of microphonics important

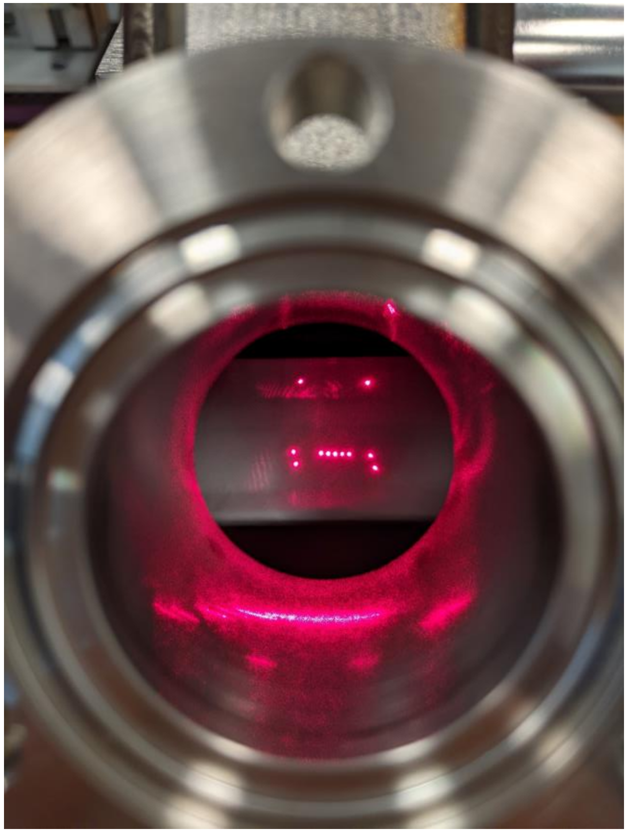


Passage of particulates detected

[Adapted from C. Zorn]

6-channel prototype at JLab – delivered 05/2021



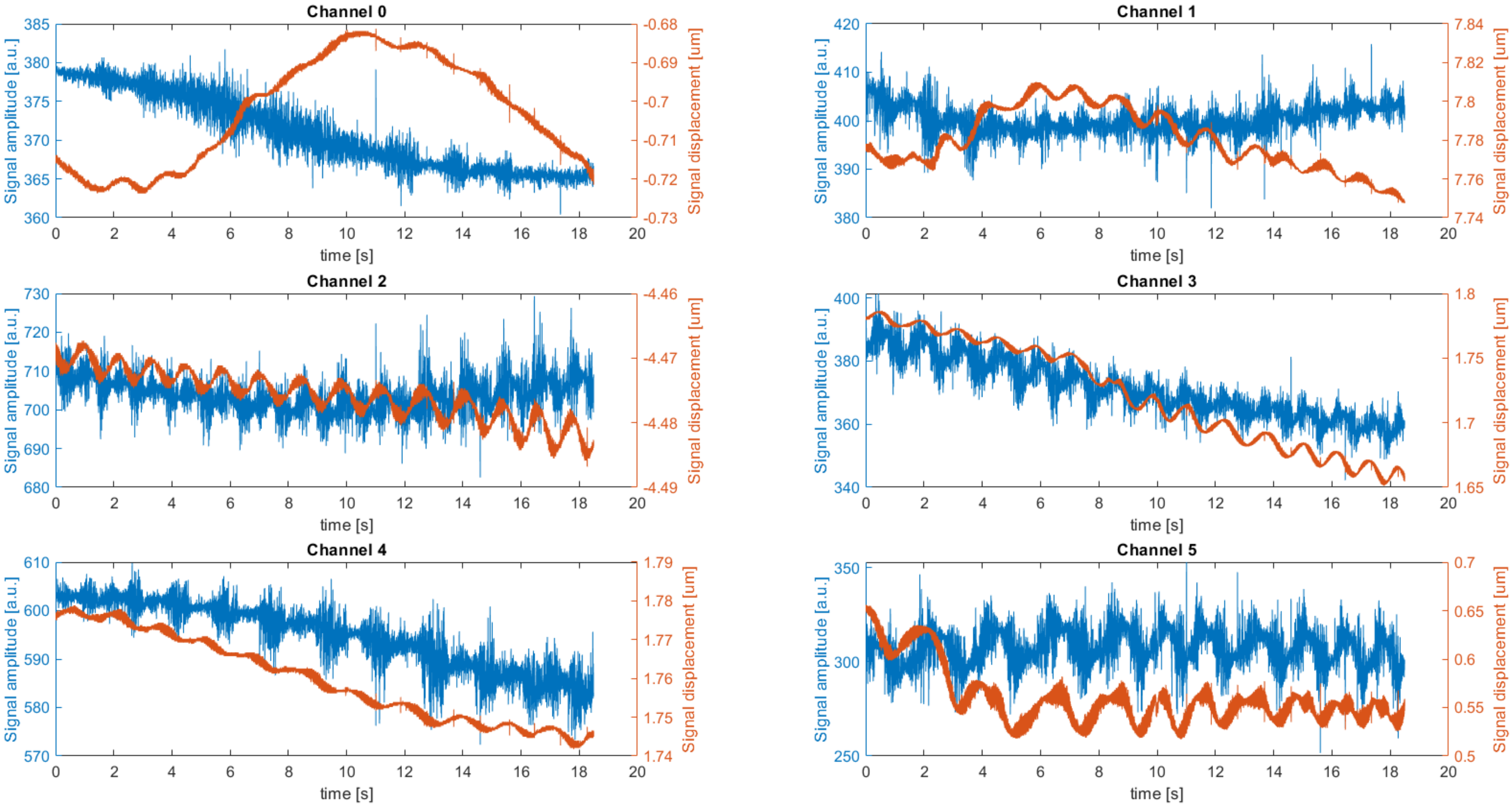


POF mounted on OSP's test apparatus
Chassis with six sensor modules in the background

POF mounted on pump drop, with visible light connected to fibers for alignment purposes

6-channel data analysis – 06142021

- Amplitude and displacement signals from all six channels, wire sweeping test



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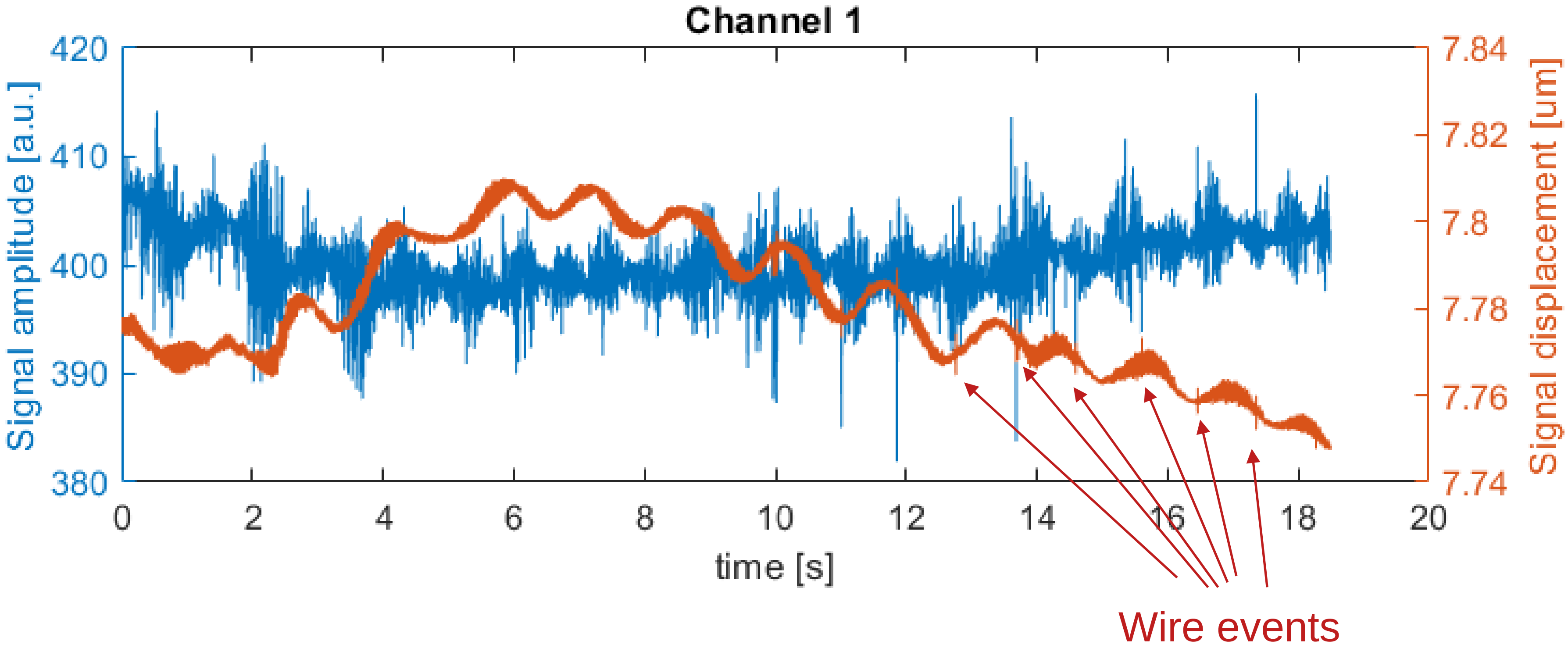
6-channel data analysis – 06142021

- In this particular dataset, no events in the first half
- Events more easily seen in the displacement data vs amplitude data
  - Higher data resolution in displacement signal – future software upgrade to enable swapping resolution between the two



