Center for Advanced
Non-Ferrous Structural Alloys
An Industry/University Cooperative Research Center

# Spatially Resolved Acoustic Spectroscopy (SRAS)

## *“Sight Through Sound”*

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DURIP N00014-17-1-2294

# Baseline:
# This is a microscope

Leeuwenhoek's work defines our definition:

*"To see small…"*

- A more complete technical description of a microscope is:
  - An instrument which
    - uses optics to direct a beam of EM radiation to
    - a specimen that is of interest where
    - the incident waves are modified by certain characteristics of the specimen
    - and for which the modified waves/particles are directed to a detector for analysis (with it's own signal modification)

# Let’s test this

| | | **Optical** (including Leeuwenhoeks) |
|---|---|---|
| ***Optics*** | Uses optics to direct a beam of EM radiation to | Light (coherent or incoherent) |
| ***Specimen Damage*** | a specimen that is of interest where | ✔ |
| ***Image Theory*** | the incident waves are modified by certain characteristics of the specimen | Reflection<br>Transmission |
| ***Detectors*** | and for which the modified waves/particles are directed to a detector for analysis | ✔<br>(from an observer to detectors) |

**SRAS is a microscopy technique that directs <u>energy impulses</u> (typically supplied by a laser) to the <u>specimen</u>, and which are <u>sufficient to interact and generate acoustic waves</u> (of varying modes) which can be measured using <u>sophisticated detectors</u>.**

**Interestingly, this structure (optics, specimen/damage, theory, detectors) are where most microscope developers and users spend <u>all</u> their time.**

# Spatially Resolved Acoustic Spectroscopy

Motivation for the work:
*Sometimes, we need data and statistics as the mesoscale!*

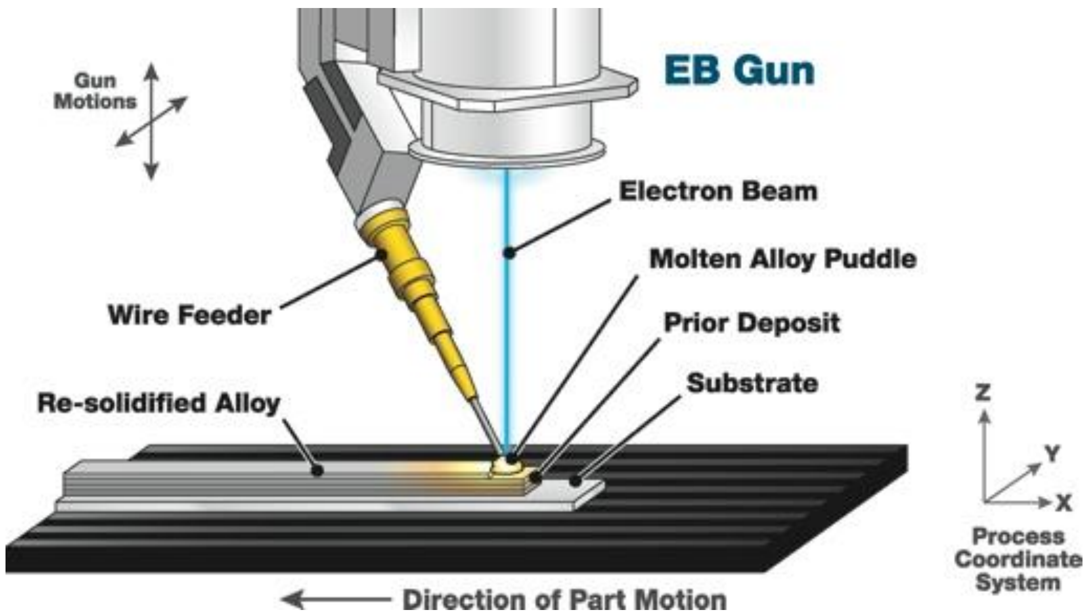
> "Failure is central to engineering. Every single calculation that an engineer makes is a failure calculation. Successful engineering is all about understanding how things break or fail." --- Henry Petroski

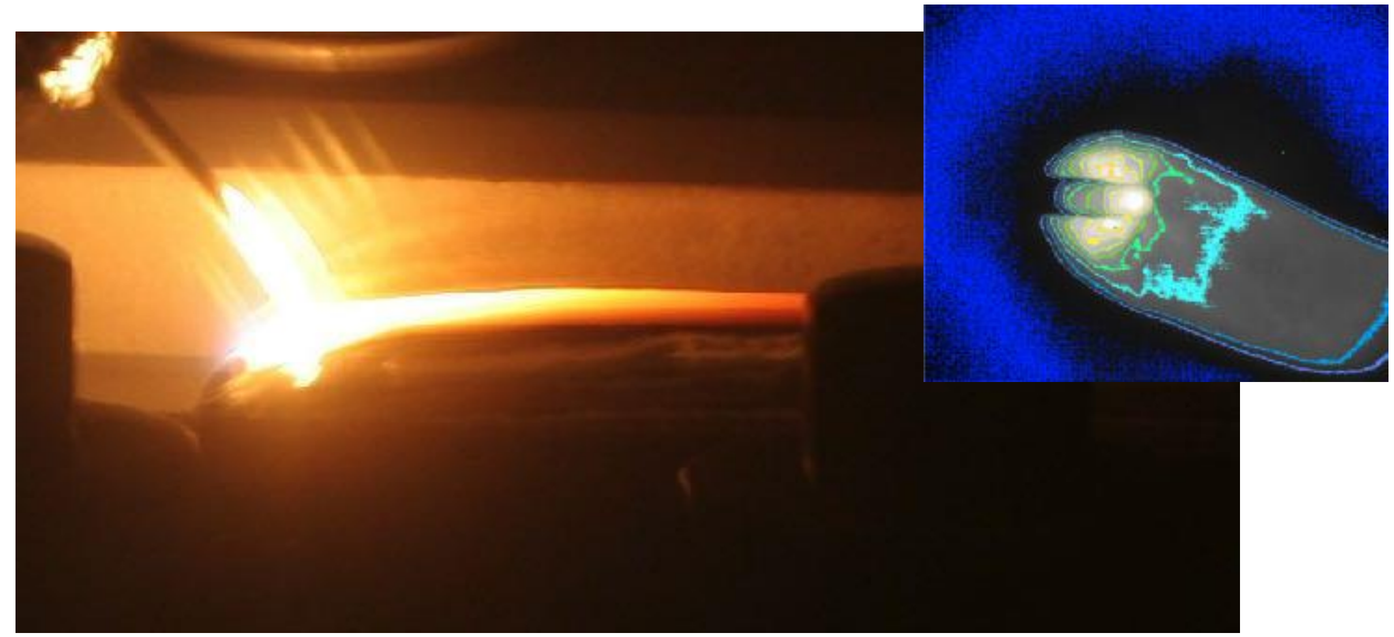
SRAS Basics

Our first data

Possibilities, probabilities, and limitations

# Motivation, part I:
# *Texture in Large-Scale AM*



2012 AeroMat presentation: "F-35 Direct Manufacturing: Materia
Qualification Results" June 20, 2012

# Motivation, part II: Microtexture?

# Spatially Resolved Acoustic Spectroscopy

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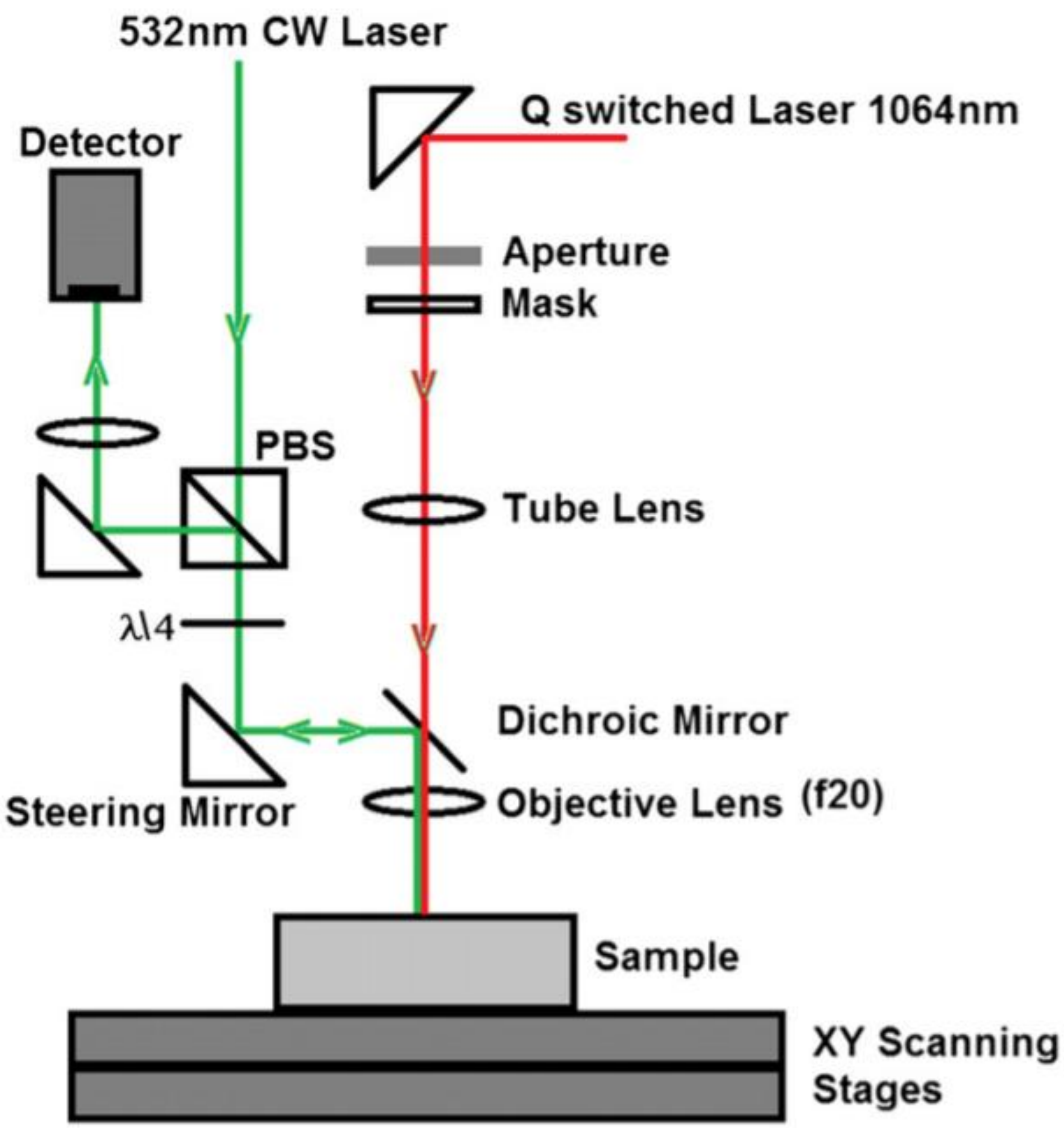
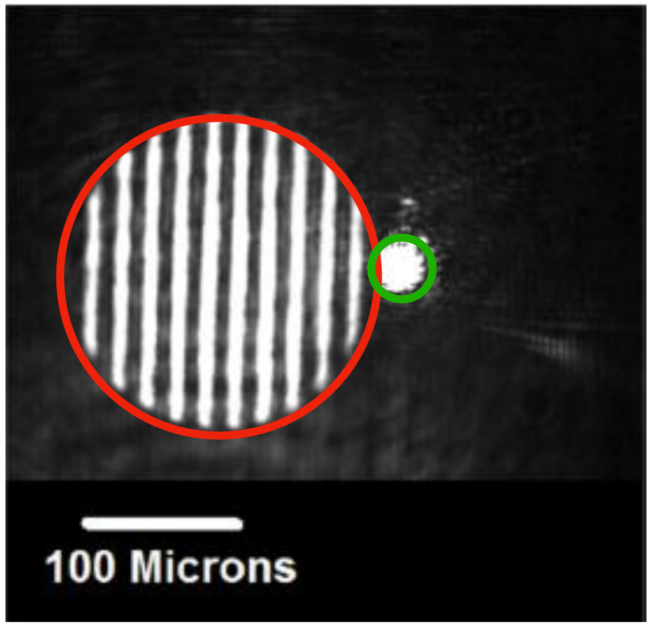
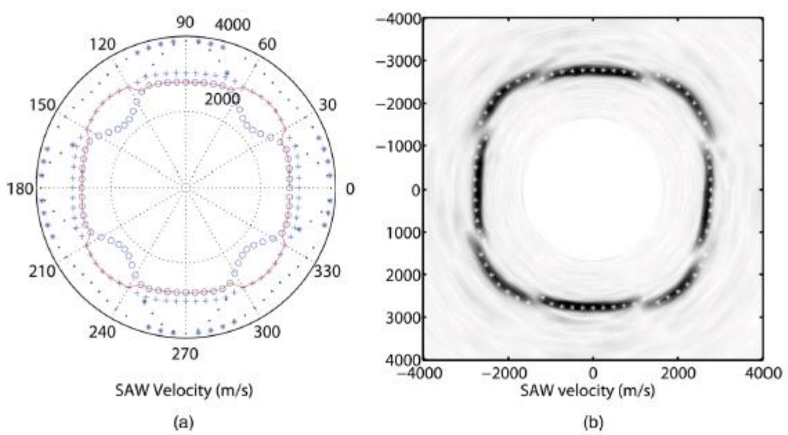
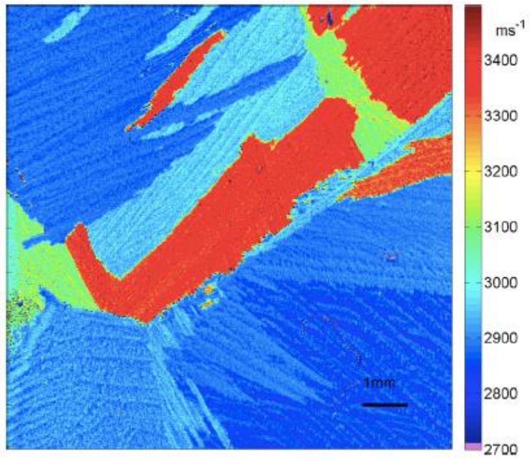



"Spatially resolved acoustic spectroscopy for rapid imaging of material microstructure and grain orientation," Richard J Smith et al, 2014, Meas. Sci. Technol. **25** 055902
DOI: 10.1088/0957-0233/25/5/055902

- Laser UT Technique
- Able to detect velocity of SAWs ***(~Mach 9)***
- Can determine crystallographic information through detection of ***nm-level surface displacements***
- Data is then coupled with simulation data of multiple wave modes (governed by the elastic stiffness tensor, $C_{ijkl}$)
- EBSD-like data with restrictions