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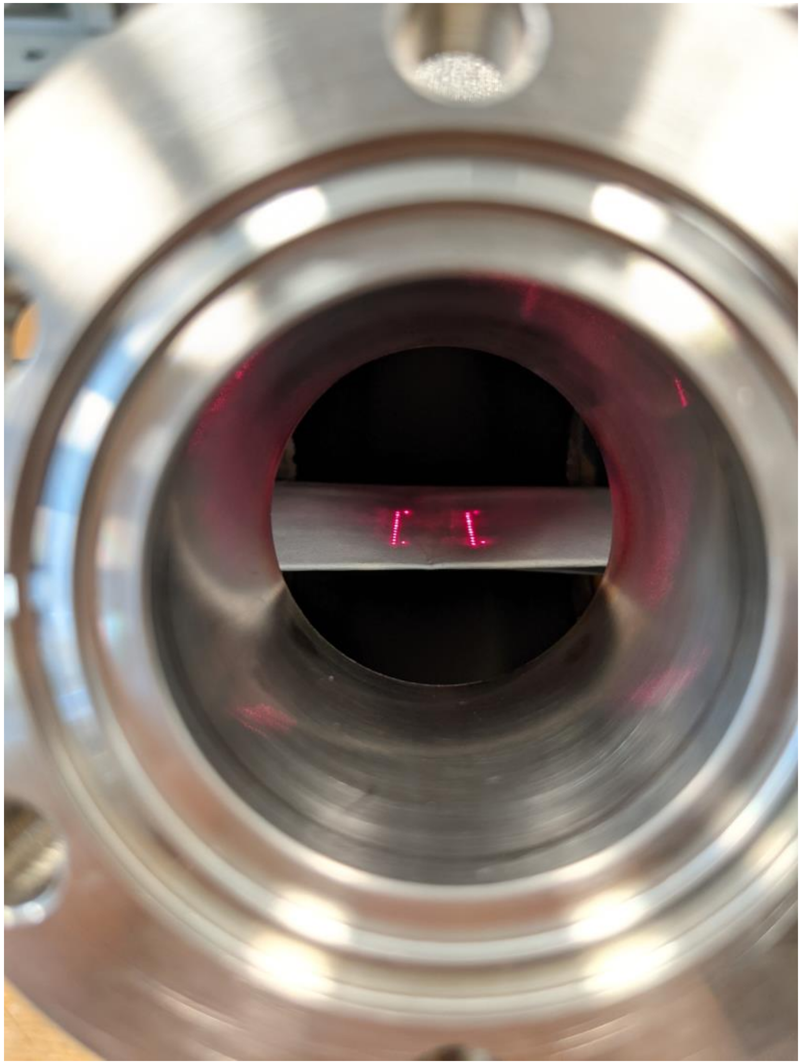
24-channel bench tests

- 18 channels delivered in July 2021 for a fully populated chassis



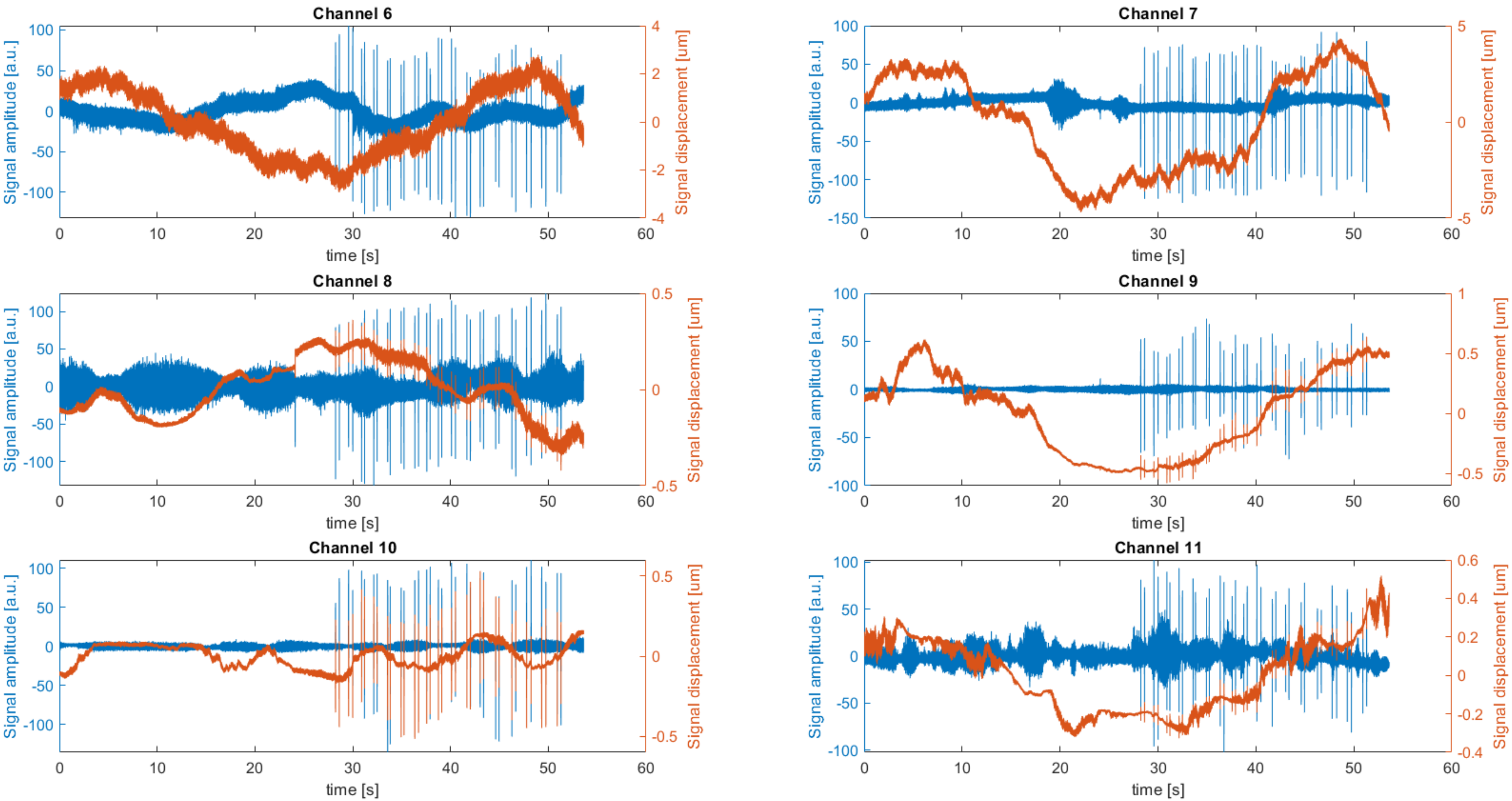
24-channel bench tests – initial pass/fail testing

- SNR improved with new laser stabilization algorithm, noise reduction algorithms in data processing

- Testing conditions: sweeping of 80 µm diameter wire across all channels (twice, back and forth) at approximately 1 Hz rep rate
  - Three datasets with approximately 34-36 wire sweeping events per dataset
  - Pass defined as capturing > 90% of wire sweeping events
  - False positive and false negative rates < 10%

24-channel bench tests – initial pass/fail testing

- 20210820_015815 raw data



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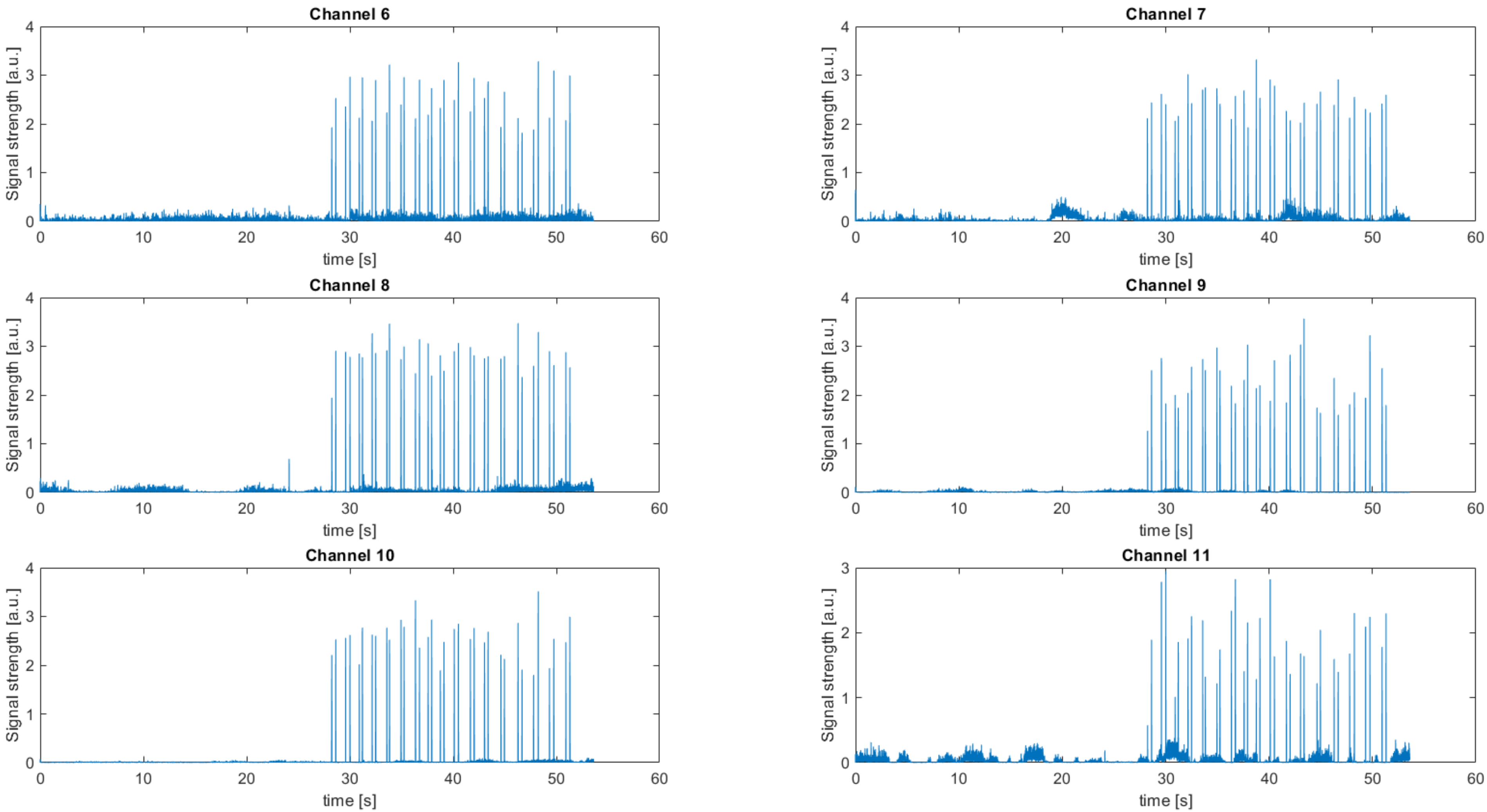
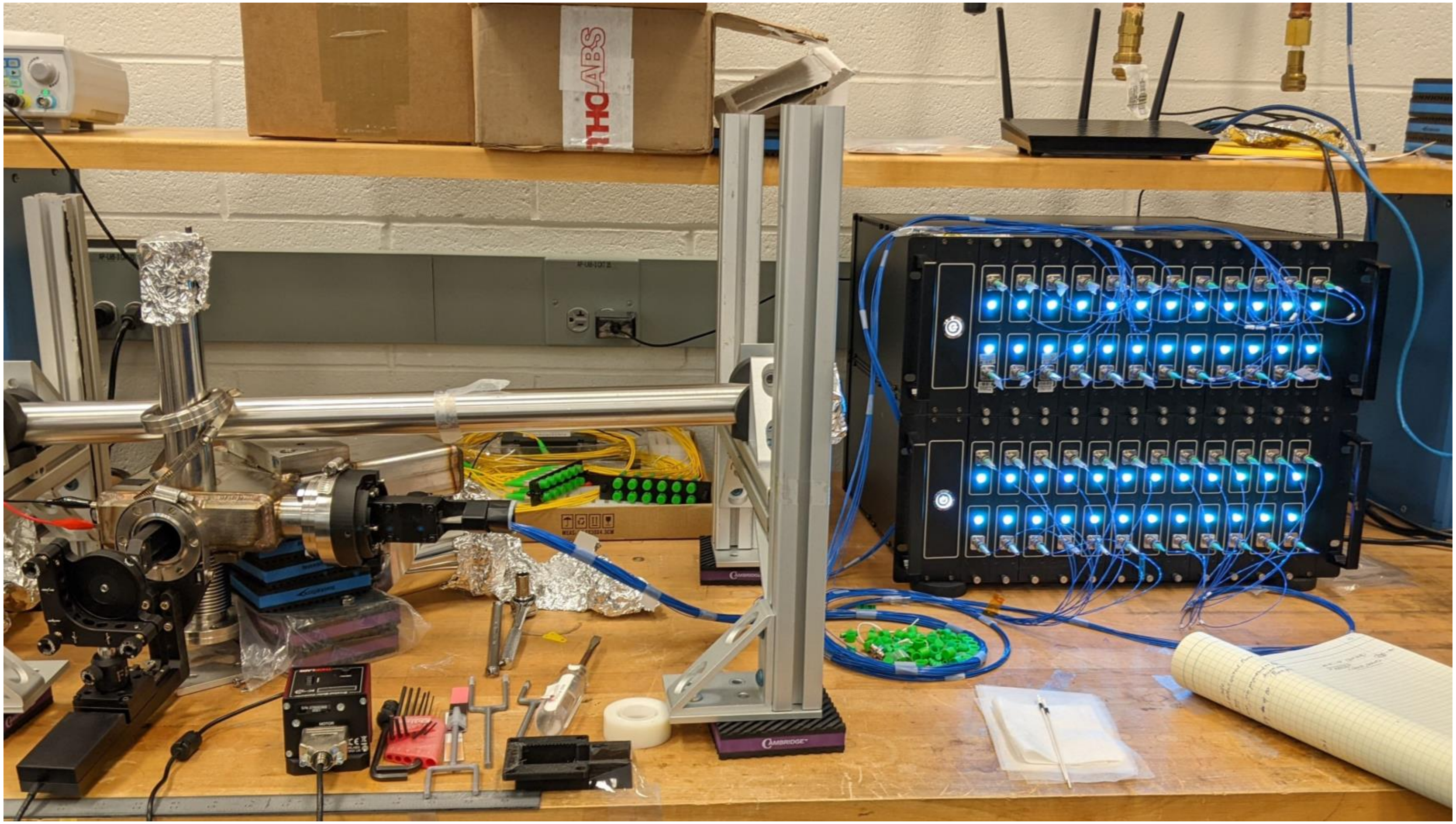
24-channel bench tests – pass/fail testing

- 20210820_015815 postprocessed data, version 2 (peak-to-peak)



48-channel bench tests

- Fully populated system delivered December 2021

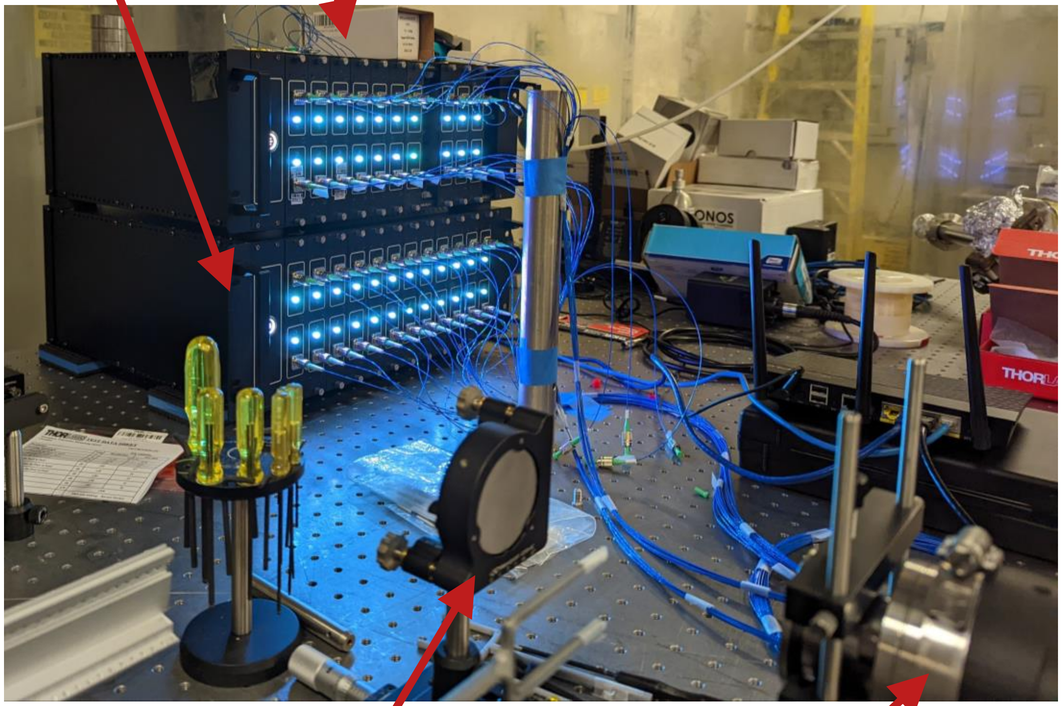


Particle detectability studies

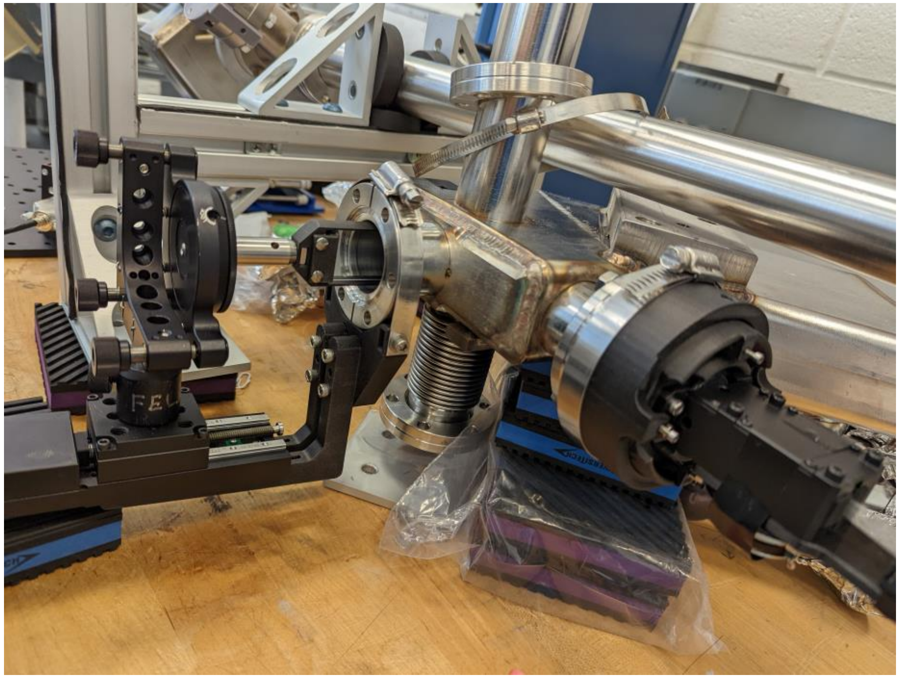
- Good SNR for wire sweeping events, but a wire is not a free particle

- It's hard to approximate free particles!