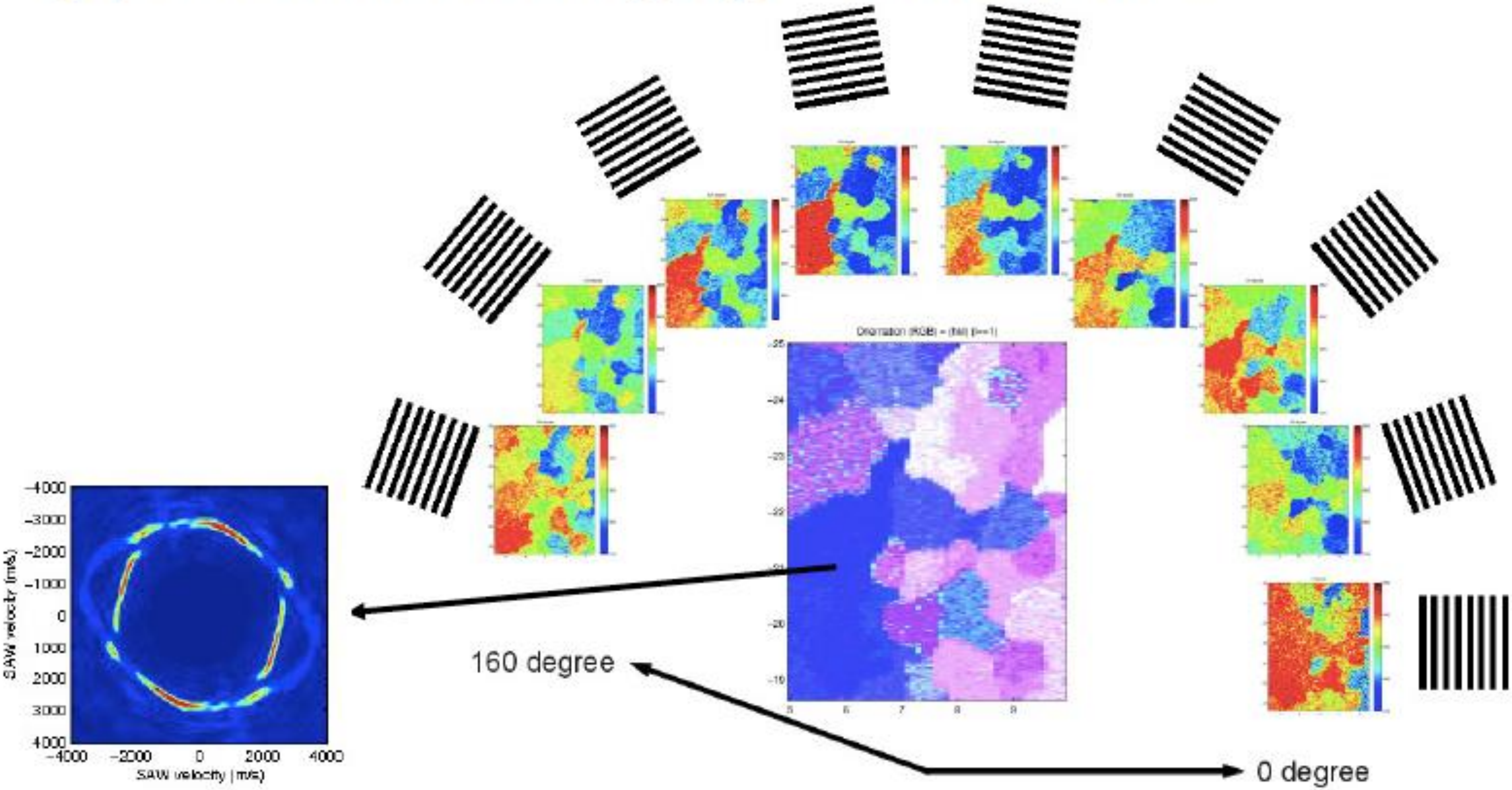


# Orientation Determination in Practice

## (2) Orientation imaging – Collect data

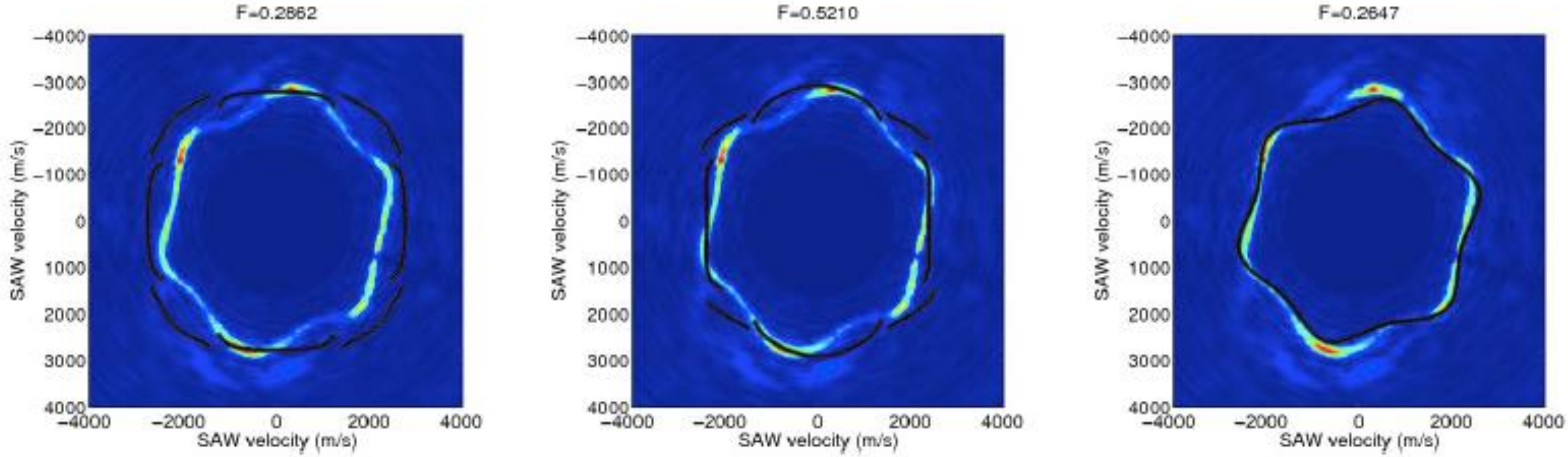


# Orientation Determination in Practice

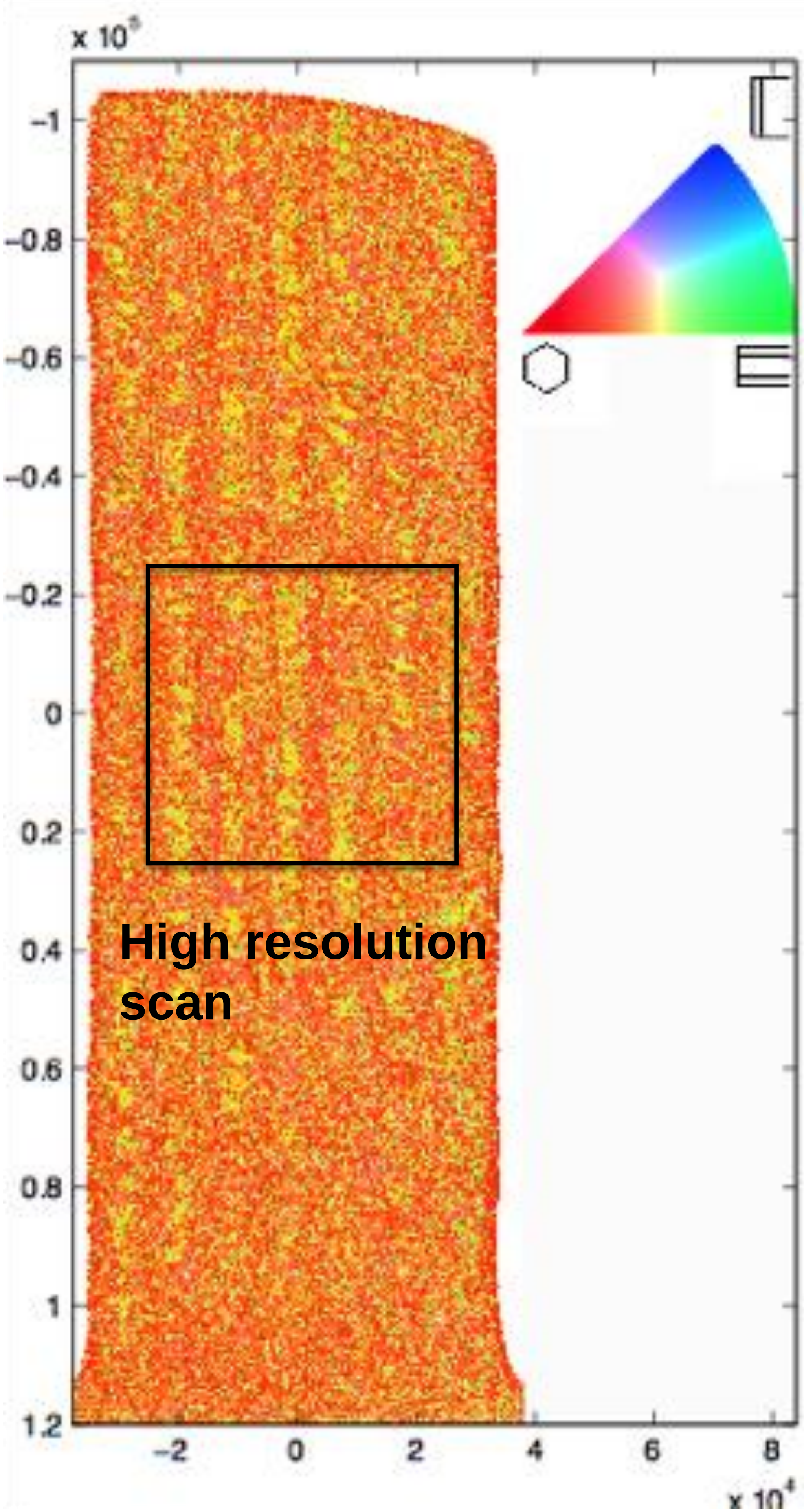
University of Nottingham
UK | CHINA | MALAYSIA

## (3) Orientation imaging - fit to data

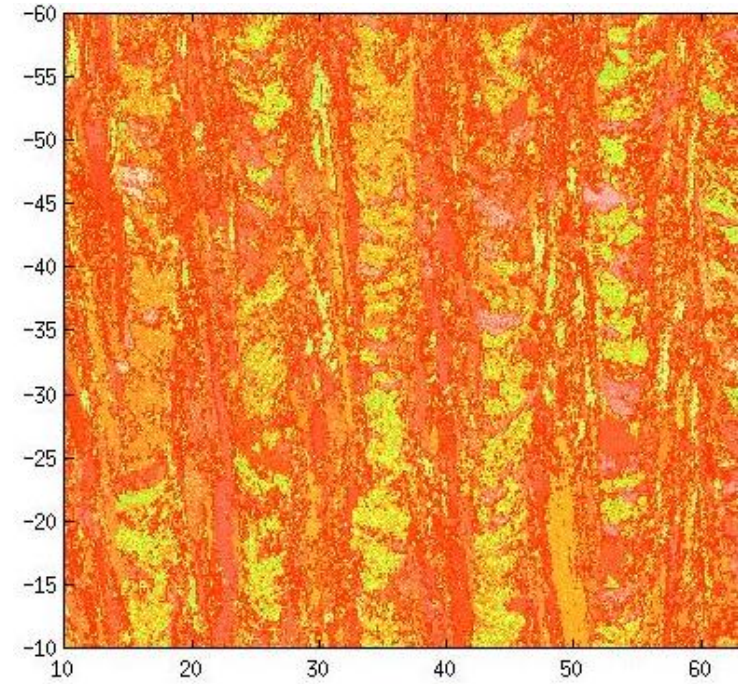
$$F(h,k,l,\theta) = \sum_{\phi=0}^{\phi=\frac{n-1}{n}\pi} A(\phi, v_{(h,k,l,(\phi-\theta))}), \ (n = 1,\ 2,\ 3,\ \ldots)$$



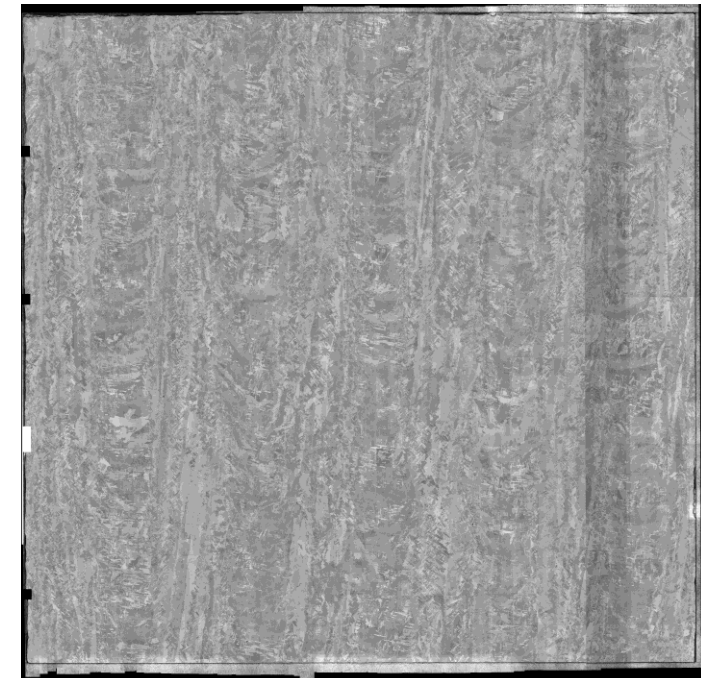

- The merit function is simply the sum of the amplitude under the black asterisks on the graph
- Repeat this procedure for all the combinations of plane and propagation direction

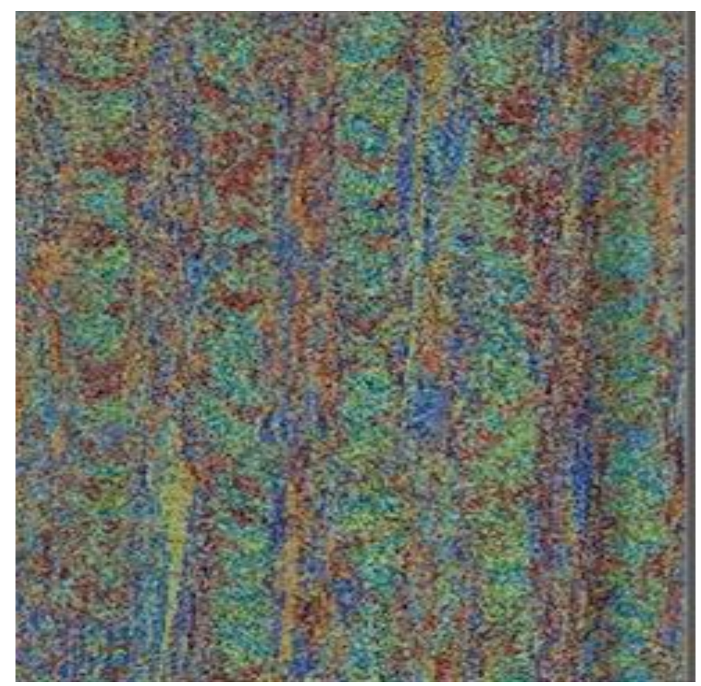


High resolution scan
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
-2
0
2
4
6
8

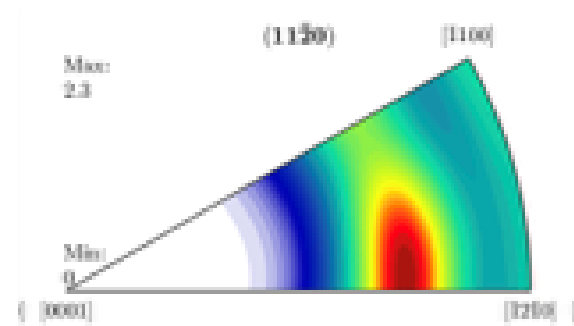



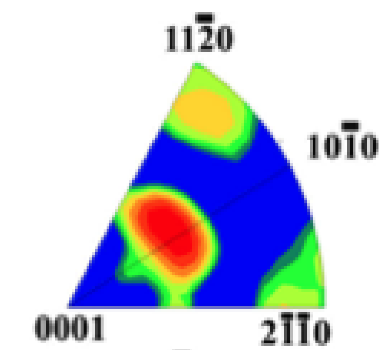
-60
-55
-50
-45
-40
-35
-30
-25
-20
-15
-10
10
20
30
40
50
60