- Current efforts focus on defects in transparent materials on translation and/or rotational stages
  - Open detector setup for ease of characterization and introduction of "events"



Particle detectability studies: linear stage test



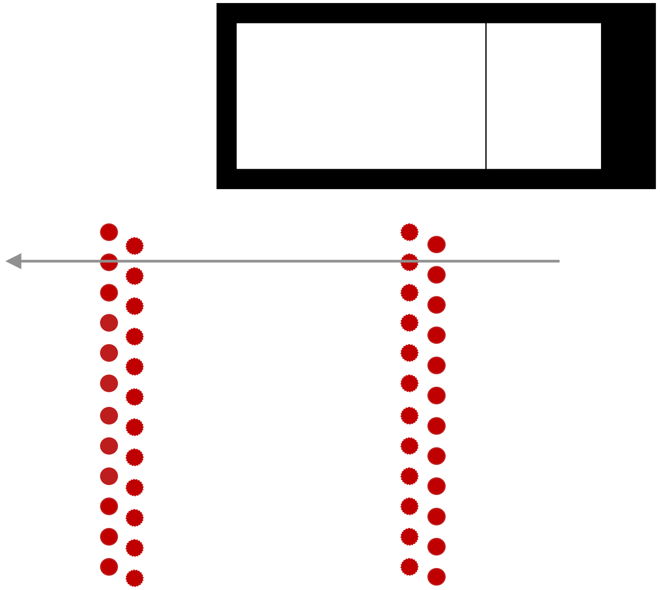
Translation stage with slide holder mounted on pump drop

~0.5 mm particle stripe, 20-70 μm “particles”

Particle detectability studies: linear stage test

- Particle stripe translated from fully extended to fully retracted within pump drop

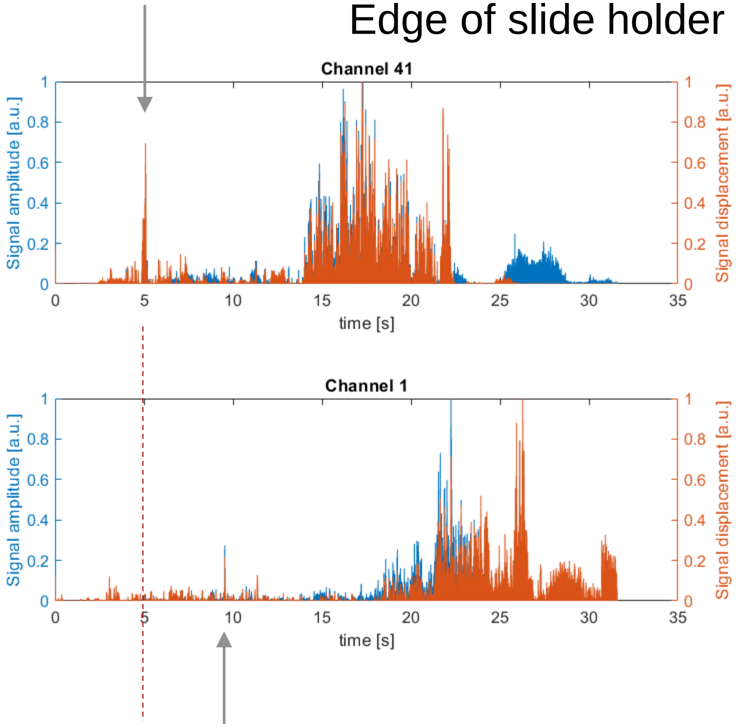
Microscope slide translated across laser arrays



Laser configuration in plane of reflection surface

Signal from stripe

Edge of slide holder



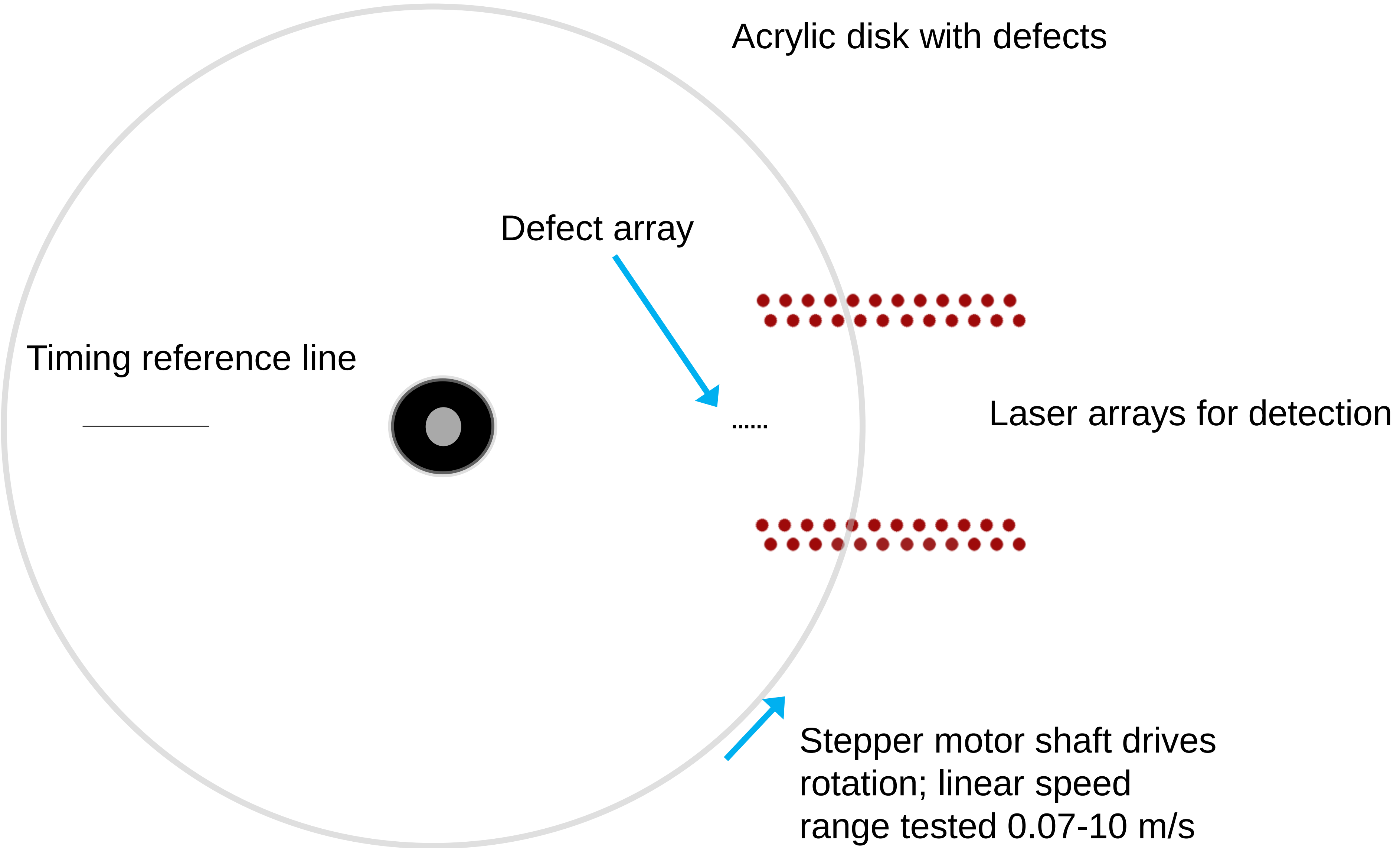
Signal from stripe
Δt=3.7 s ⇒ 9 mm spacing between these arrays

Particle detectability tests

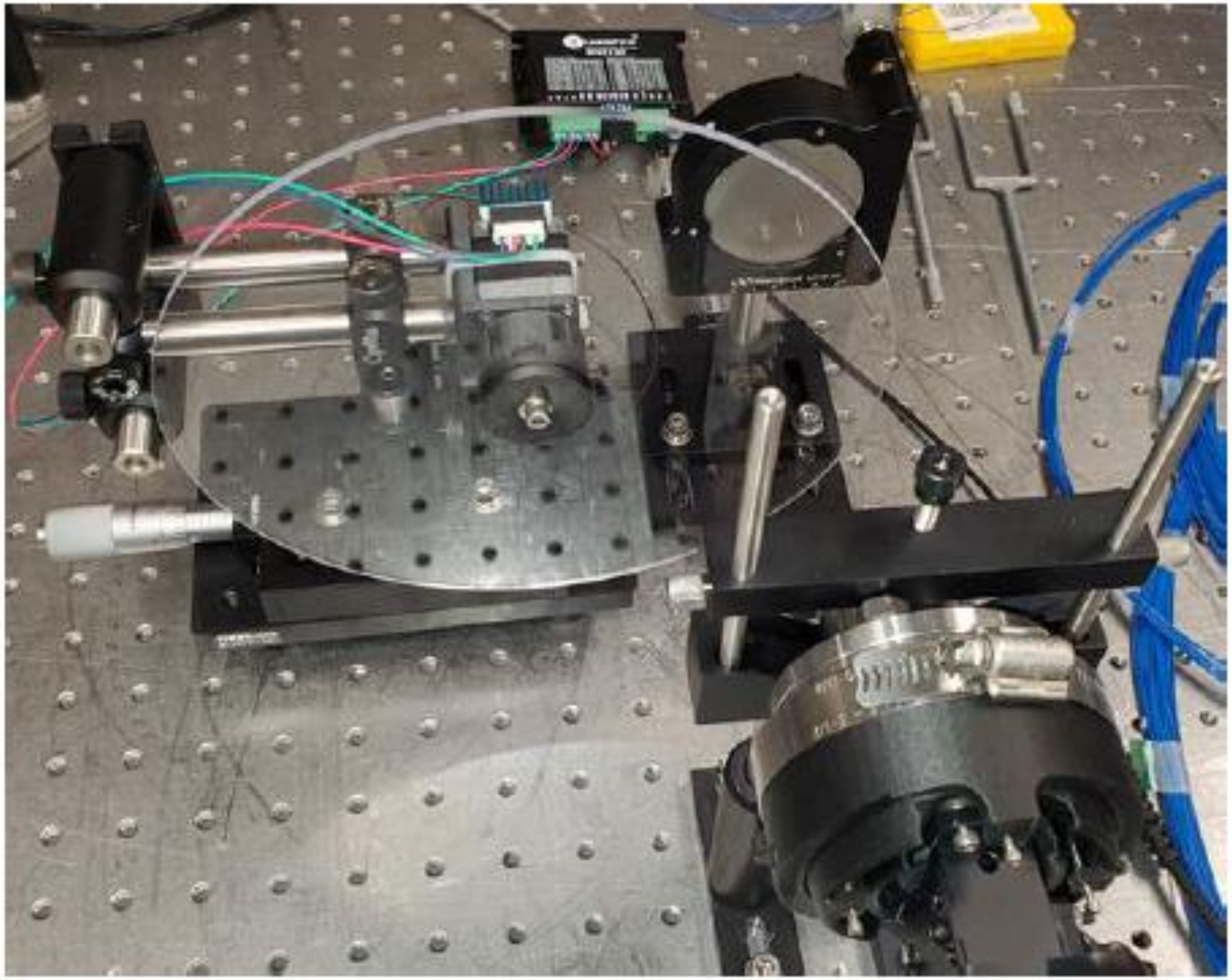
- Opening up the setup gives greater flexibility in testing methods
  - Separation of detector mounting surface from reflection plane
- Rotational stage setup allows for higher linear speeds
  - Known time structure helps us verify the signals we are seeing are induced by the generated defects
- Defects are generated on acrylic disks using a 350 nm UV laser
  - Vary power and exposure time to vary defect size

- OSP simulations suggest a lower limit of ~100 um for detectable particle size with current hardware
  - Based on change in received power in laser