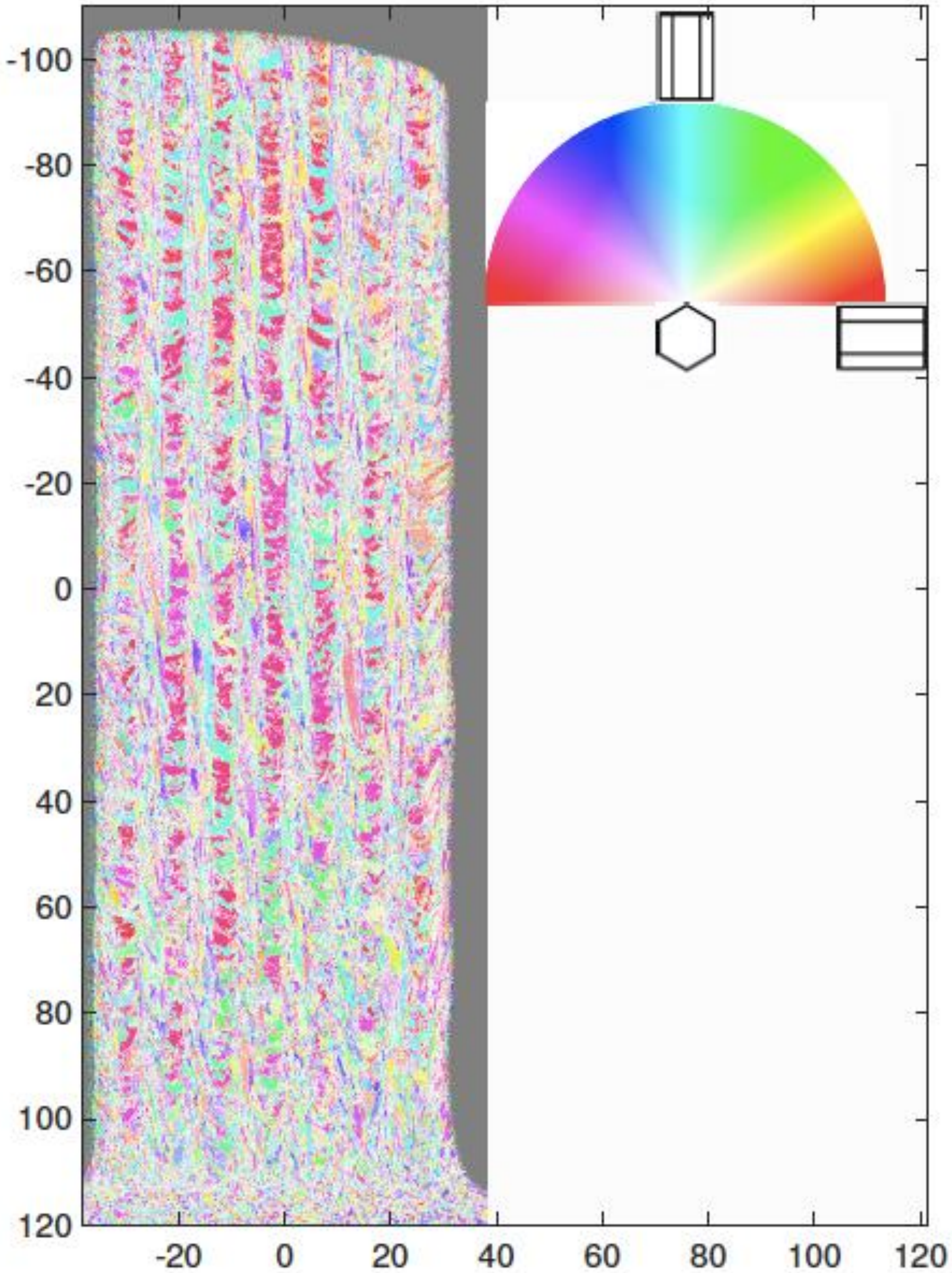


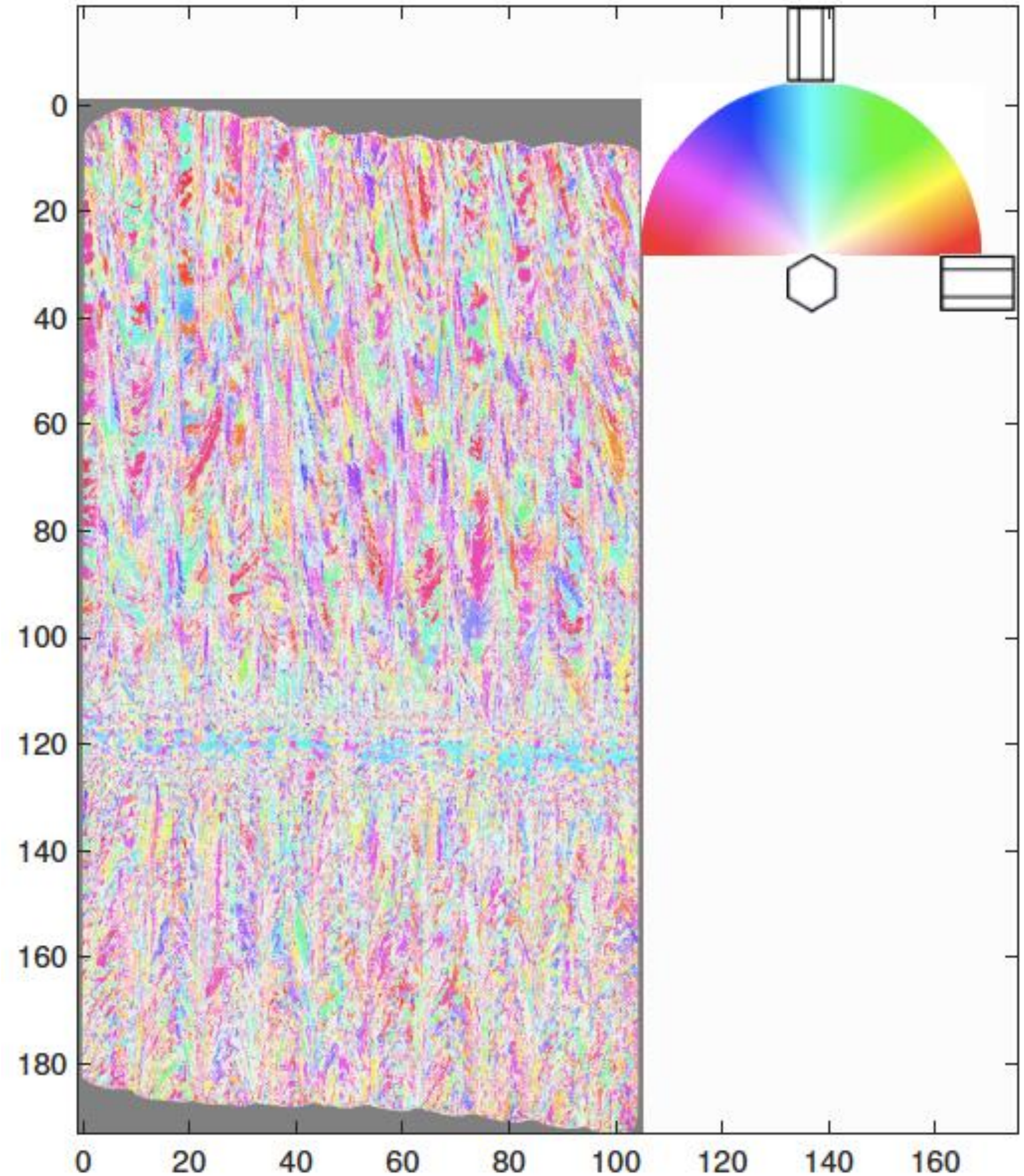
5 1 6 2 7 3 8 4 9
15 mm



11$\bar{2}$0
10$\bar{1}$0
0001
2$\bar{1}\bar{1}$0



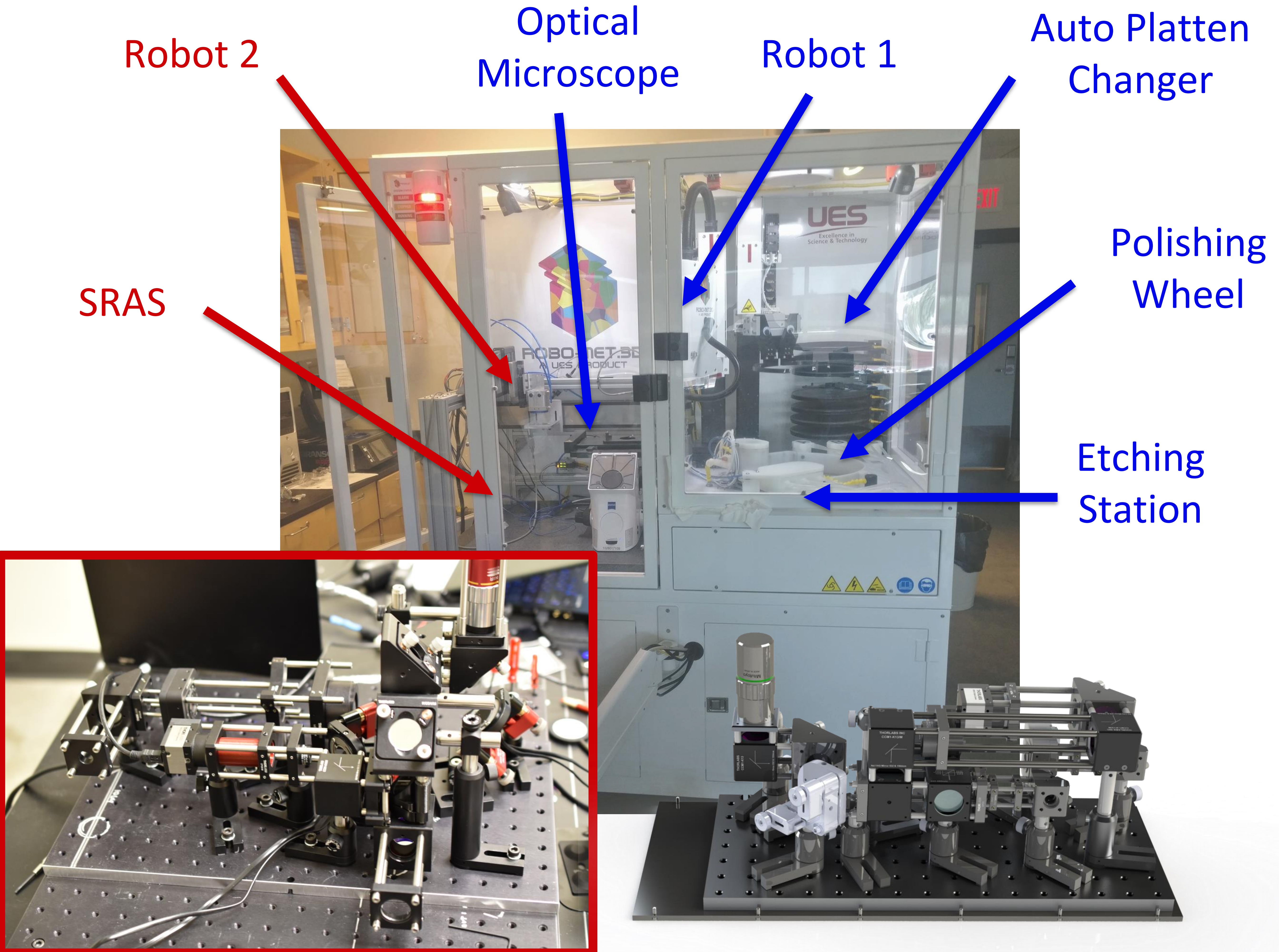

In these two scans, we *may* have more orientation data than all EBSD scans of AM Ti-6Al-4V combined.

So, let's make a SRAS system…

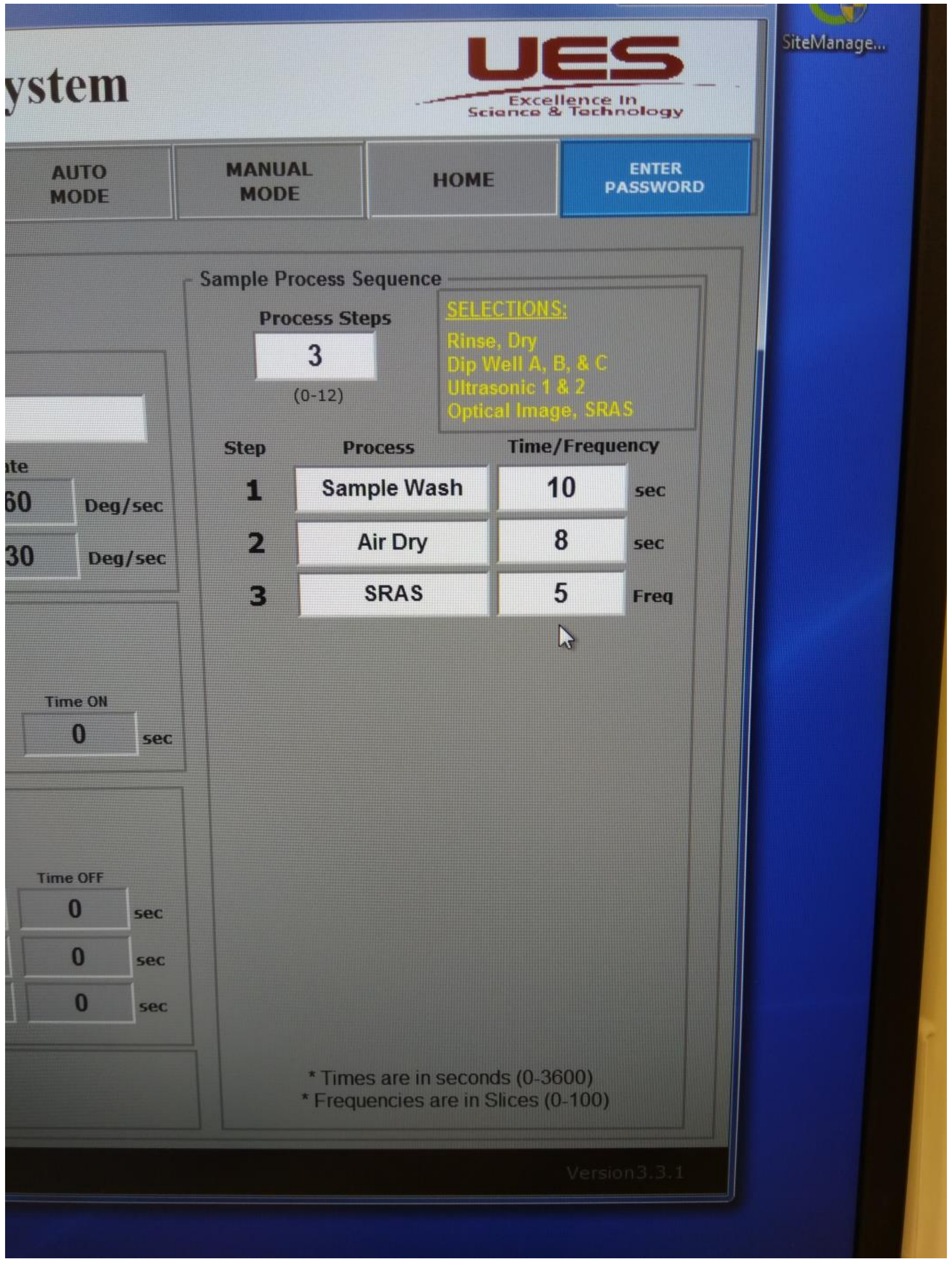
…but let's integrate it into a serial sectioning tool

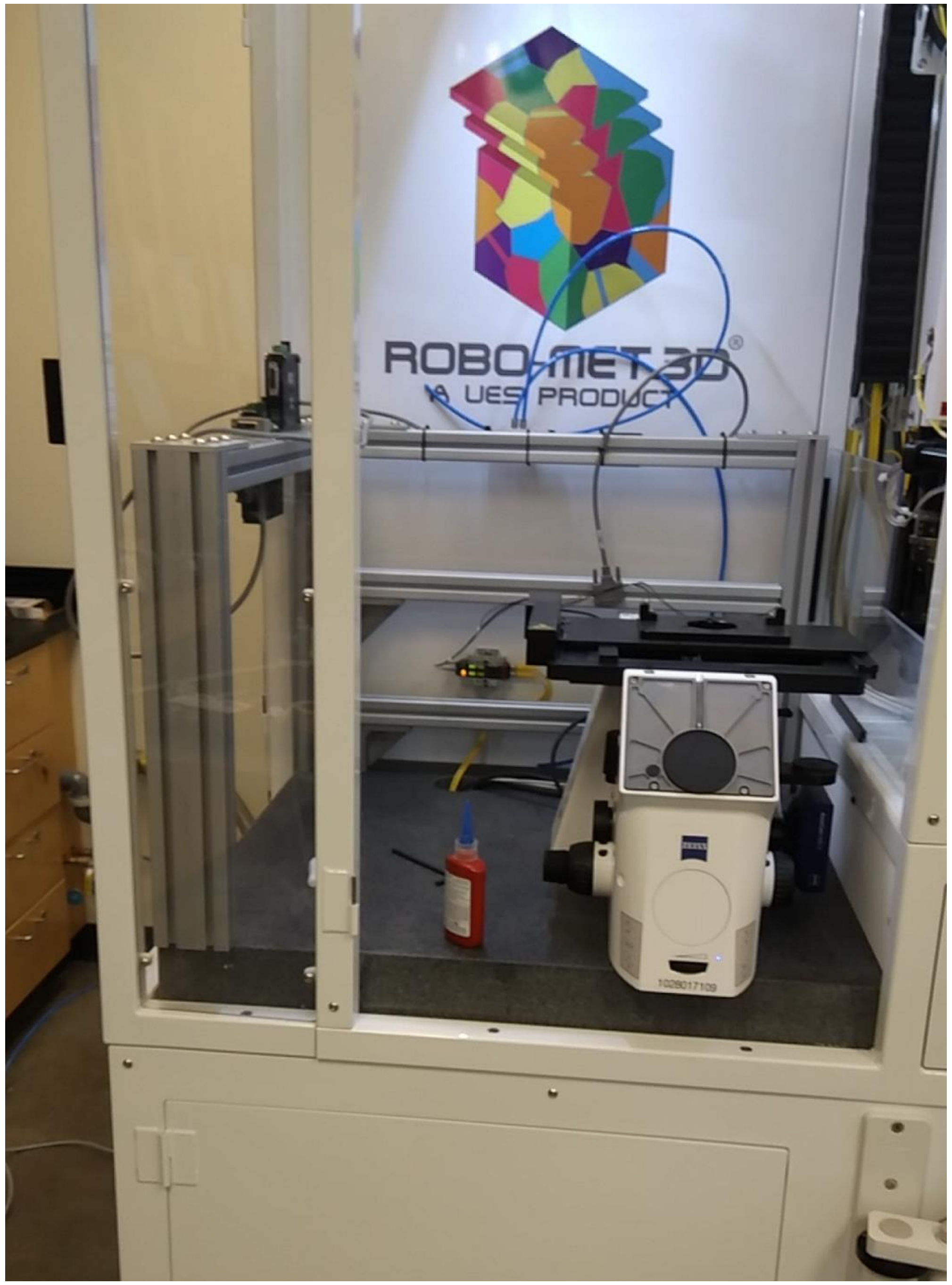
(as if SRAS is not hard enough)

With credit given to:
The Art of Electronics (Horowitz & Hill)


Robot 2
Optical Microscope
Robot 1
Auto Platten Changer
Polishing Wheel
SRAS
Etching Station

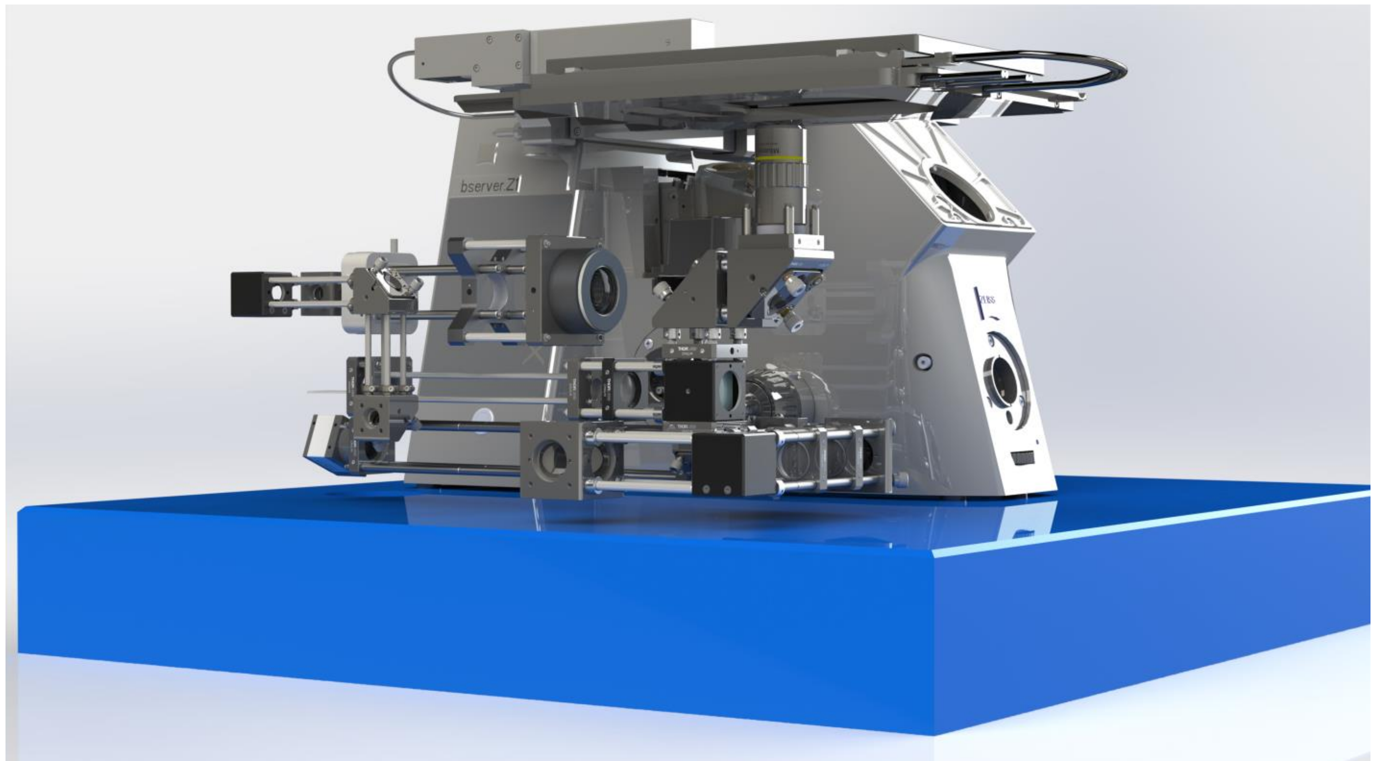
# Modified RoboMet.3D PLC & Custom Transfer System

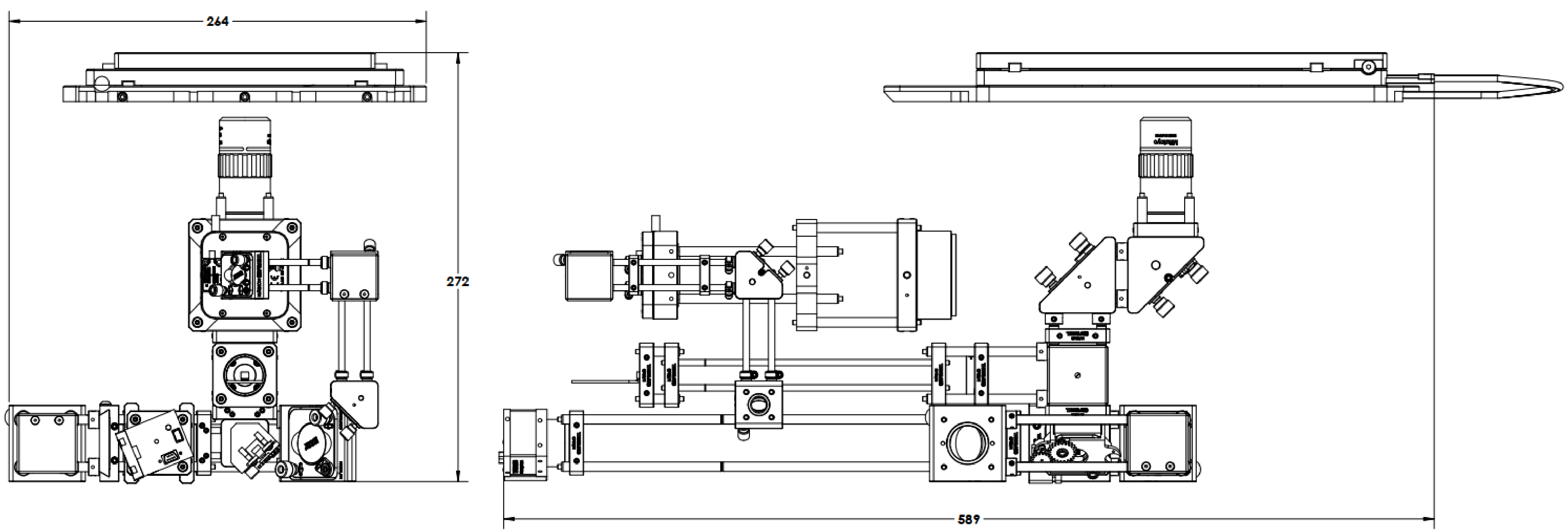


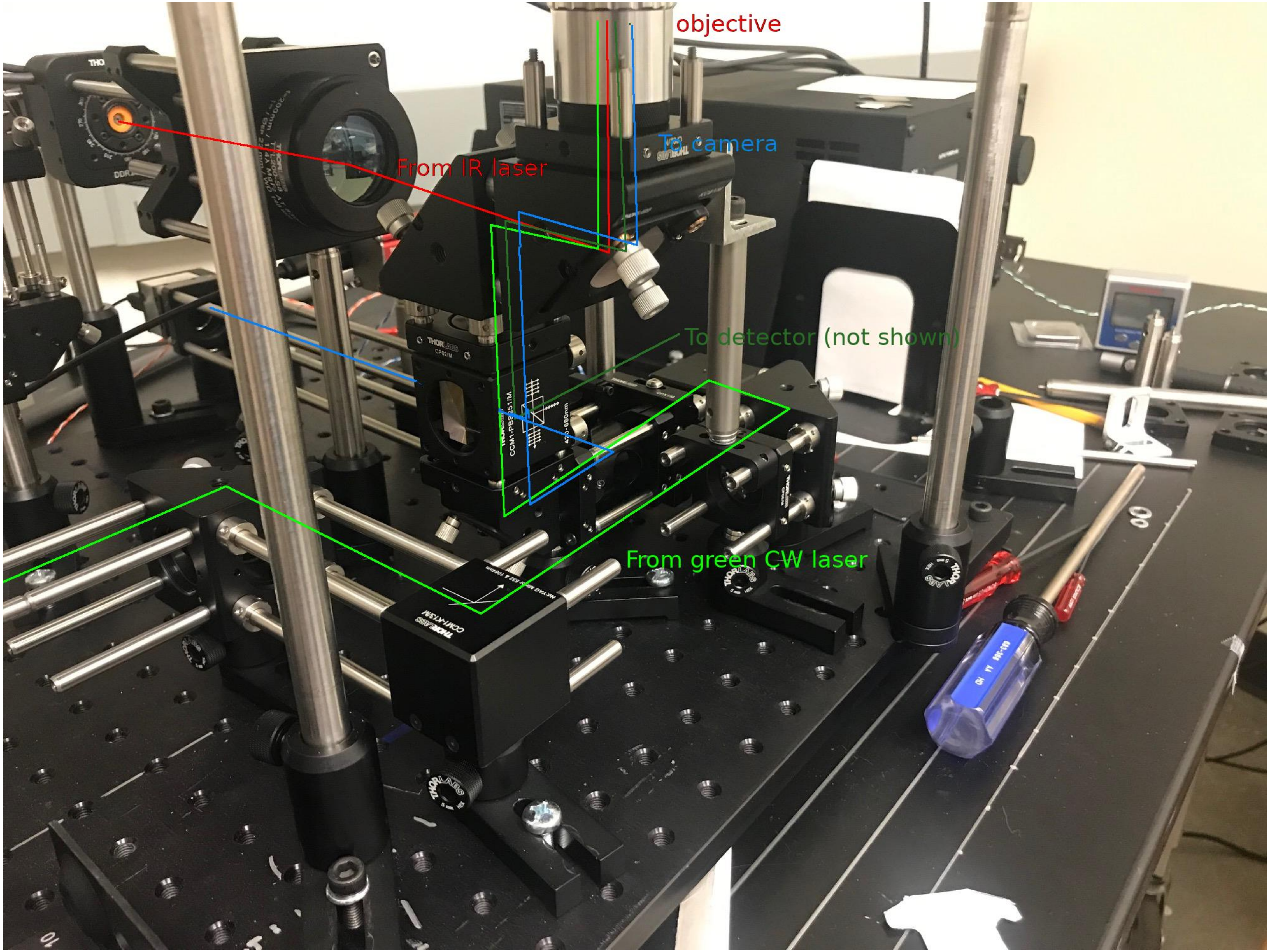
# Engineering a new system

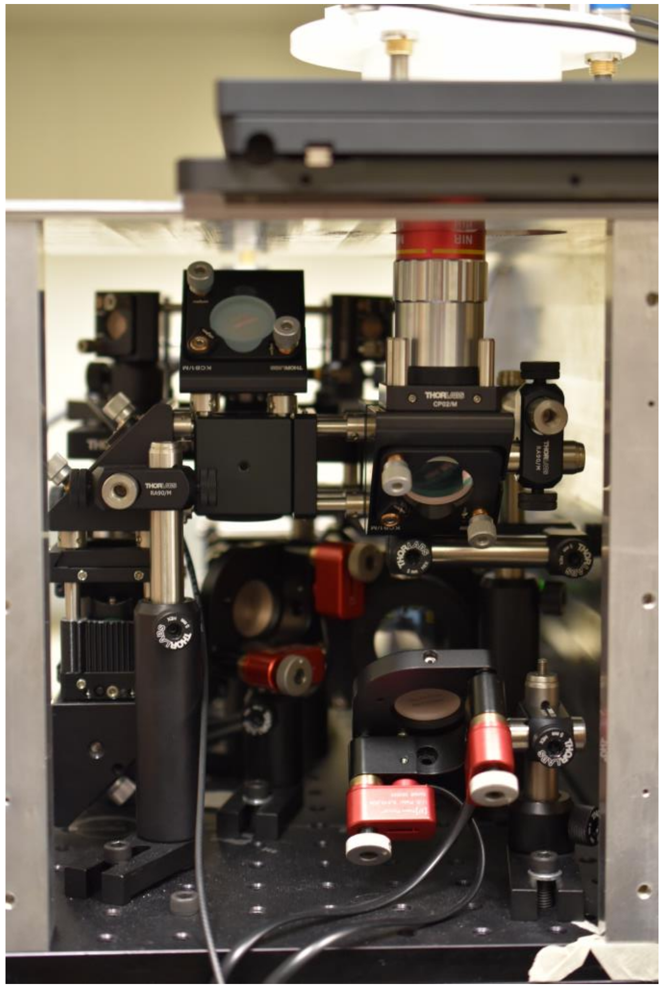
- Must wrap a 2D system to a 3D package
- Tight space constraint
- Safety (Class 1 Required)!
- Critical detector components no longer exist
- Bandwidth (150-500 MB/s if we collected everything!)

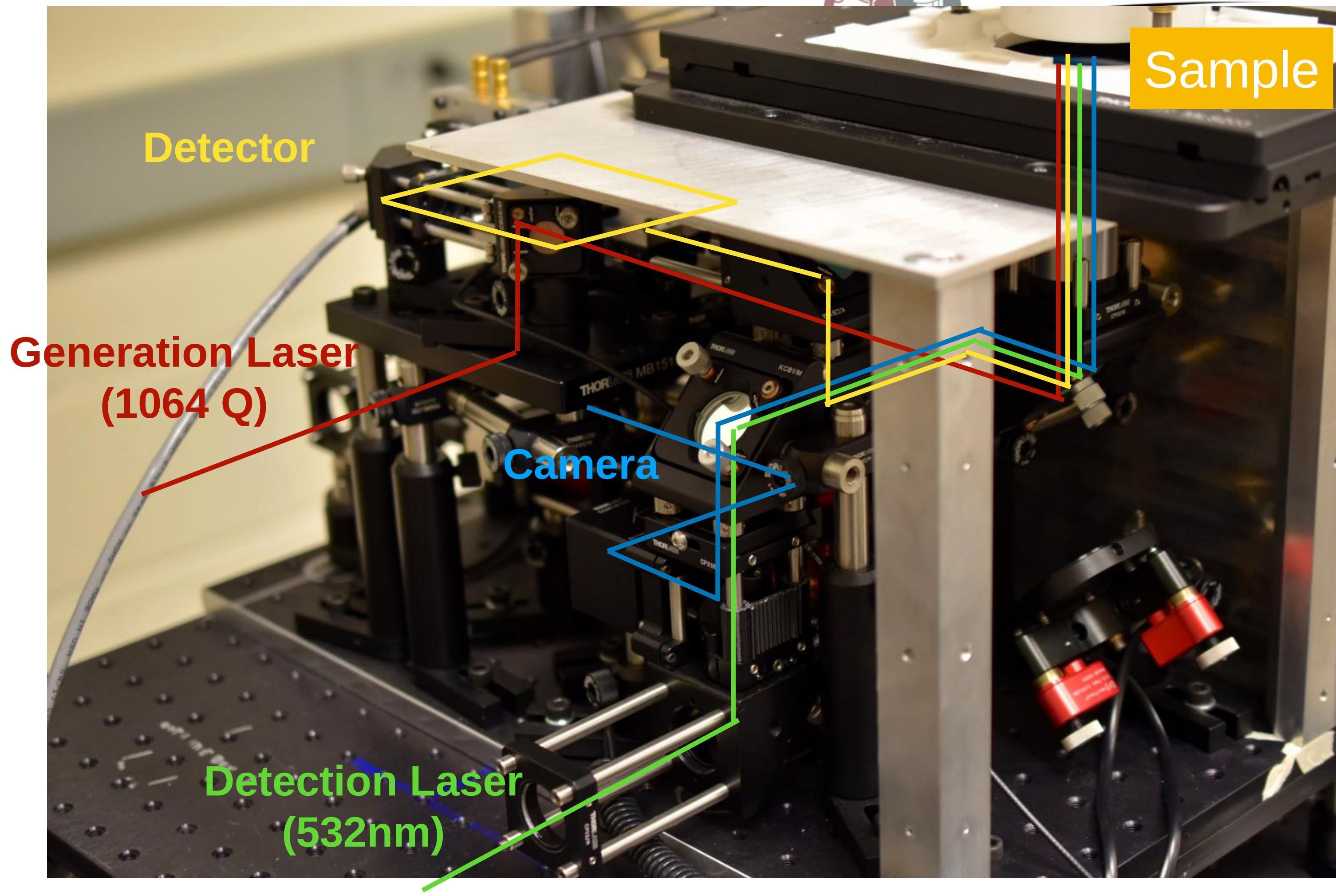




# First Original 3D Beam Path








| Subsystem | | |
|---|---|---|
| Generation Laser | Type | Q-switched |
| | Wavelength | 1064 nm |
| | Pulse Energy | >50 uJ |
| | Pulse Duration | <900 fs |
| | Frequency | 20-100 kHz (continuous pulse) |
| Detection Laser | Type | CW |
| | Wavelength | 532 nm |
| | Mode | $TEM_{00}$ |
| | Power | 0-500 mW ~200 mW |

| Subsystem | | |
|---|---|---|
| Stage | Speed | 250 mm/s |
| | Acceleration | 2500 $mm^2$/s |
| | Backlash | None |
| | Accuracy | <0.25 um |
| | Incremental Movement | <100 nm |
| Detector | Type | Balanced Split PD |
| | Generation | New (1st since ~2011) |
| | Frequency | < 500 MHz |
| | Spatial Resolution | ~ 25 um |

# Detector (Nottingham "Slow")

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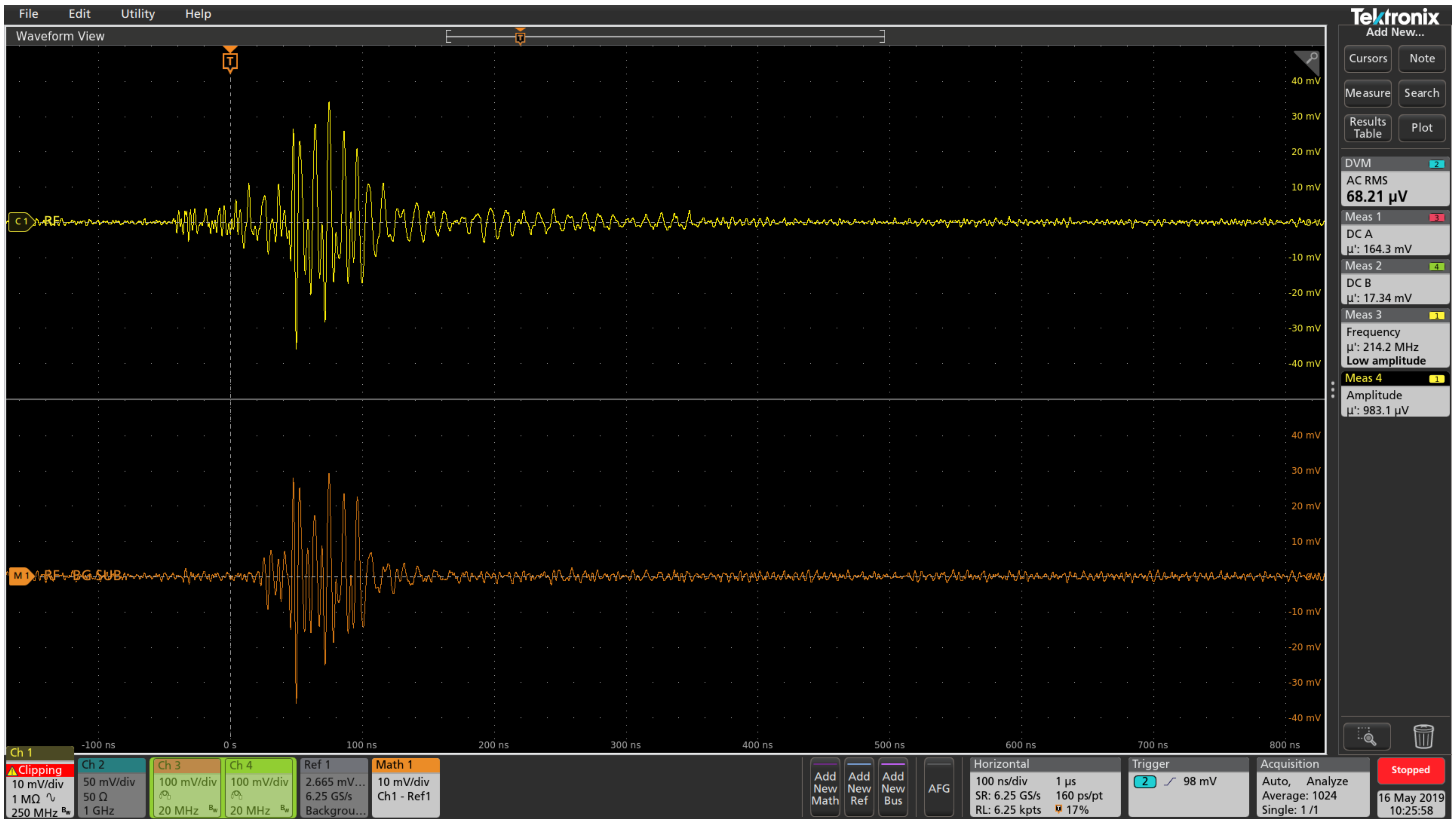
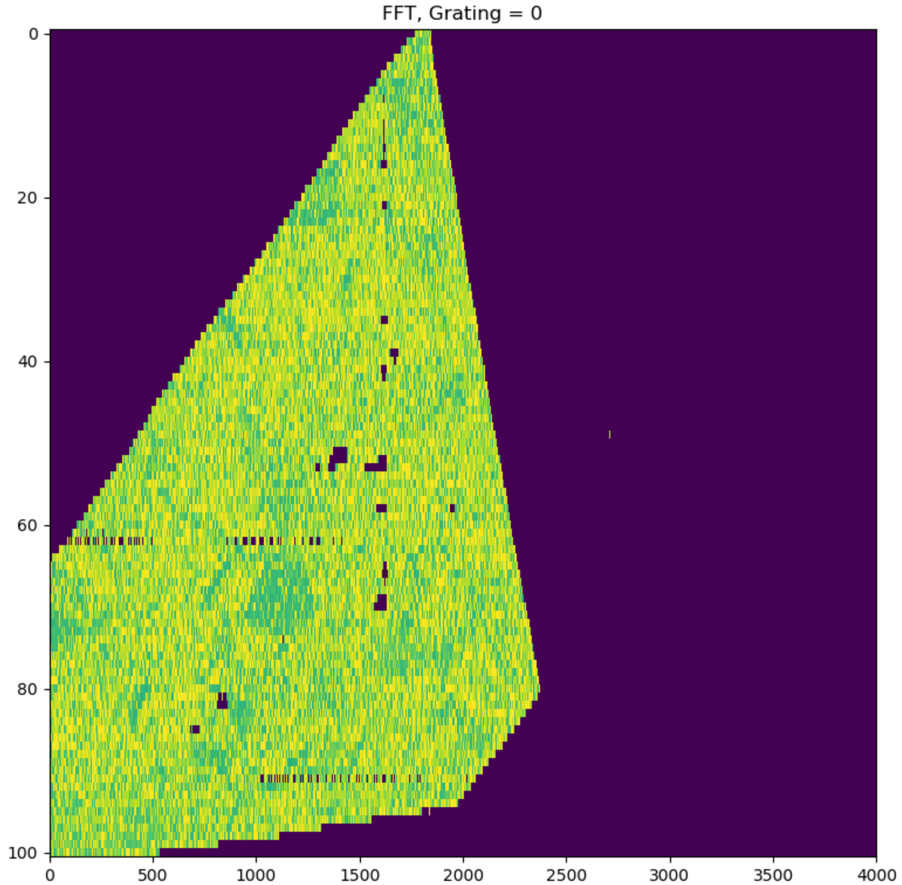
## First signals (June)