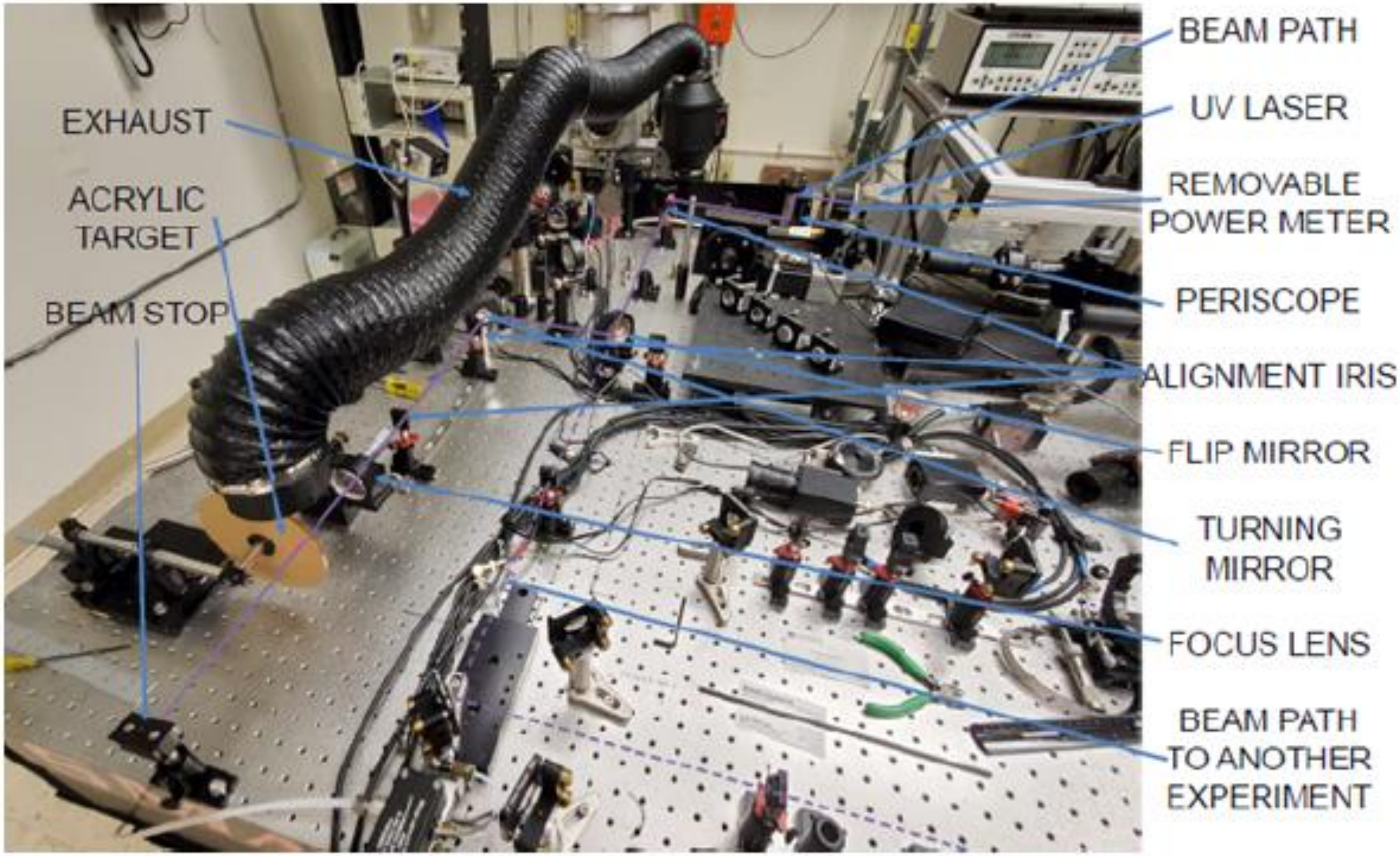
Rotational stage testing setup



Rotational stage testing setup

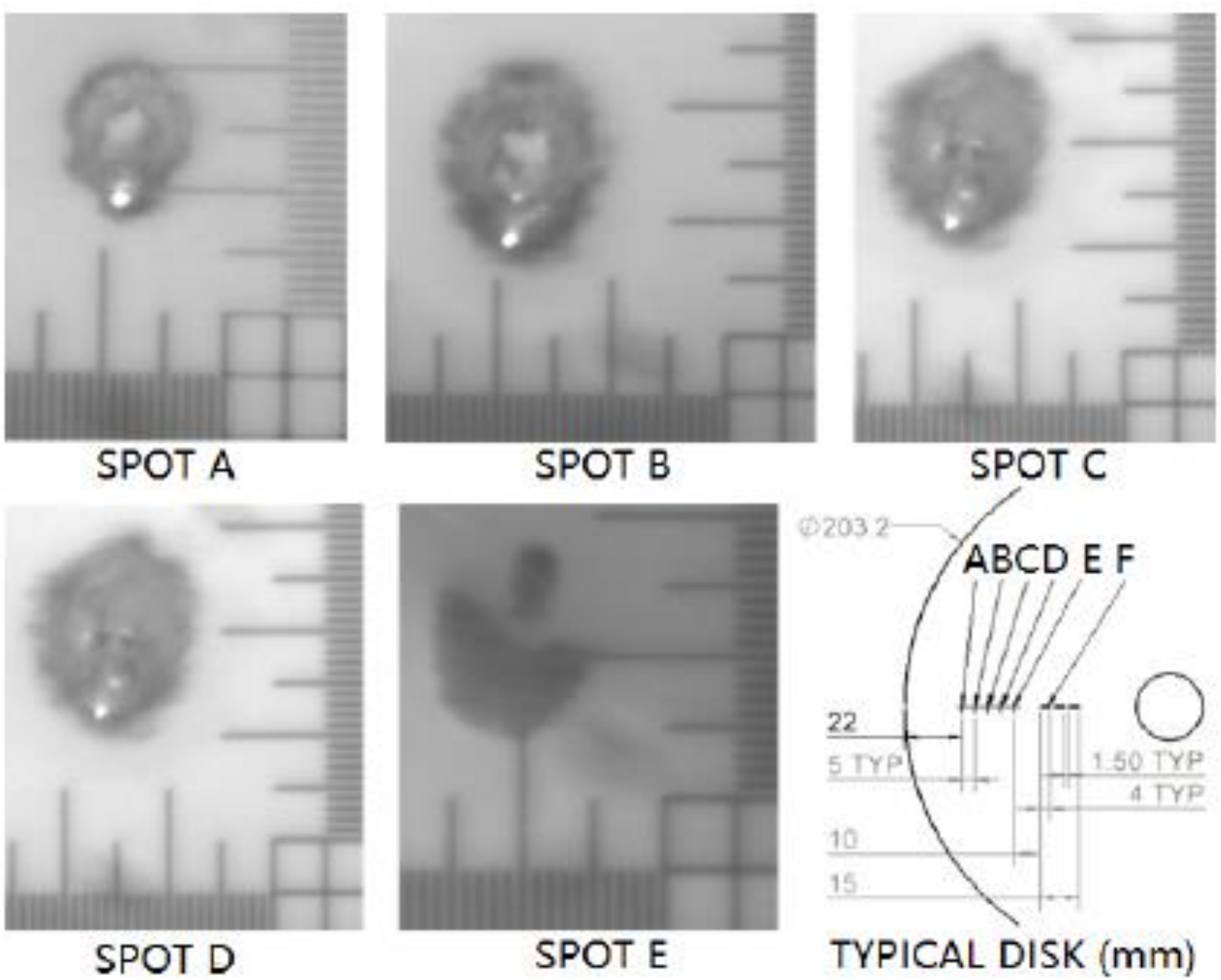


Defect generation setup



Defect generation setup

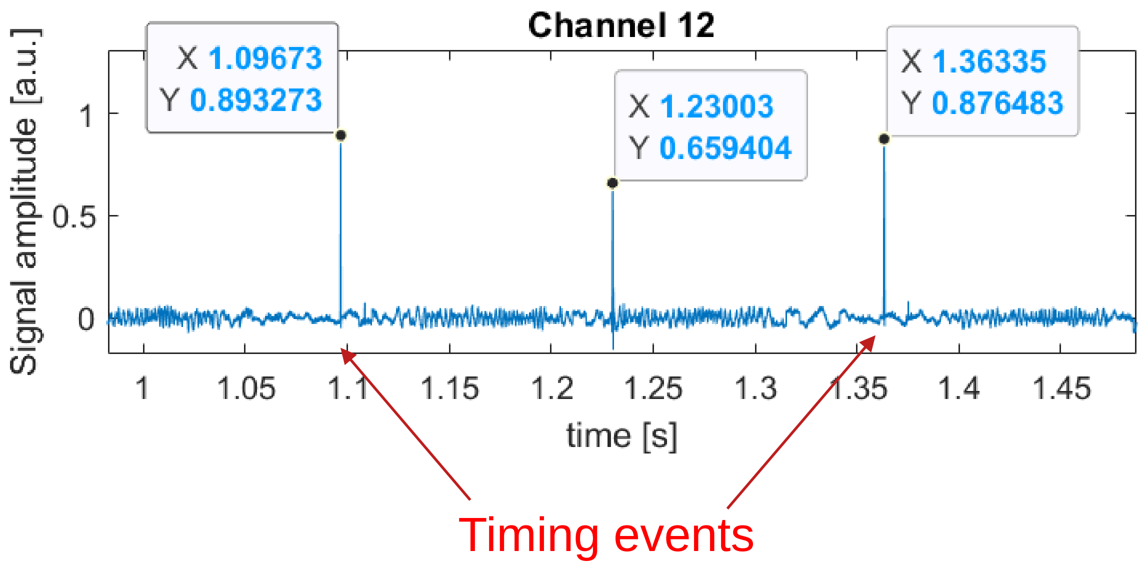
- Defects filled with metallic ink after laser exposure



Spot A: ~125 um
Spot B: ~180 um
Spot C: ~190 um

Not pictured: timing reference line at 180 degrees to defects

Verifying time structure of data



- Timing reference lines show as much stronger signal peaks
- Period of timing reference lines easily corresponds to revolution period of the acrylic disk
- True signal peaks from defects can only occur in time window halfway between reference lines