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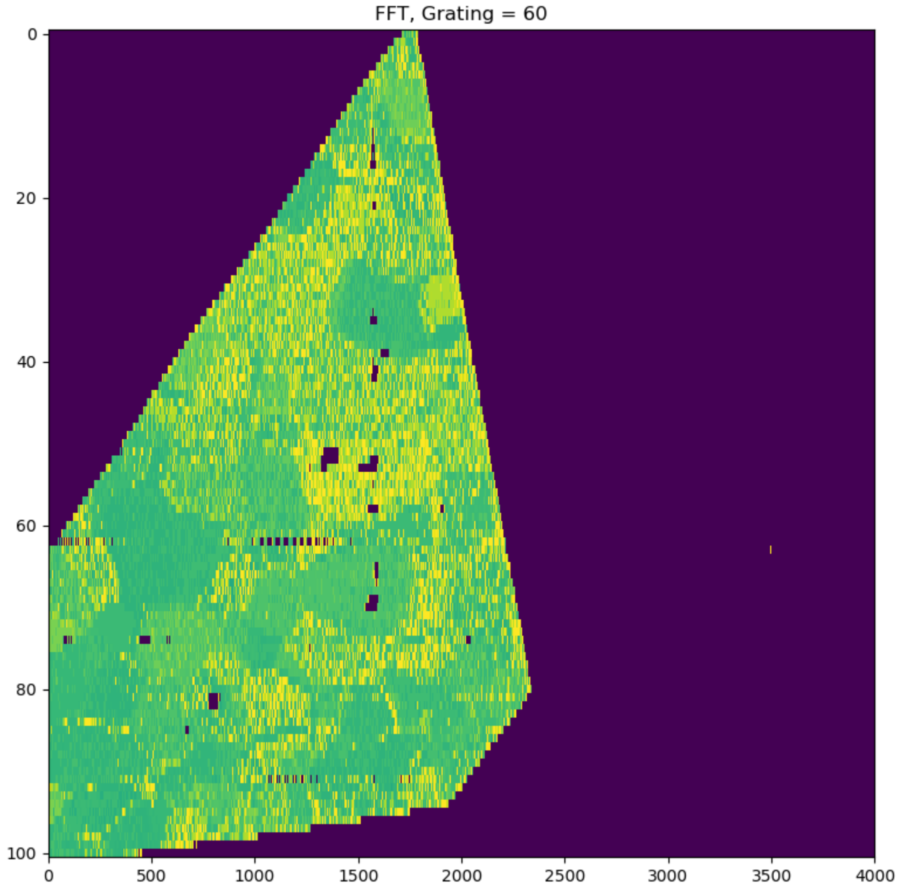
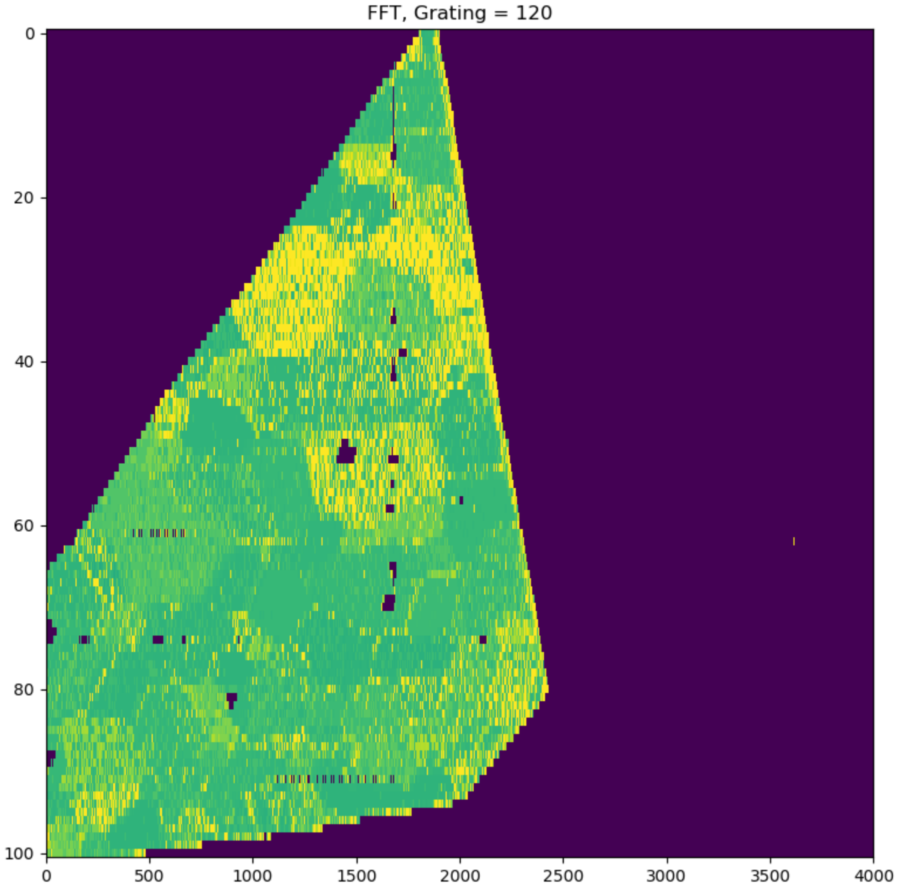
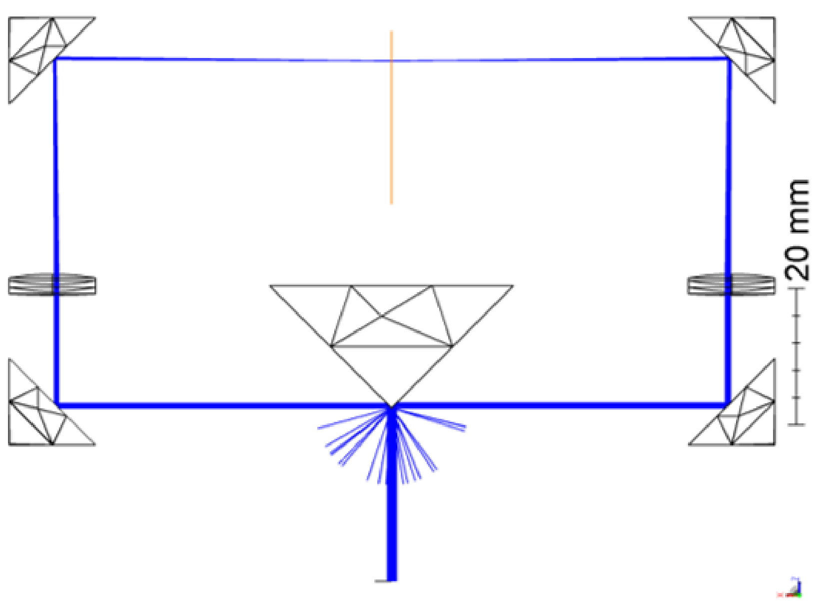
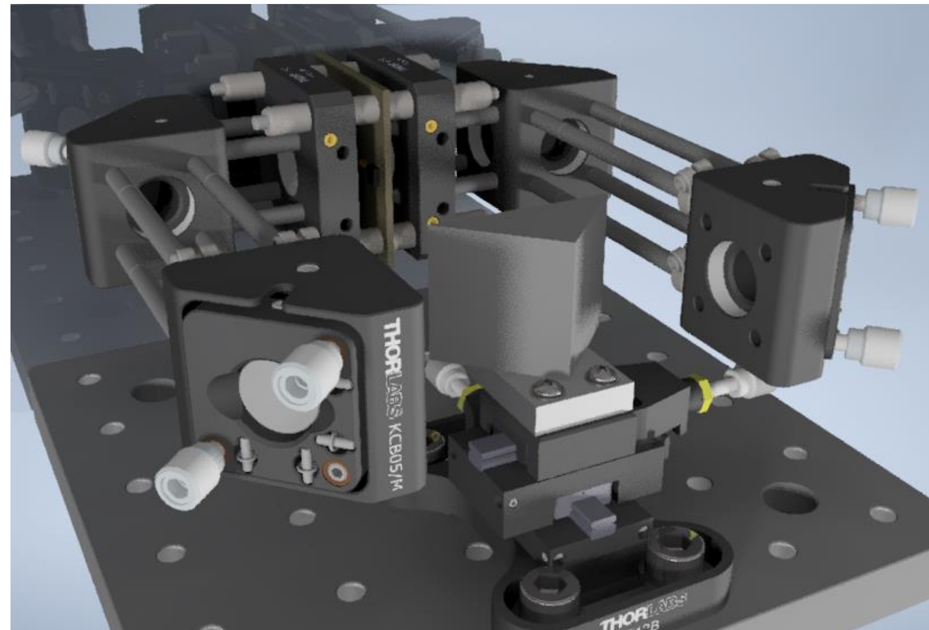
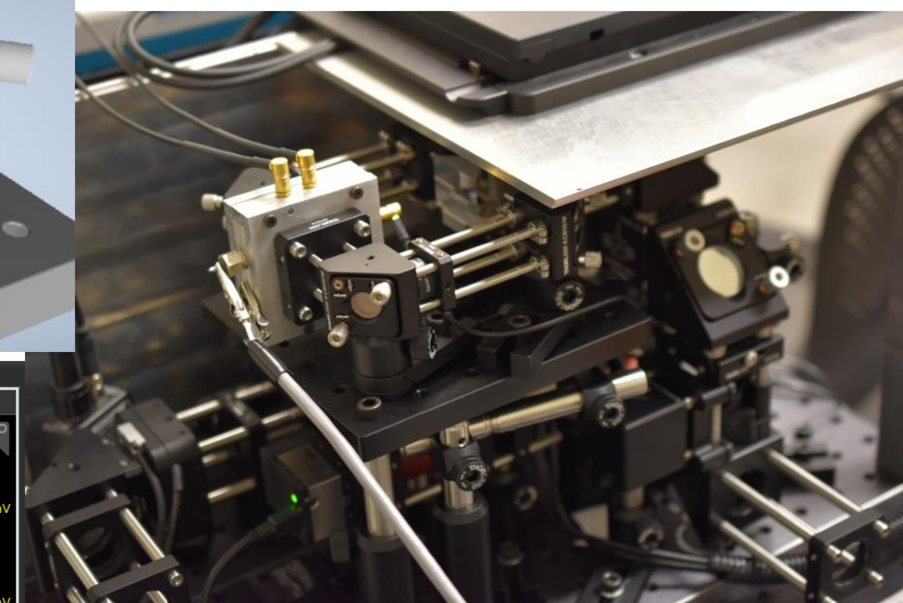


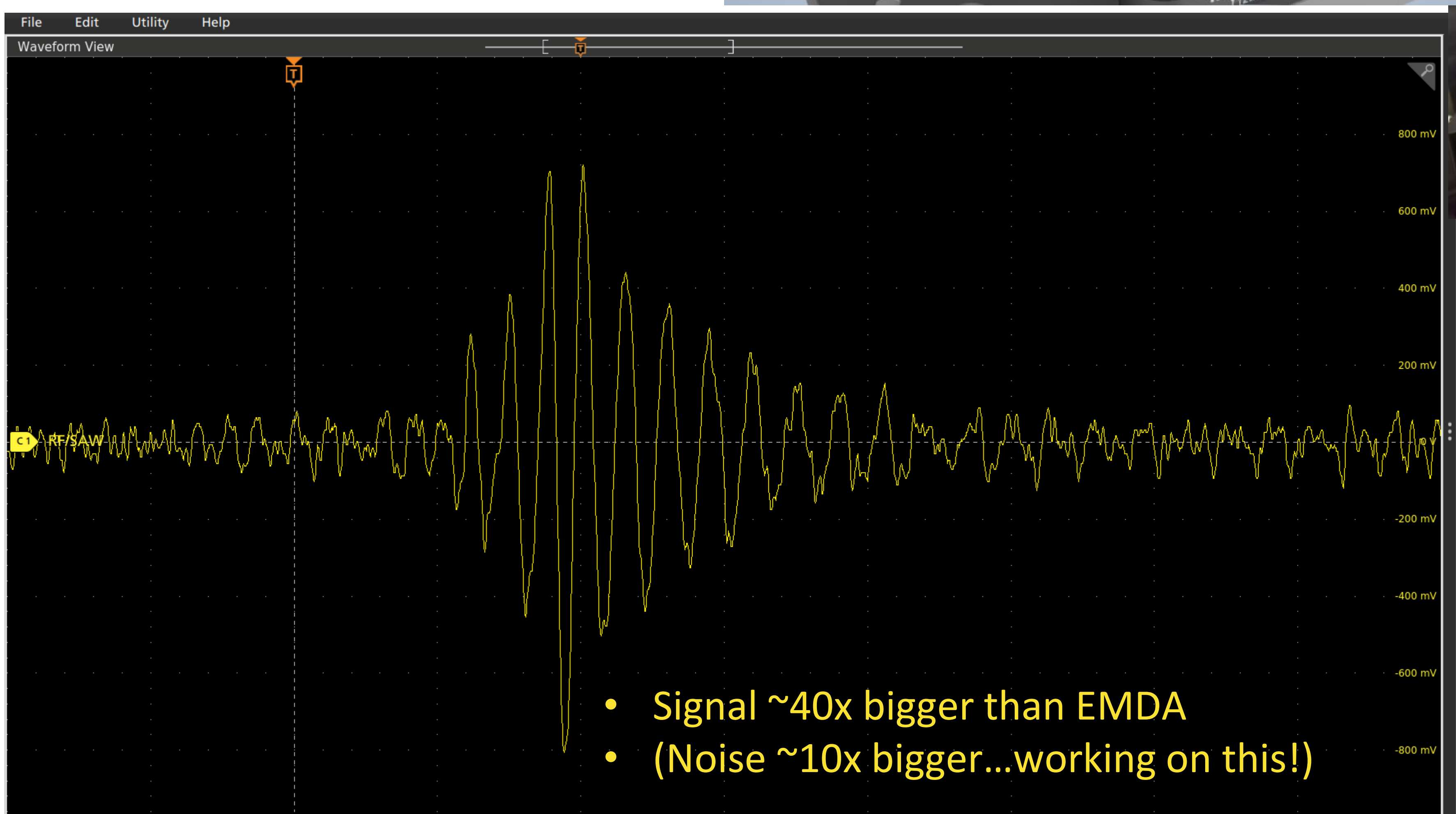
# Detector (Gen 2 - new design)





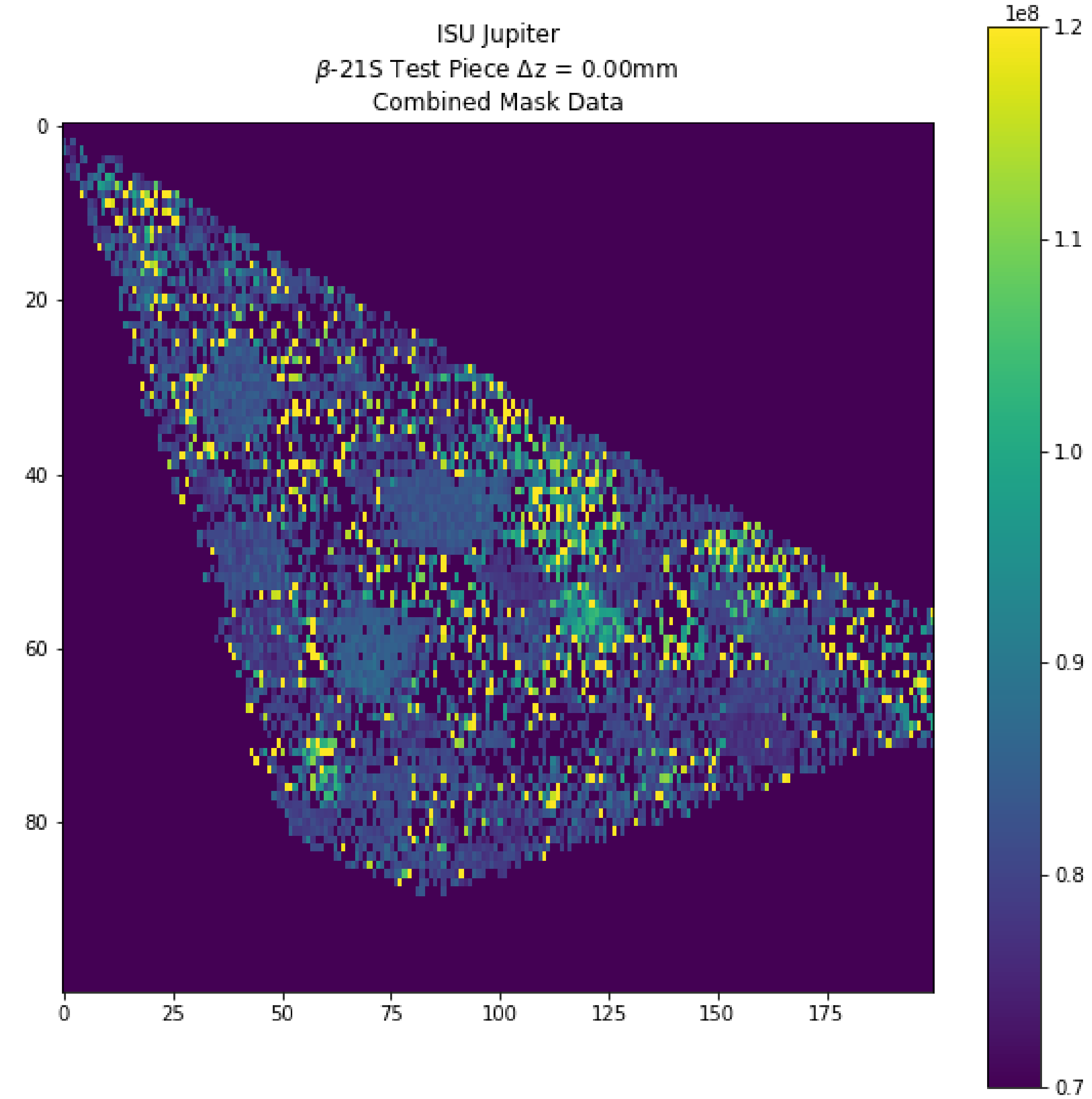
**November**



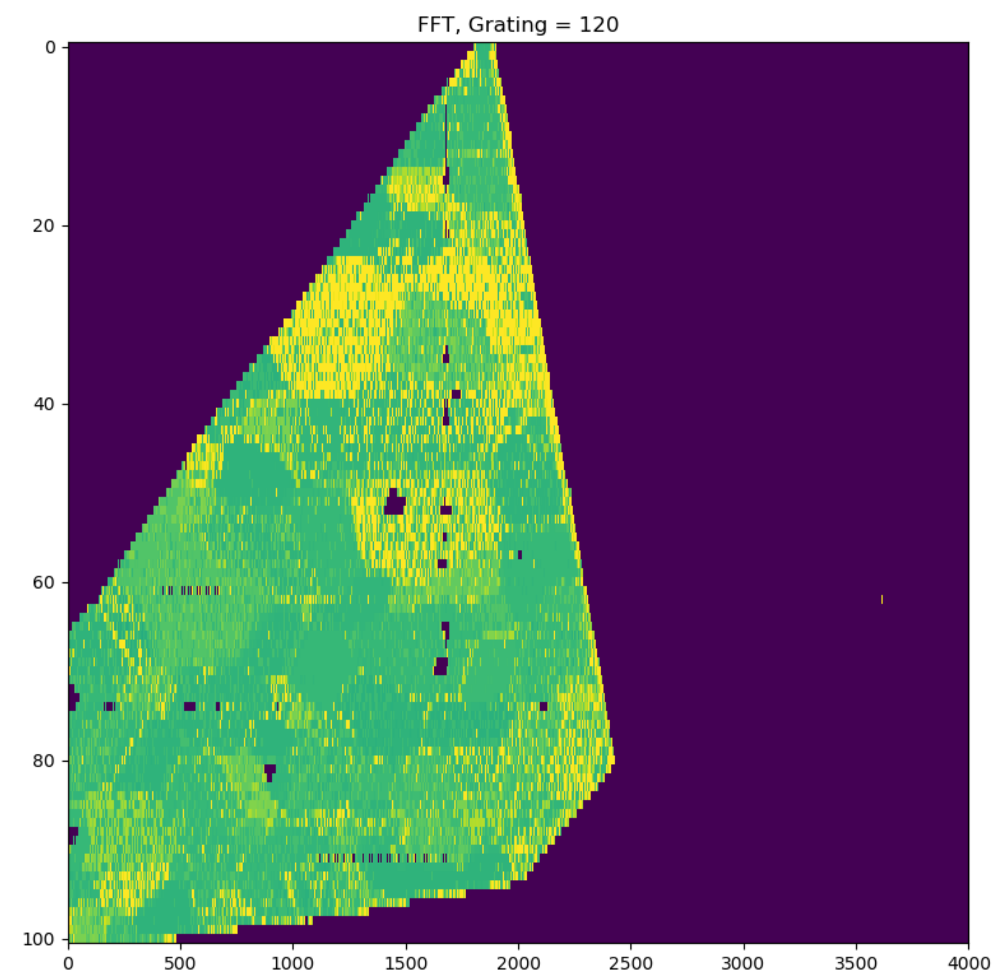

- Signal ~40x bigger than EMDA
- (Noise ~10x bigger…working on this!)