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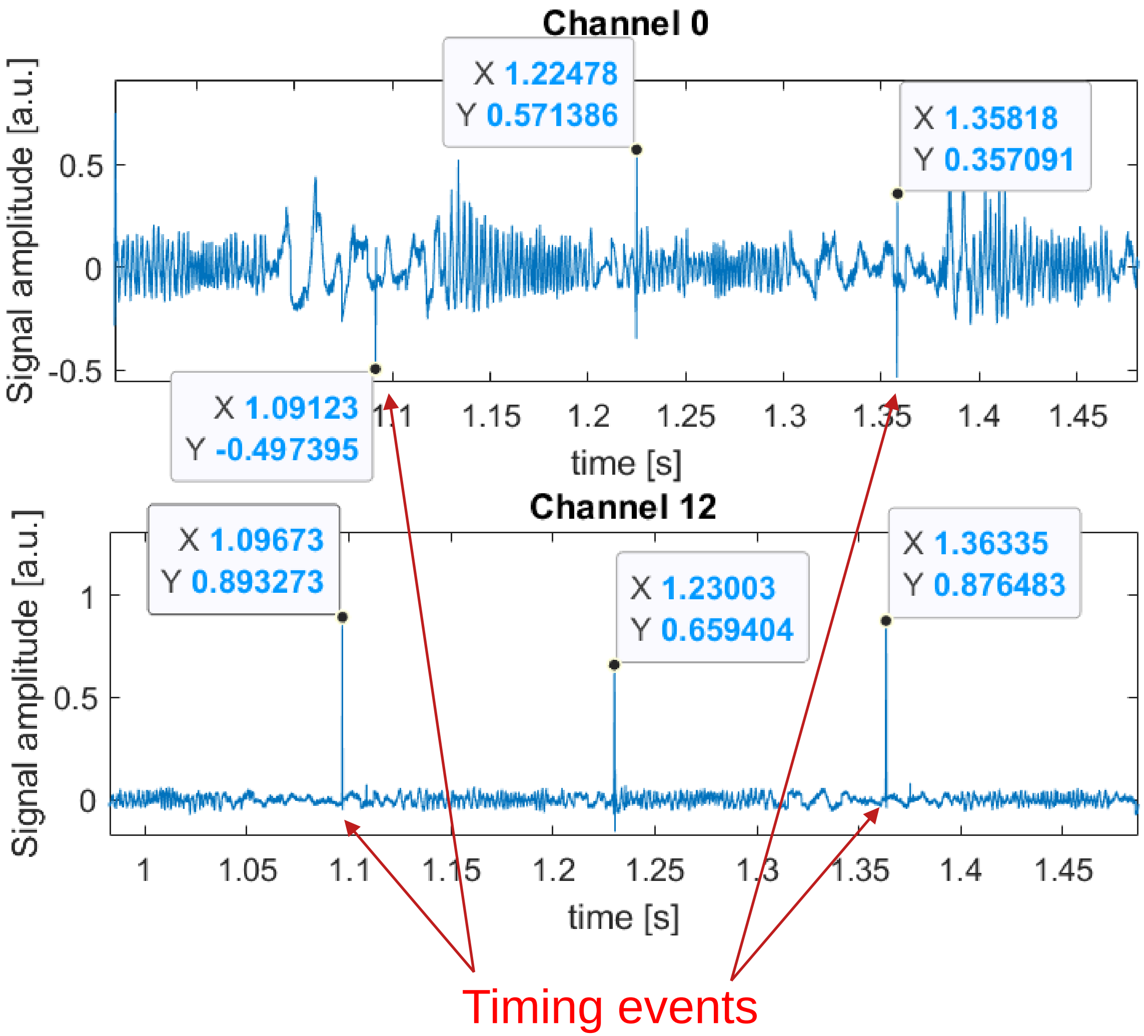
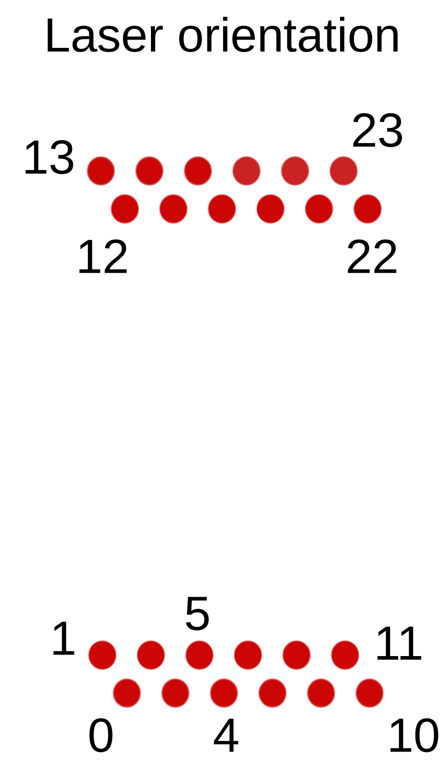
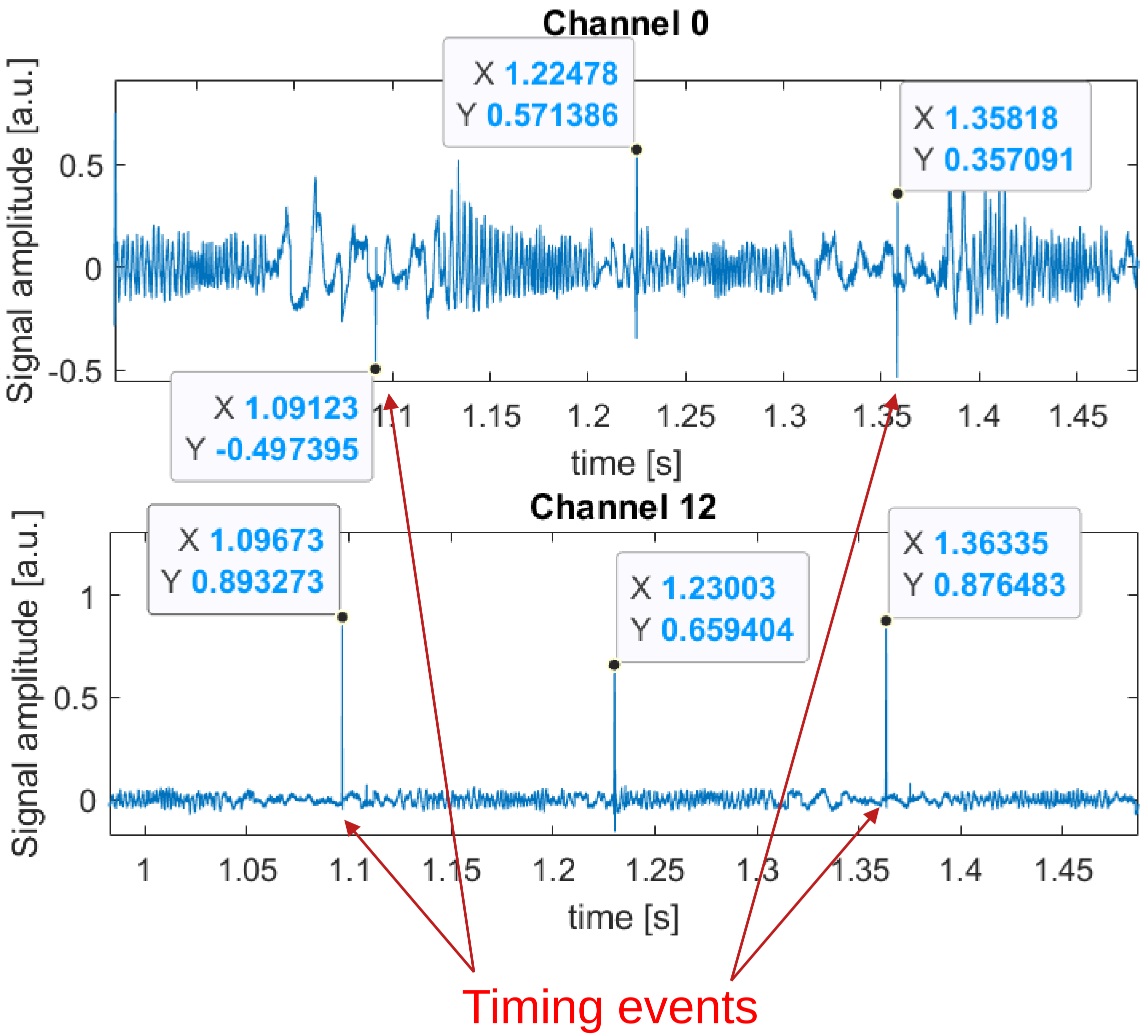
Determining defect speed





Determining defect speed



Defect spot B at r=74.6 mm
Rotation frequency 3 kHz

Stepper motor resolution of 800 steps per revolution

True linear speed of timing line at r=74.6 mm: 1.758 m/s

Physical linear separation between channel 0 and 12
Δl=9.83 mm*

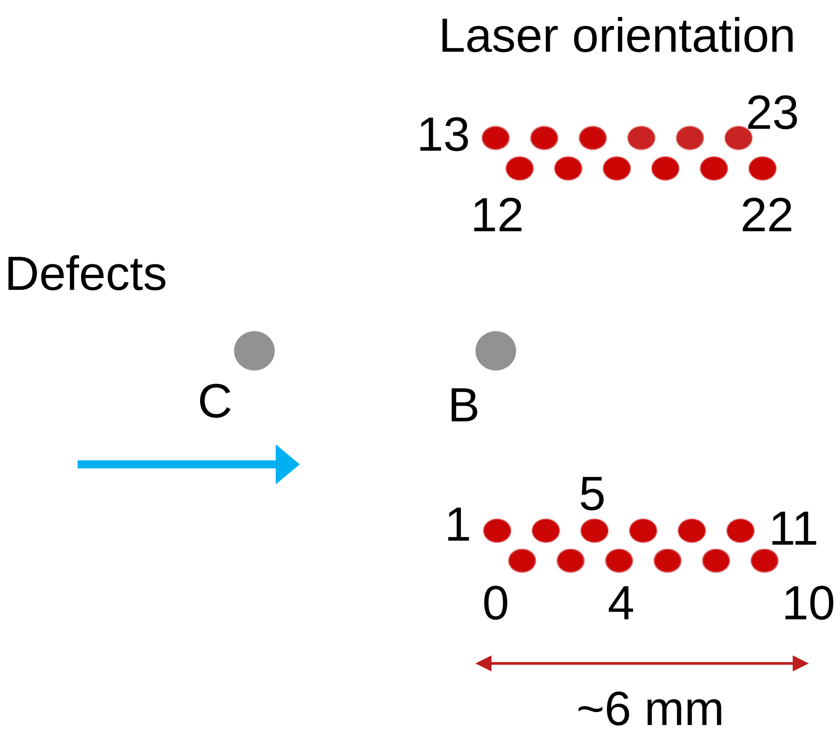
Time between events
Δt=1.23003-1.22478
=0.00525 s