# Present State-of-the-Art

- ISU Alpha system running, efforts being spent on improving resolution, data acquisition and data transfer rates
- Current RAW data is ~15 MB/mm$^2$
- Potential to move away from oscilloscope storage for data

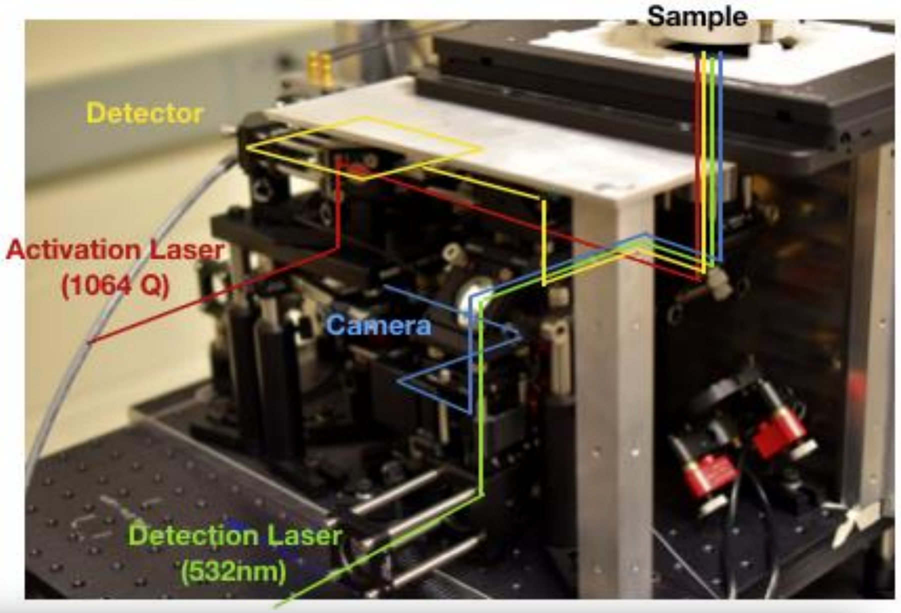



1st scan acquired



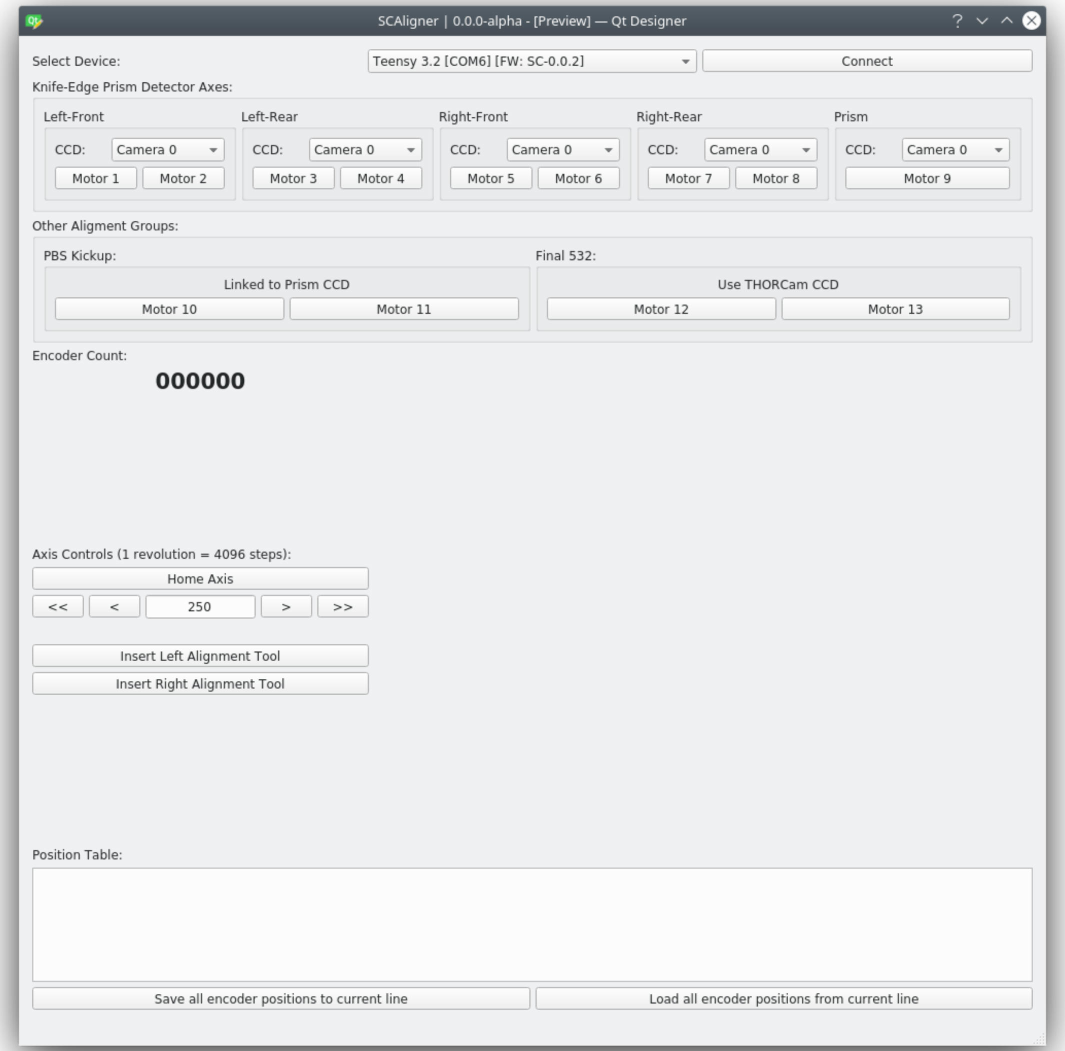

latest scan

# What is left…in the short term




## Left to resolve:

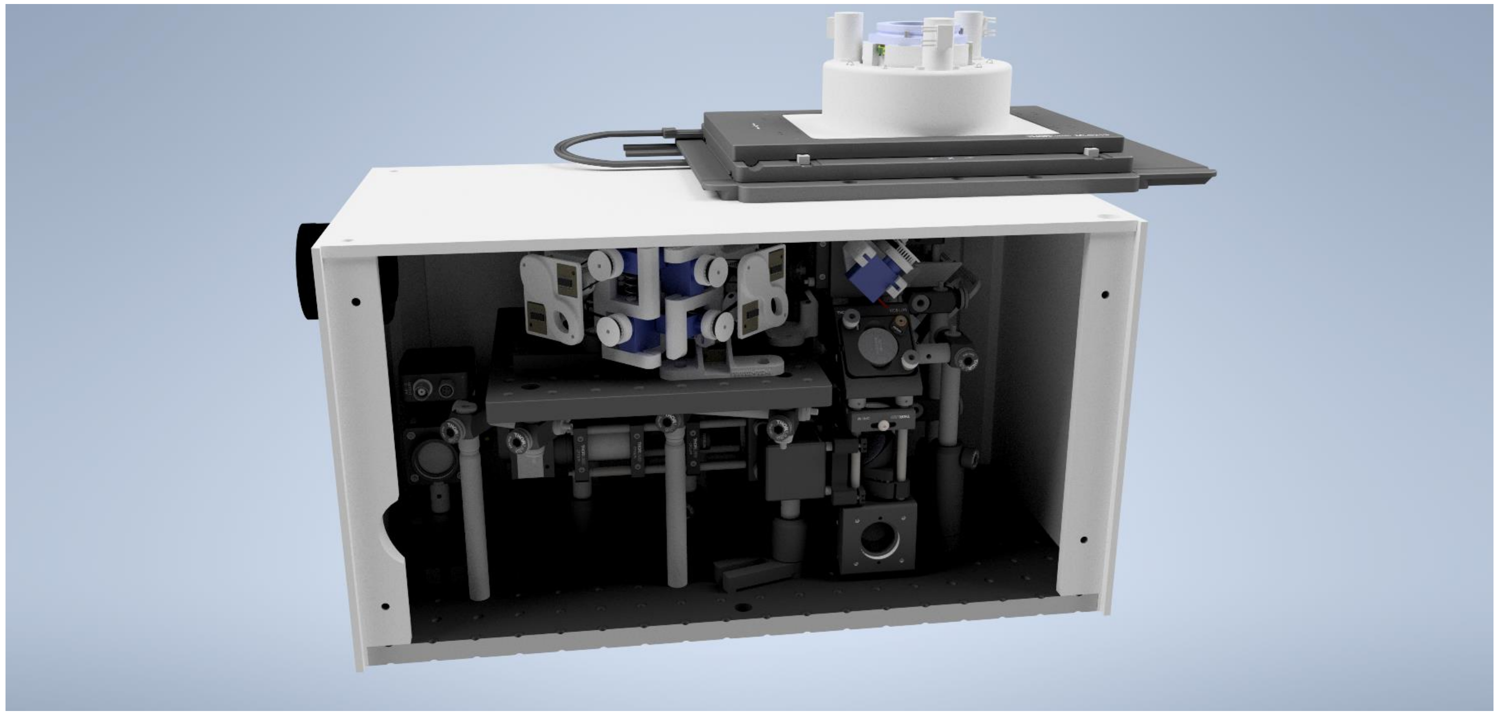
1. Taking hands out of the system
   - Finish up work on detector alignment firmware.
   - Link firmware to PC control application
2. Make the system "Class 1" laser safe
   - Install interlock control system.
   - Verify behavior during fault conditions.




## Future:

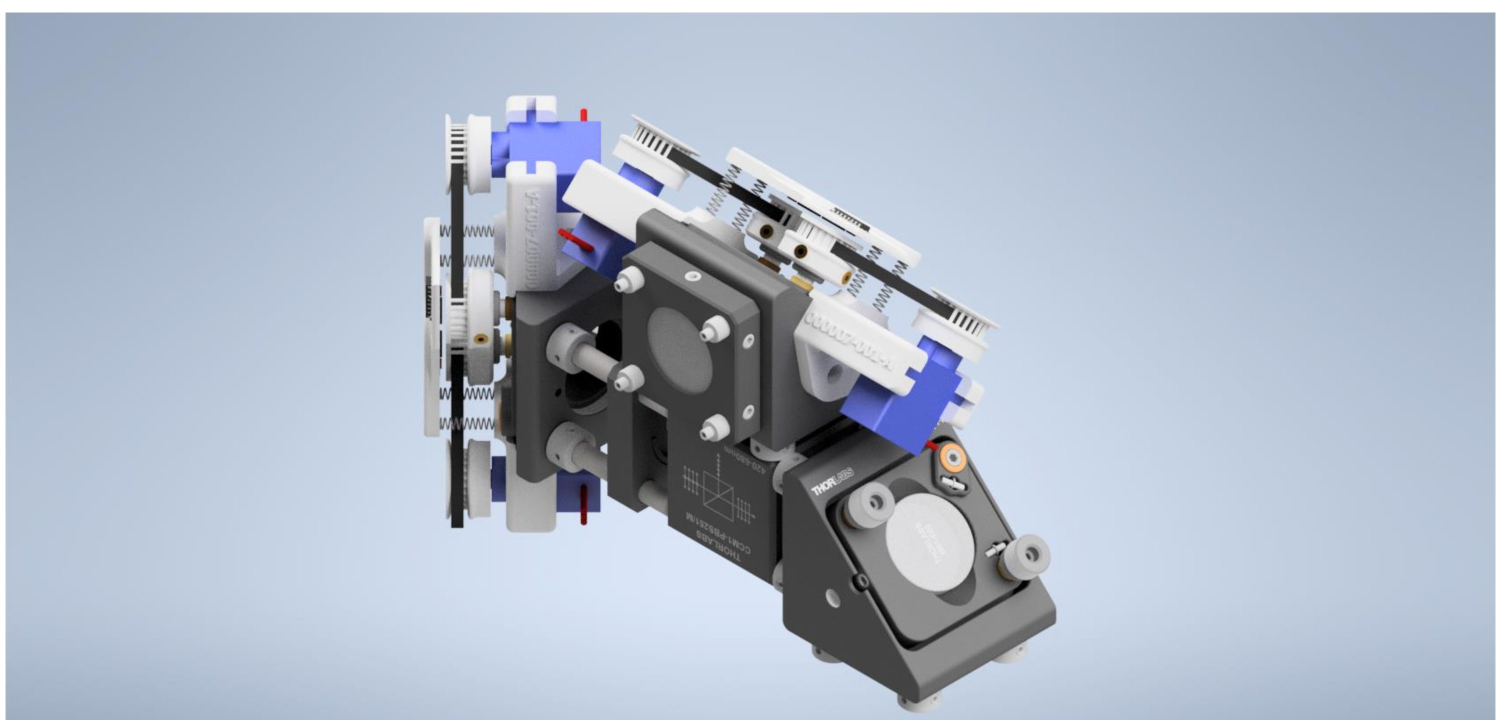
- Transition to fiber coupled lasers
- Direct collection via capture card/FPGA

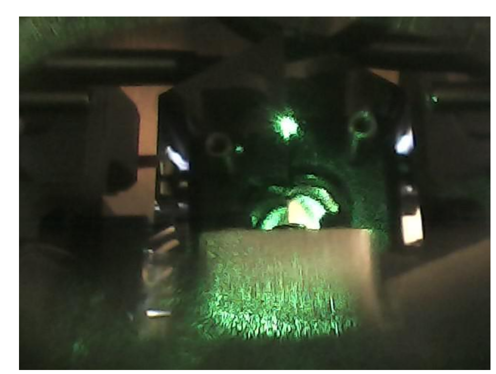
# Remotely Operable

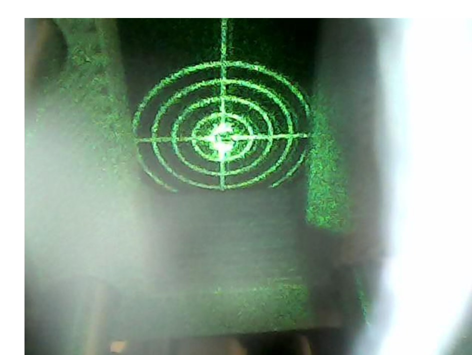


**Kinematic Requirements:**

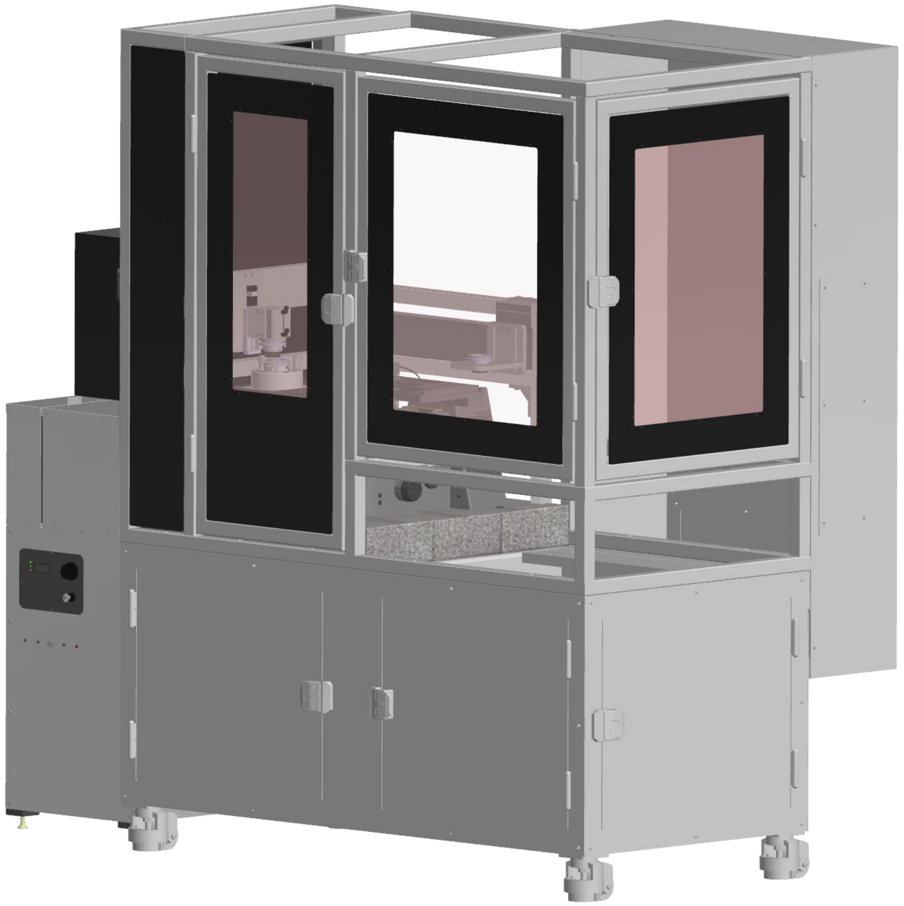
- **Must be stable in power-off configuration**
- **Relatively fast rotation required.**
- **Compact physical package with relatively high torque.**

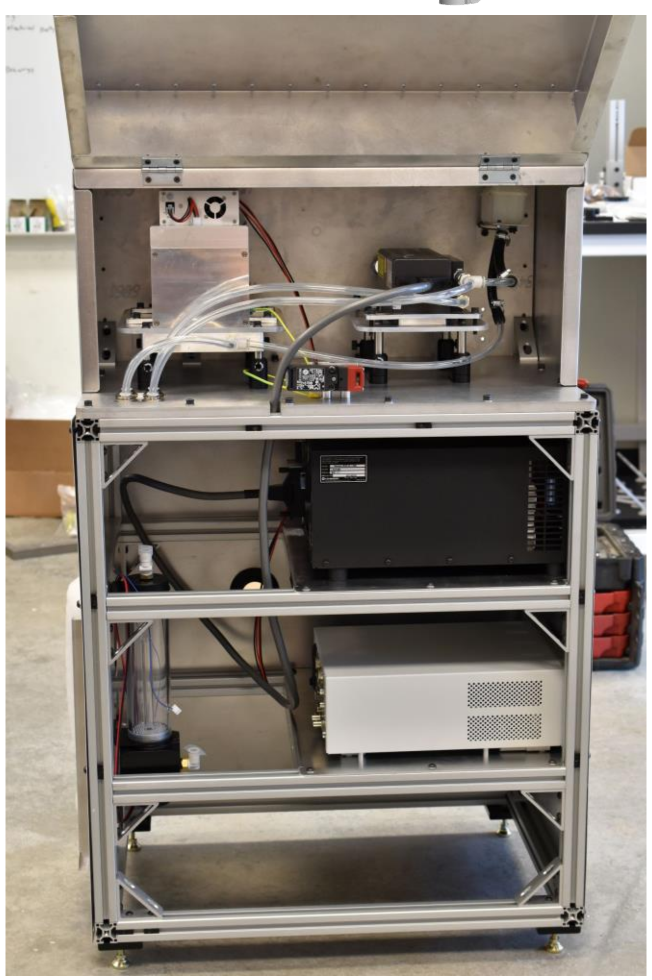






# "Class 1"





# What is left…in the long term

Future possibilities

1. Rough surfaces - possibly even in the “as built” condition
2. Non planar (i.e., curved) surfaces
3. Non linear analysis paths (i.e., for MSA of electronic devices)
4. Improved resolution (a “quantum leap” to 1um resolution?)
5. Time resolved experiments
6. Real-time determination (requires both a Gen-3 detector, laser upgrades, and clever databased approaches)