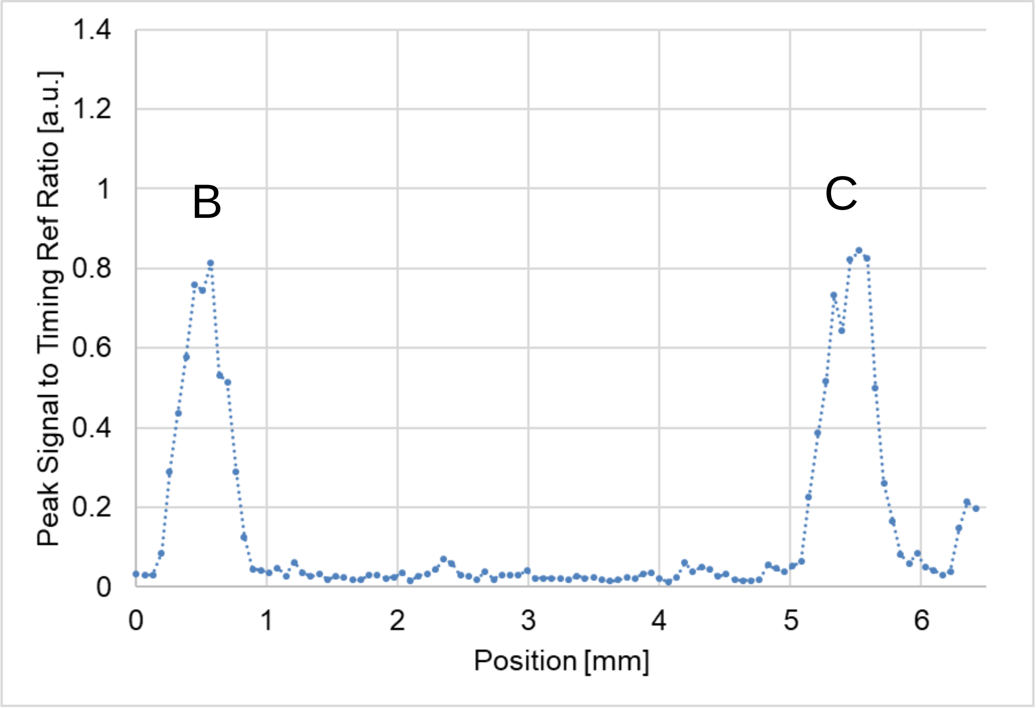
v=$\Delta l/\Delta t$=1.874 m/s

7% discrepancy

Detectability threshold testing

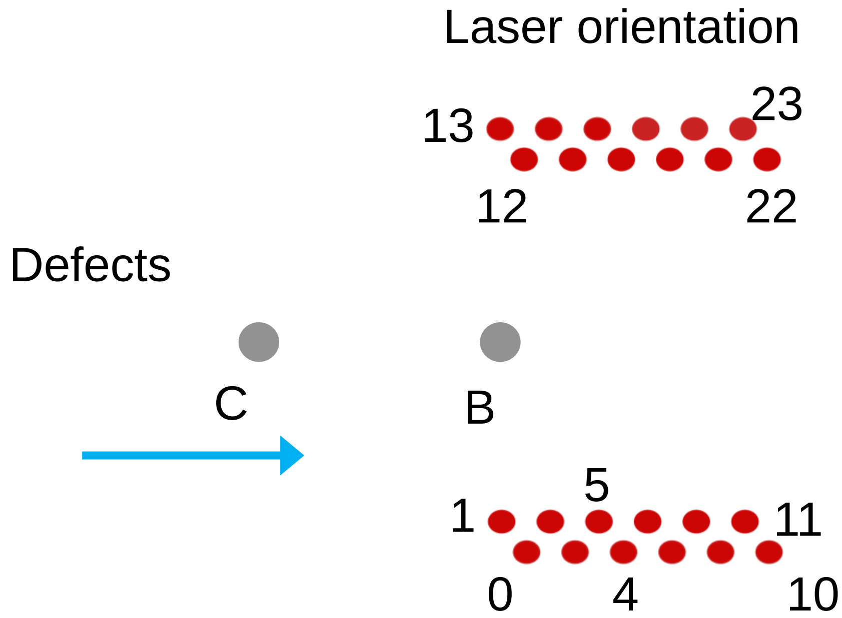
- Typical response of single channel when translating defects across 6.5 mm range
  - Spot B (feature size ~180 um) response in laser channel 00
  - Y-axis plots ratio of peak data signal to peak timing reference signal



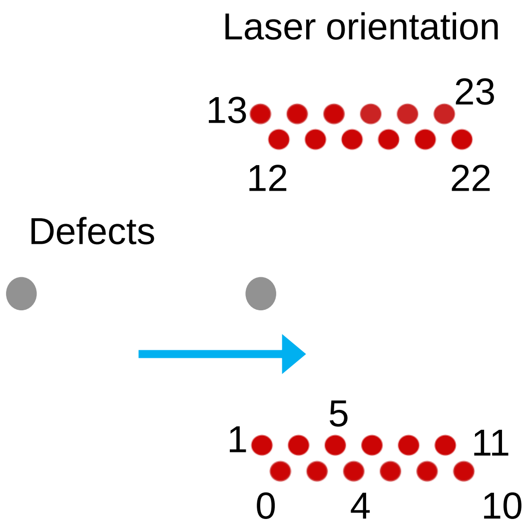


Detectability threshold testing

- Laser beams are focused on internal reflection plane, but particulates pass through the beams at a plane upstream of this location
- Beams are larger at detection plane; particulates may induce signals in two adjacent detection channels
- Current efforts are focusing on understanding this response by translating the defects across all active laser beams

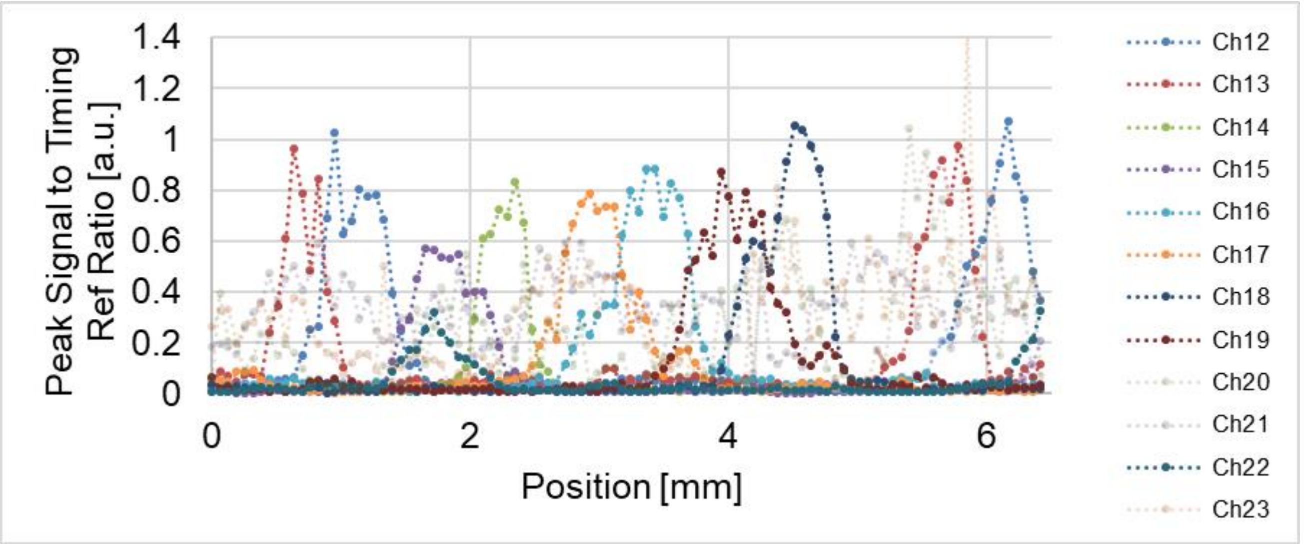


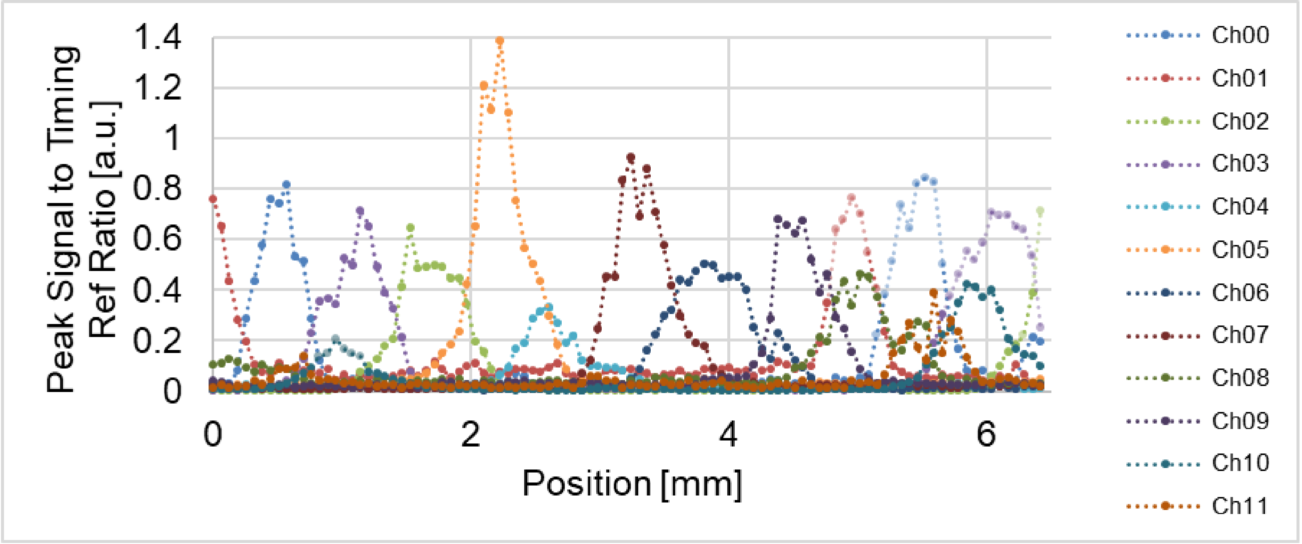
Detectability threshold testing



More uniform response for top row of lasers

Overlapping curves tell us events may be seen by two adjacent channels at once





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Detectability threshold testing

- Similar tests done translating spot A (125 vs 180 um)
  - Approaching the predicted 100 um lower bound for particle size

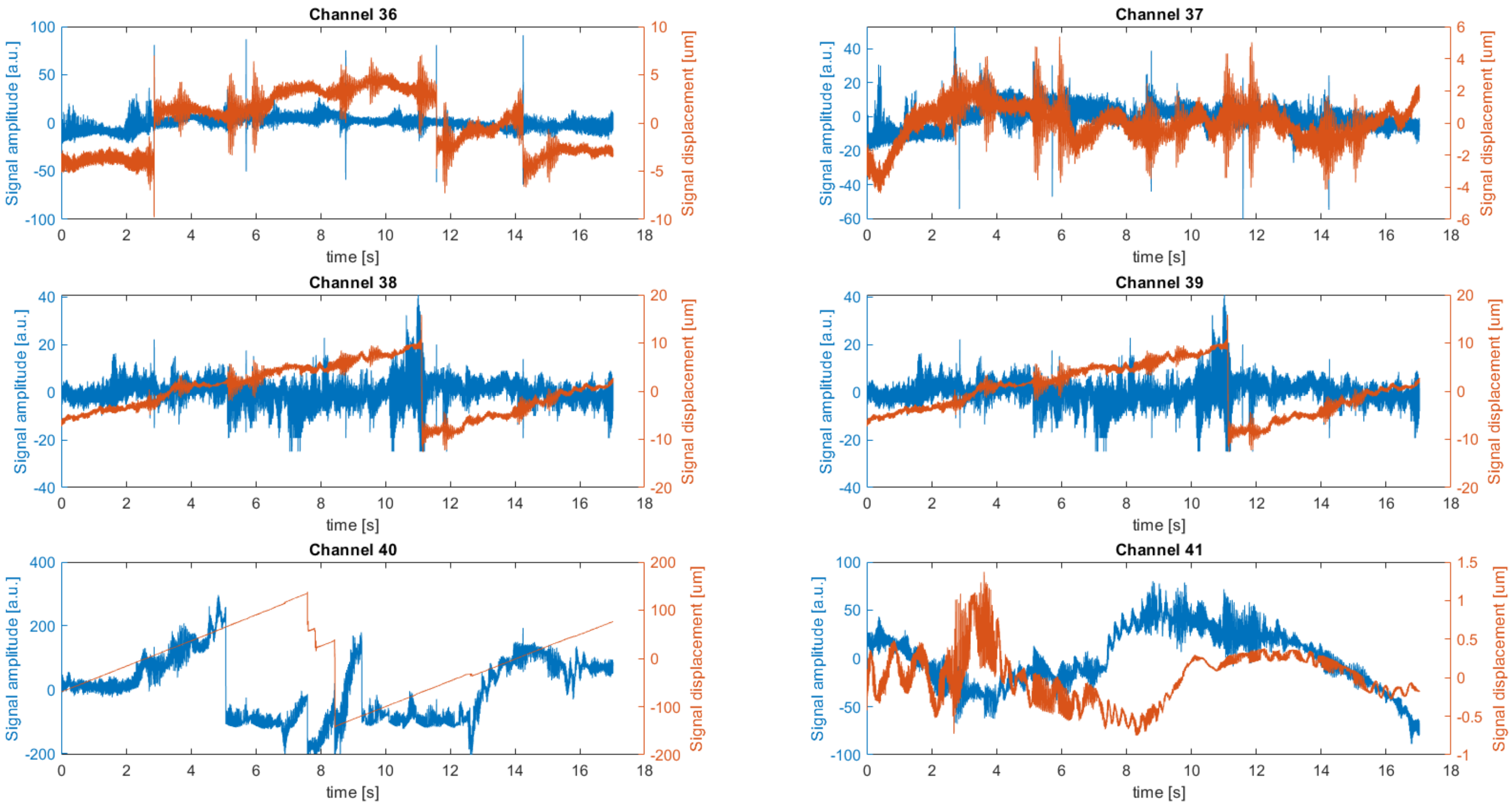
Current challenges

- Data processing in current detectability threshold studies relies heavily on the known time structure of the real signal
  - Restricts background signal range to short window around timing line
  - Future work will have to evaluate how this signal processing changes when the time structure is unknown
  - Multiple events?

- Single particle event testing – well controlled source of single particulates
  - Laser-induced projectile impact testing (LIPIT) as a particle source?

Autonomous event identification

- A spike associated with an “event” has specific features that are identifiable by eye
  - Very obvious what is signal and what is noise for “large” events



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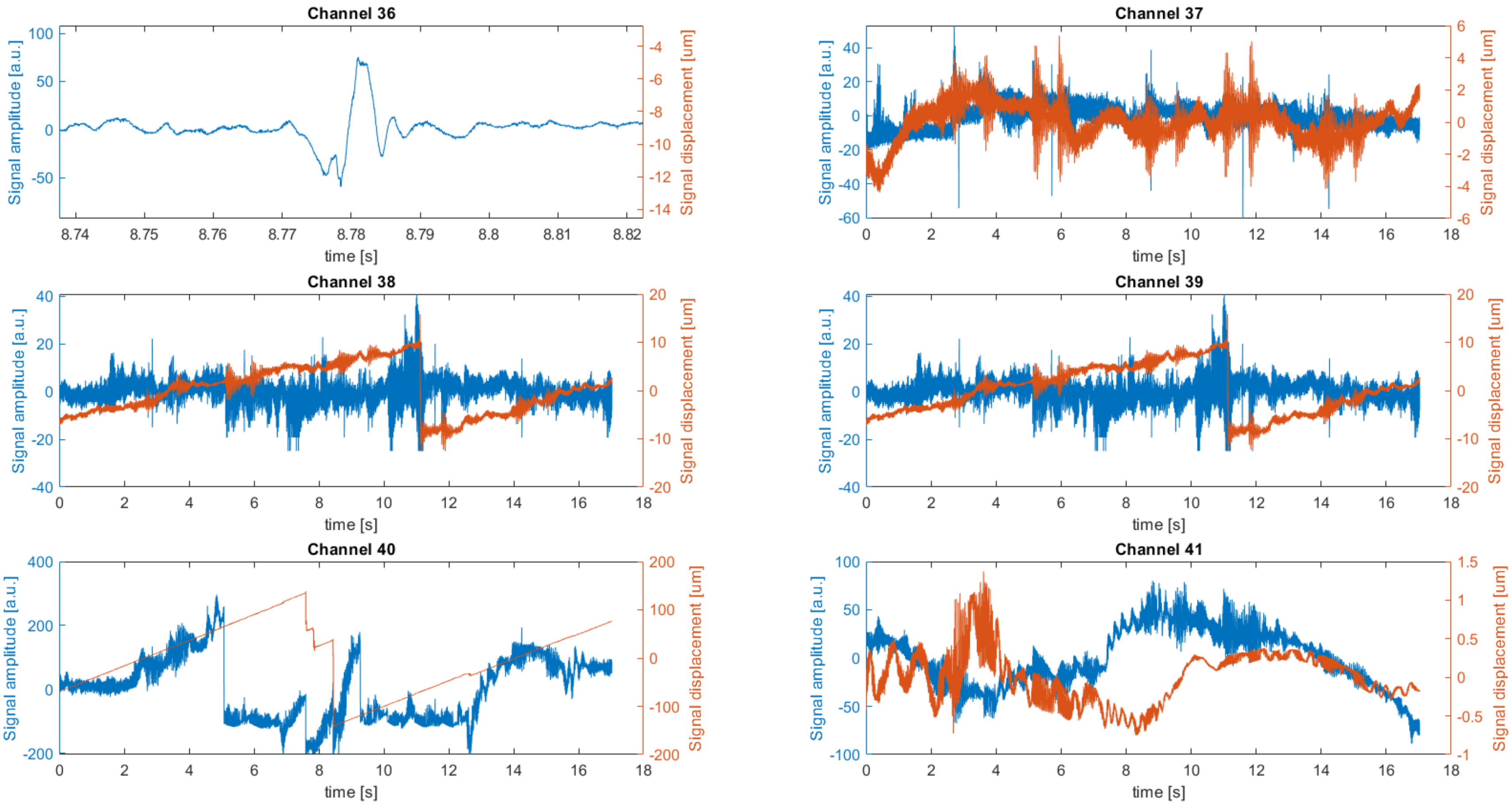

Autonomous event detection

- Potential for machine learning application for event identification
  - Submitted a proposal to NP AI/ML FOA call to apply ML techniques for autonomous event identification
- Event triggering for data saving
- Evaluation of more complex system response (i.e. simultaneous events)

Field test prospects

- System characterization and hardware limitations still barriers to a field test
  - Increased fiber length to keep electronics out of the tunnel

- Initial tests of radiation hardness were promising – no degradation in system response

- Utility of system with 100 um lower bound on event size

Summary

- Evidence of long distance transport of particulates in CEBAF motivates exploring methods to monitor particulate transport
- JLab and OmniSensing Photonics have been developing a non-invasive laser-based particulate counter
  - Tests with current system indicate a lower limit on detectable event size on the order of 100 um
  - Event speeds in the range of ~ 7 cm/s to 10 m/s have been measured with the system
- System characterization is challenging and ongoing
- Potential for a field test remains