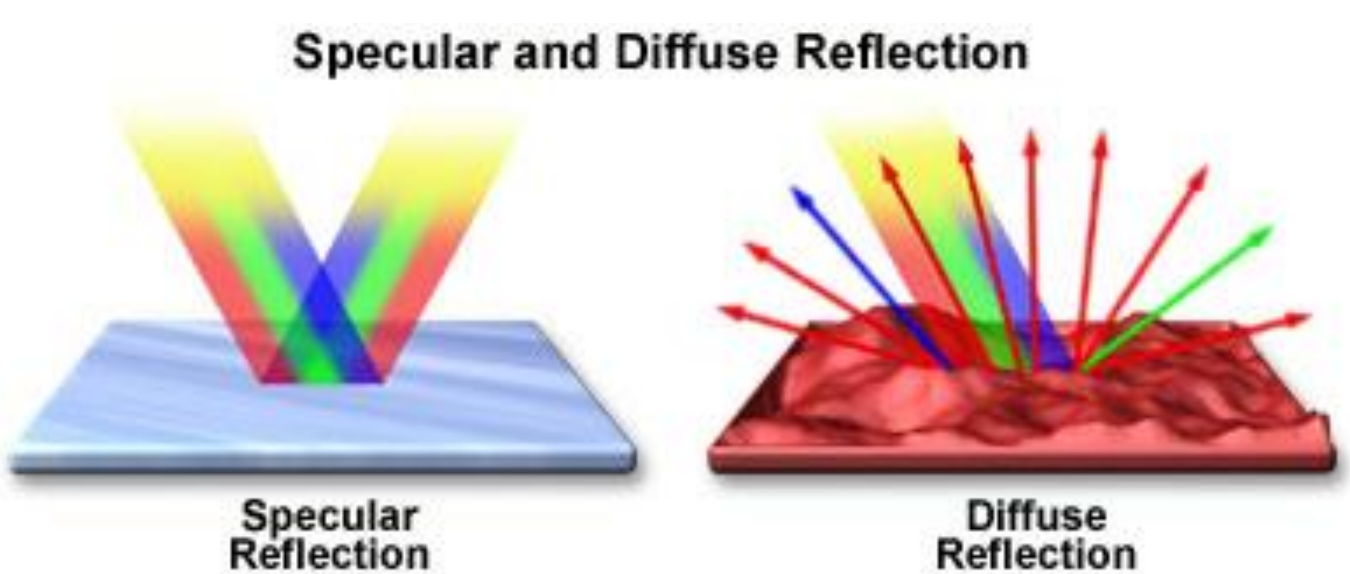
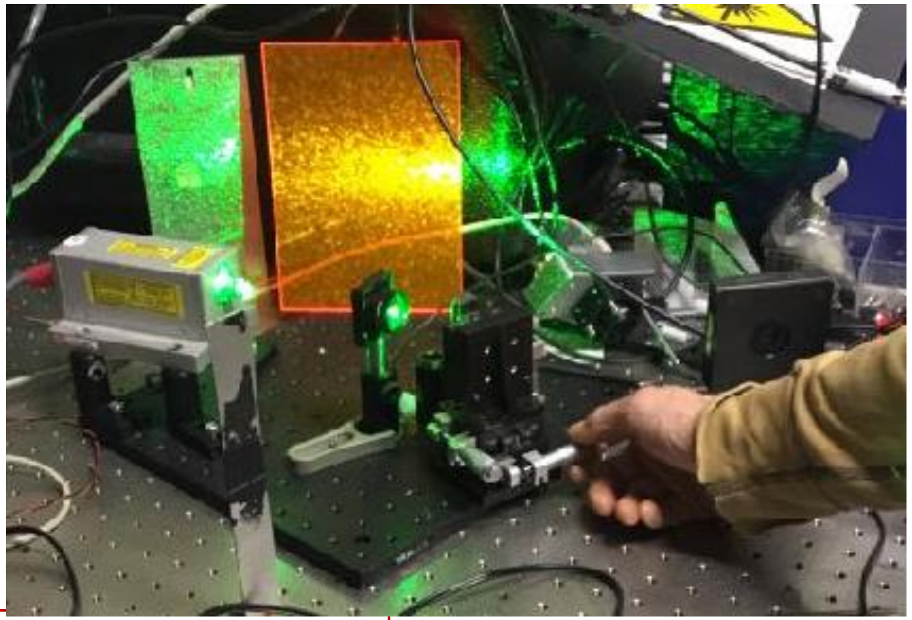
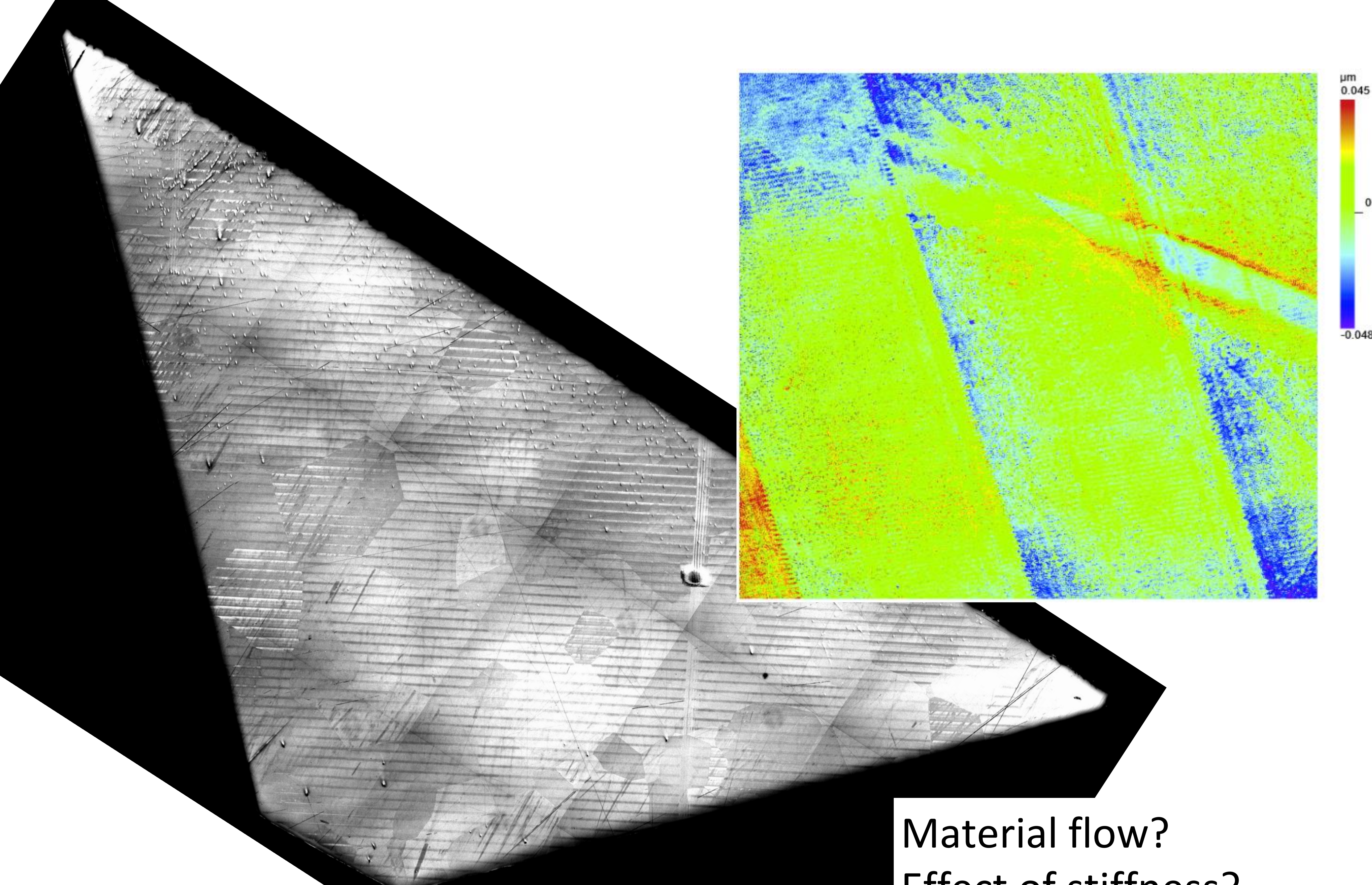



Figure 1

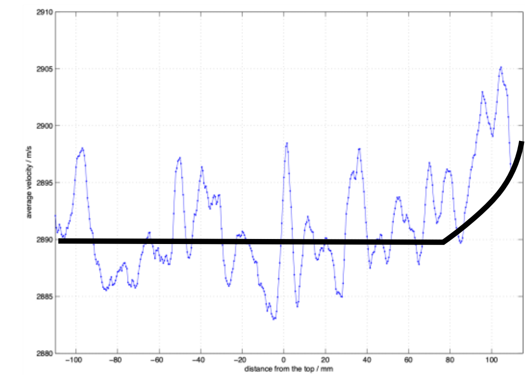





Material flow?
Effect of stiffness?
Plastic Deformation?

# Bottom Line:
# Possibilities and Limitations






<u>Possibilities</u>:

- Rapid orientation microscopy at large length scales ($dm^2$) and in 3D ($cm^2$)
- Time resolved experiments of dynamics
- Measure/map any ***<u>single</u>*** variable that affects $C_{ij}$ (including composition)

<u>Probabilities</u>:

- Orientation microscopy on rough surfaces (demonstrated in UK)
- Orientation microscopy on curved surfaces (theoretically possible)

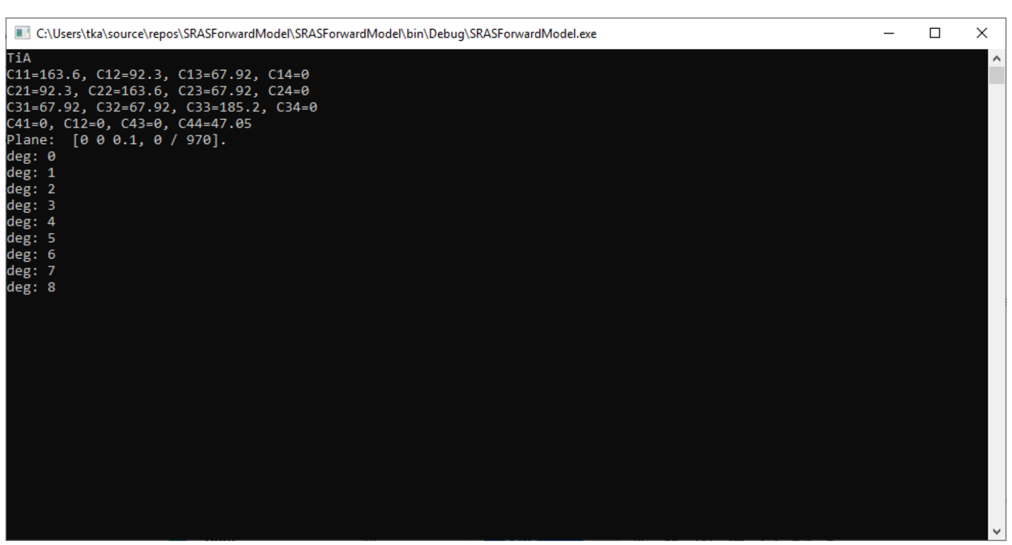
<u>Limitations</u>:

- No split photo diode with sufficient bandwidth (resolved for now)
- Resolution (but a higher resolution should be possible)
- Data and bandwidth is a challenge (but solvable)
- Manufacturing infrastructure (resolving…but it takes time)
- Sparsity in scientists
- Multiple variables will convolve the signal

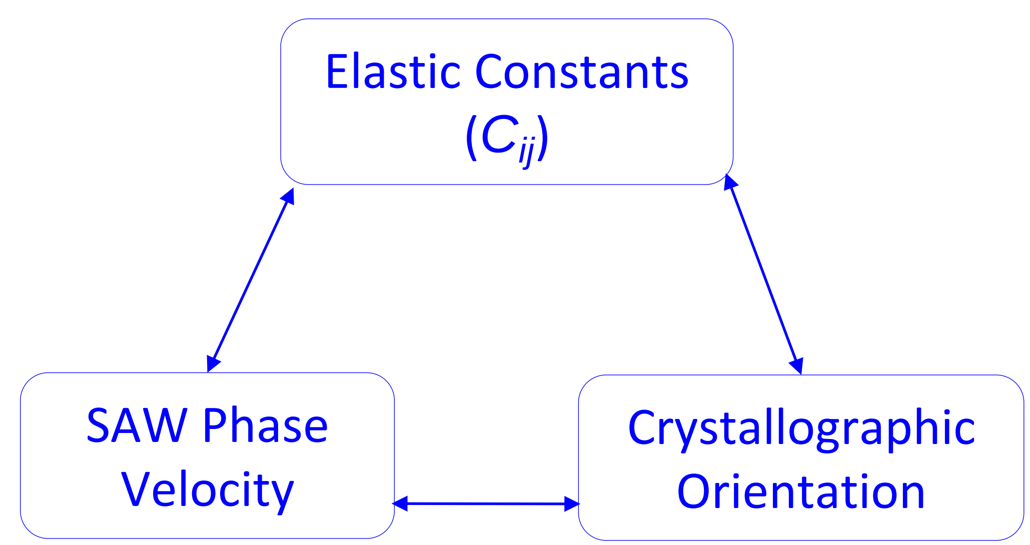
# Post-process workflow

<u>The forward model:</u>

- Math says that if you have any two adjacent points on the triangle, you ***should*** be able to get the third.
- Solving for orientation as a function of phase velocity and $C_{ij}$ is unstable at best and quixotic at worst.
- Brute Force the solution using a "forward model". Then match results.

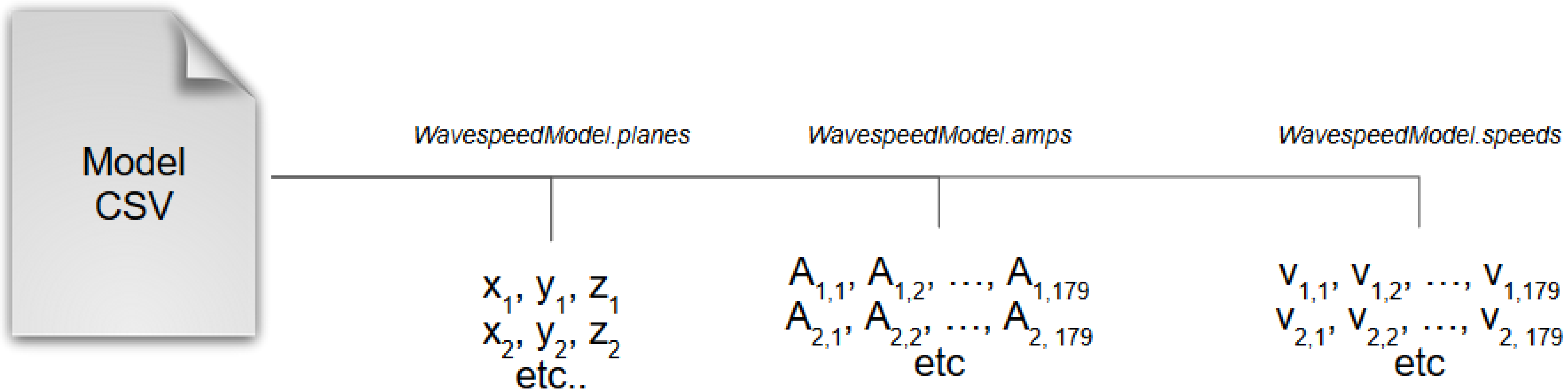



*Elastic constants, SAW Phase Velocity, and Crystallographic Orientation are interrelated.*



# Post-process workflow

**Now what?**



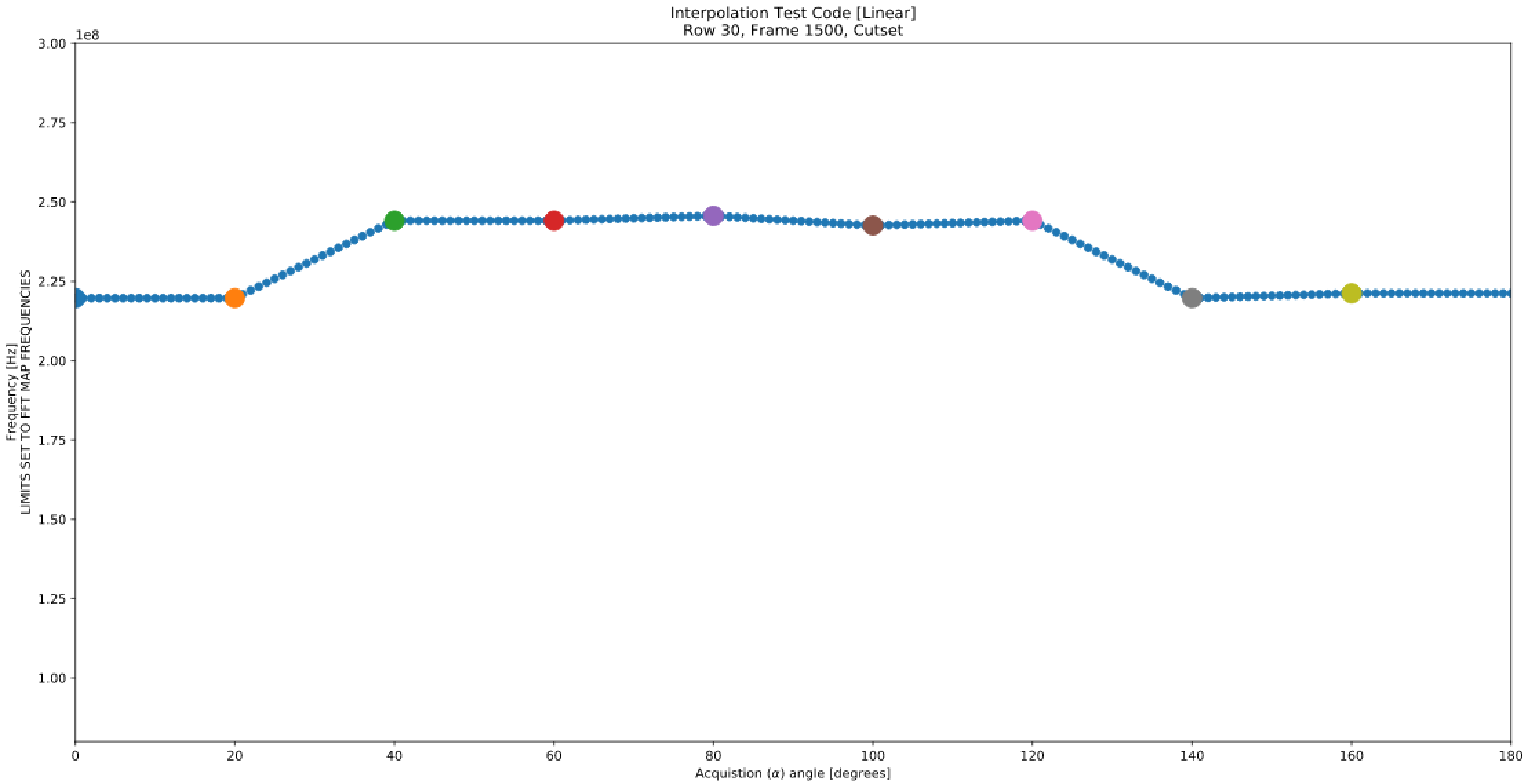

Split the model CSV into a series of row-linked object properties for ease of lookup.

<u>For every row:</u>

- <u>For every pixel:</u>
  - Extract experimentally acquired speeds at this pixel
  - Interpolate speeds between 0-180 and weight accordingly
  - <u>For every plane in the model:</u>
    - <u>For 1* shifts in the model:</u>
      - Compare model v. experimental, assign fitness score
  - Choose highest score out of all planes + rotations and assign as plane normal.
  - Delta between model speed and required rotation is Phi

Repeat 80,000 times or so.

# Post-process workflow



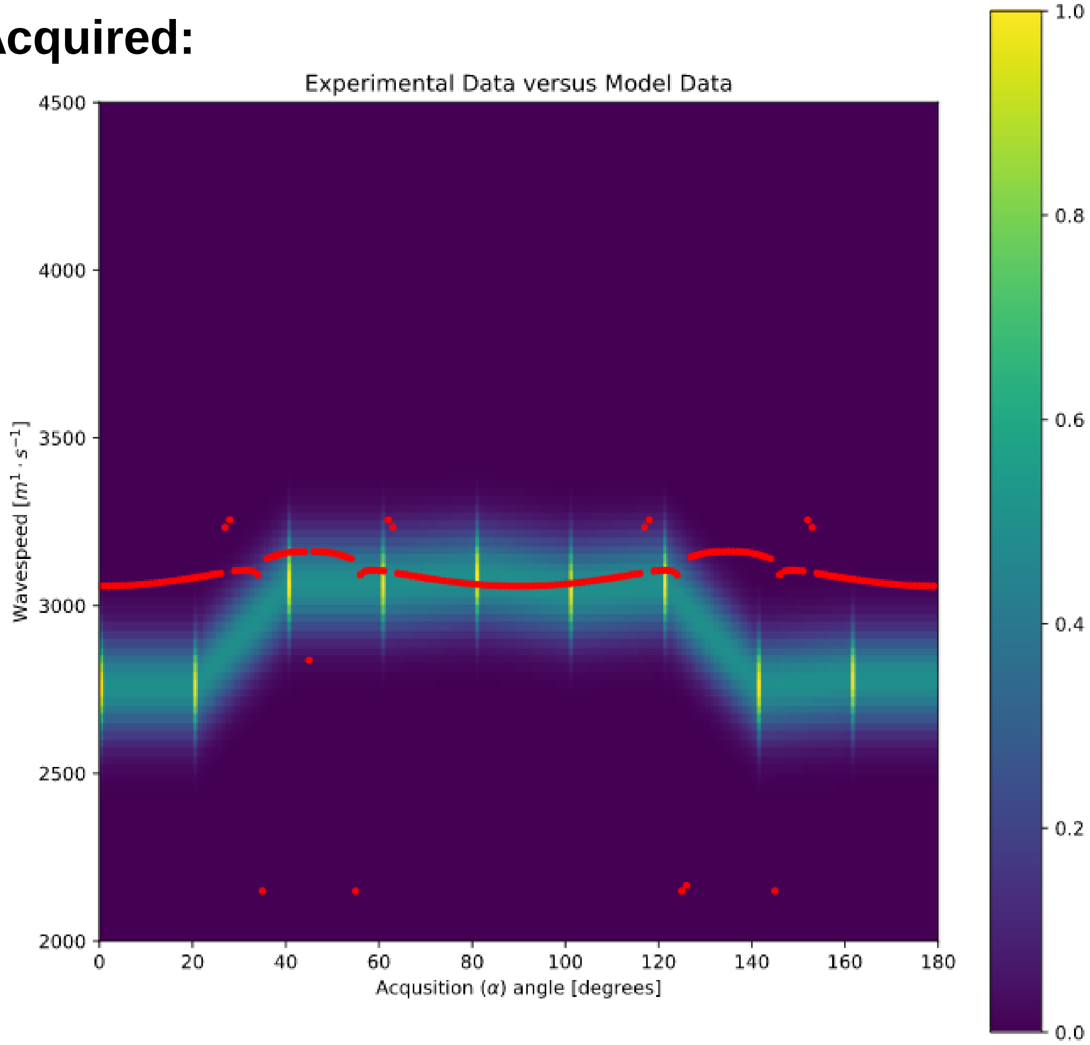

**Example of interpolated experimental frequency data.**

Small blue dots – Interpolated linear piecewise

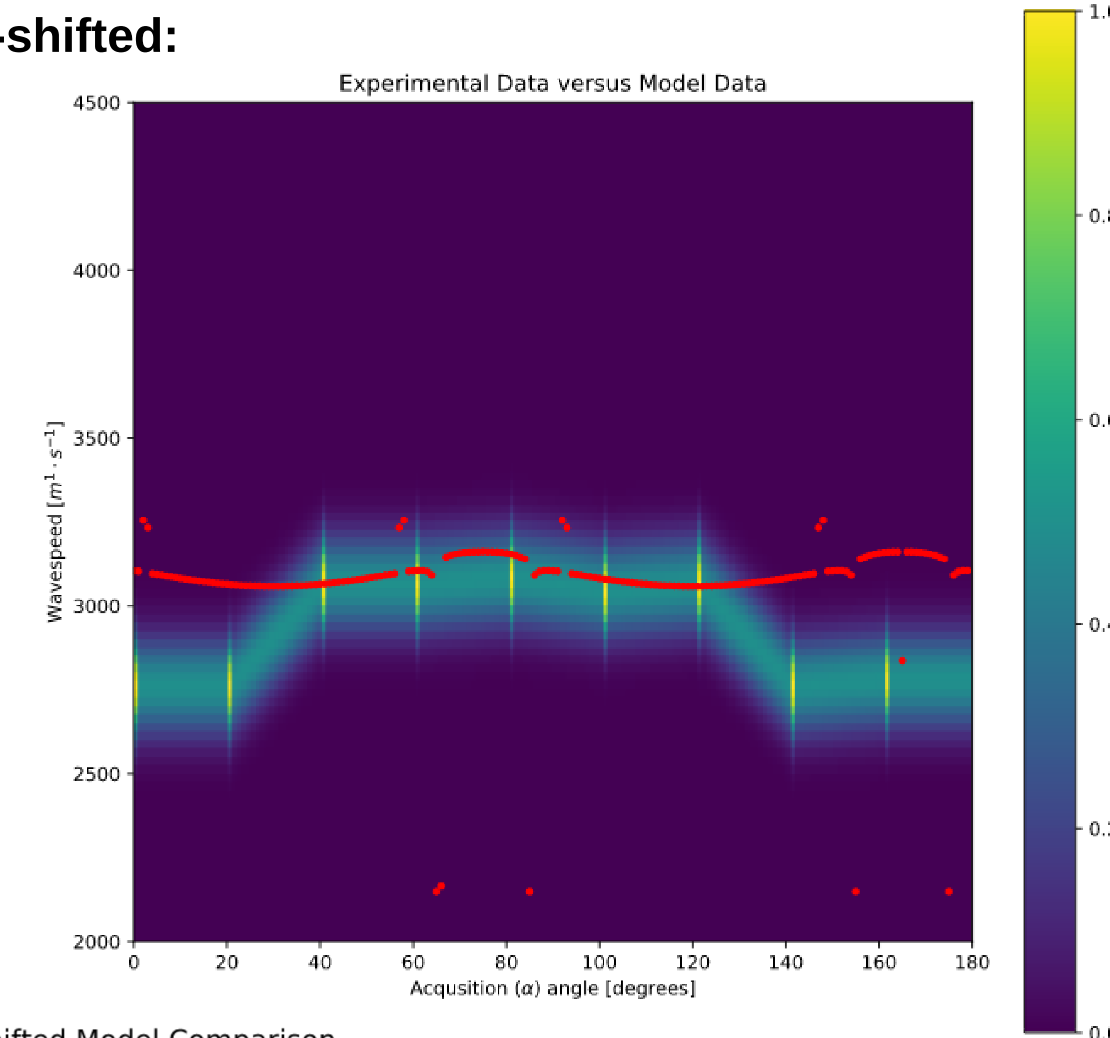
Large multicolored dots – Data from SRAS scans for pixel

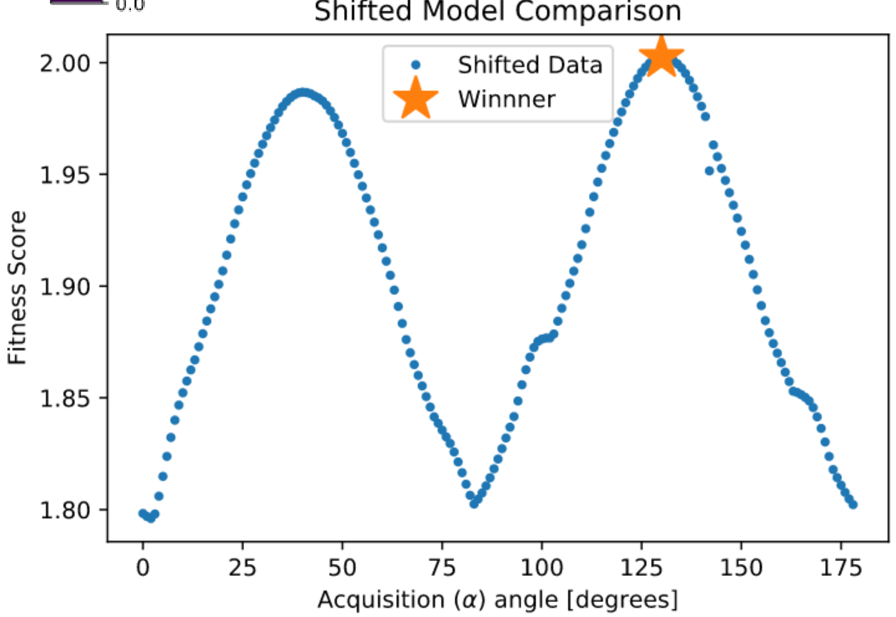
# Post-process workflow

**As Acquired:**




**α-shifted:**



# Jun-Oct Update

# Post-Processing Workflow Progress

- $C_{ij}$-specific matching algorithm has been rewritten in C for speed.
- 22x speedup as compared to pure-python implementation. (This is using NumPy as well)
- Tool is being developed to auto-generate high-speed portion of code for a given $C_{ij}$ solution set.

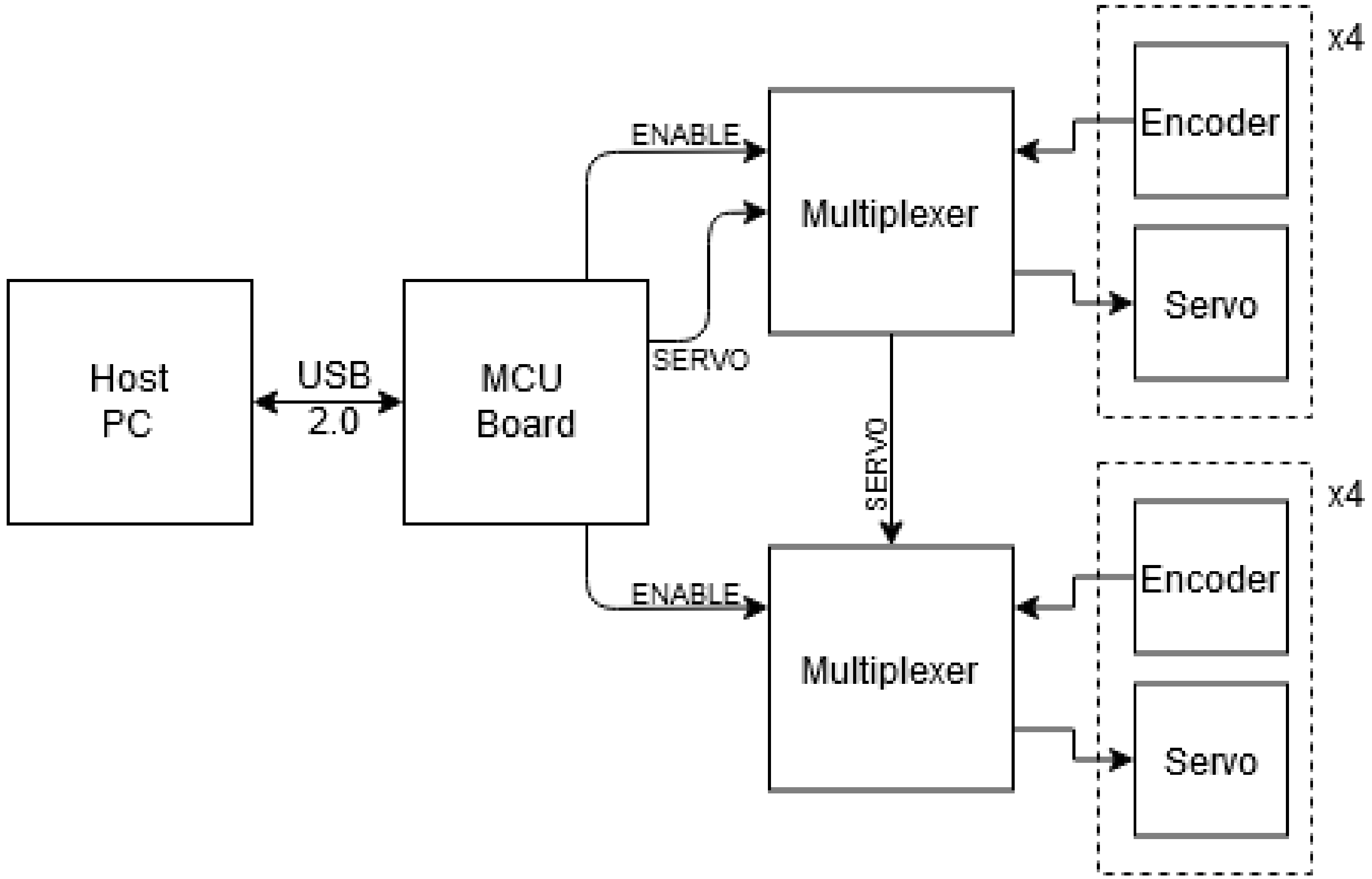
# Detector Progress

- Electronic control system has evolved 3 generations
  - GEN1: Individual 32-bit up/down counters and always-on servo signals
  - GEN2: 4-into-1 OR-Multiplexed encoder signals. Switchable single-servo control.
  - GEN3: Individually selectable encoder signal and servo routing. Infinitely expandable through addition of SIPO (Serial-In, Parallel-Out) registers

- Positioning hardware has evolved 2 generations
  - GEN1: Homing via stall detection of servo.
  - GEN2: Low profile homing switch using modified KCB05/M mount.

# Detector Progress

## GEN3 Servocontroller

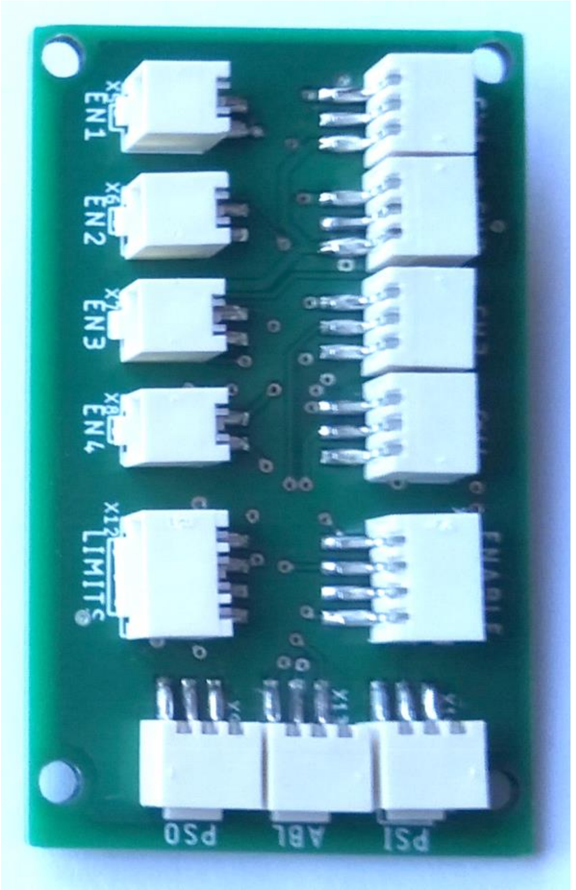



Finalized block diagram for the servocontroller hardware system.
(Only two of four multiplexer modules are shown for brevity)

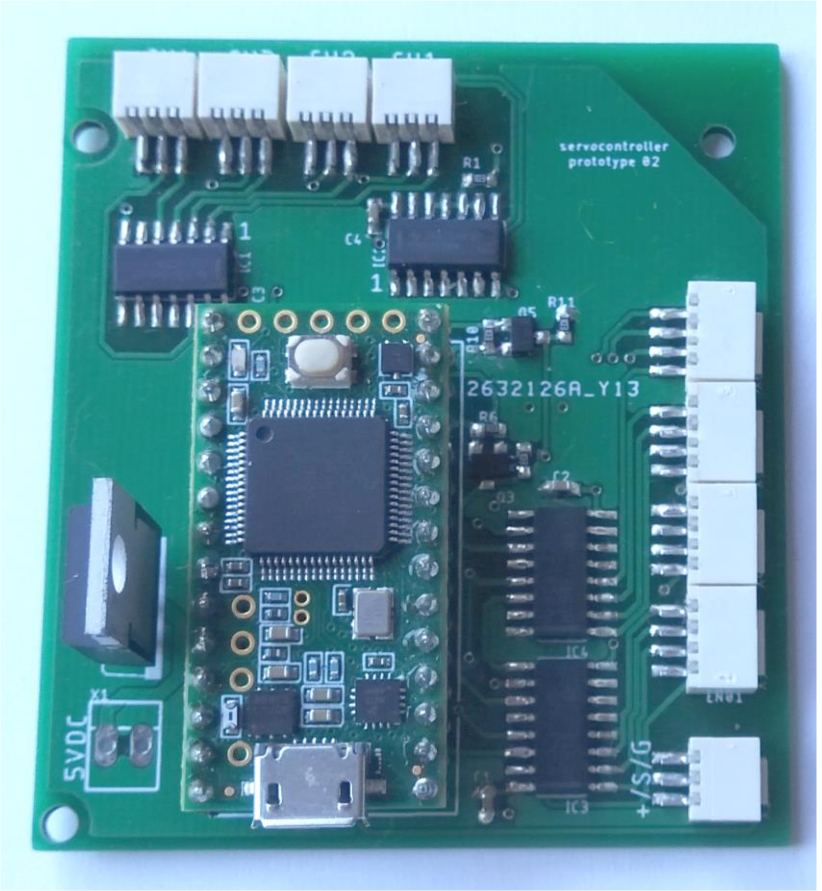
- Initial capacity:
  16 continuous channels
  2 range-limited channels
- Expandable as needed through addition of multiplexer modules
- Encoder precision is programmable between 128-4096 pulses/rev
- Firmware uses simple JSON-based message protocol

# Detector Progress

GEN3 Servocontroller



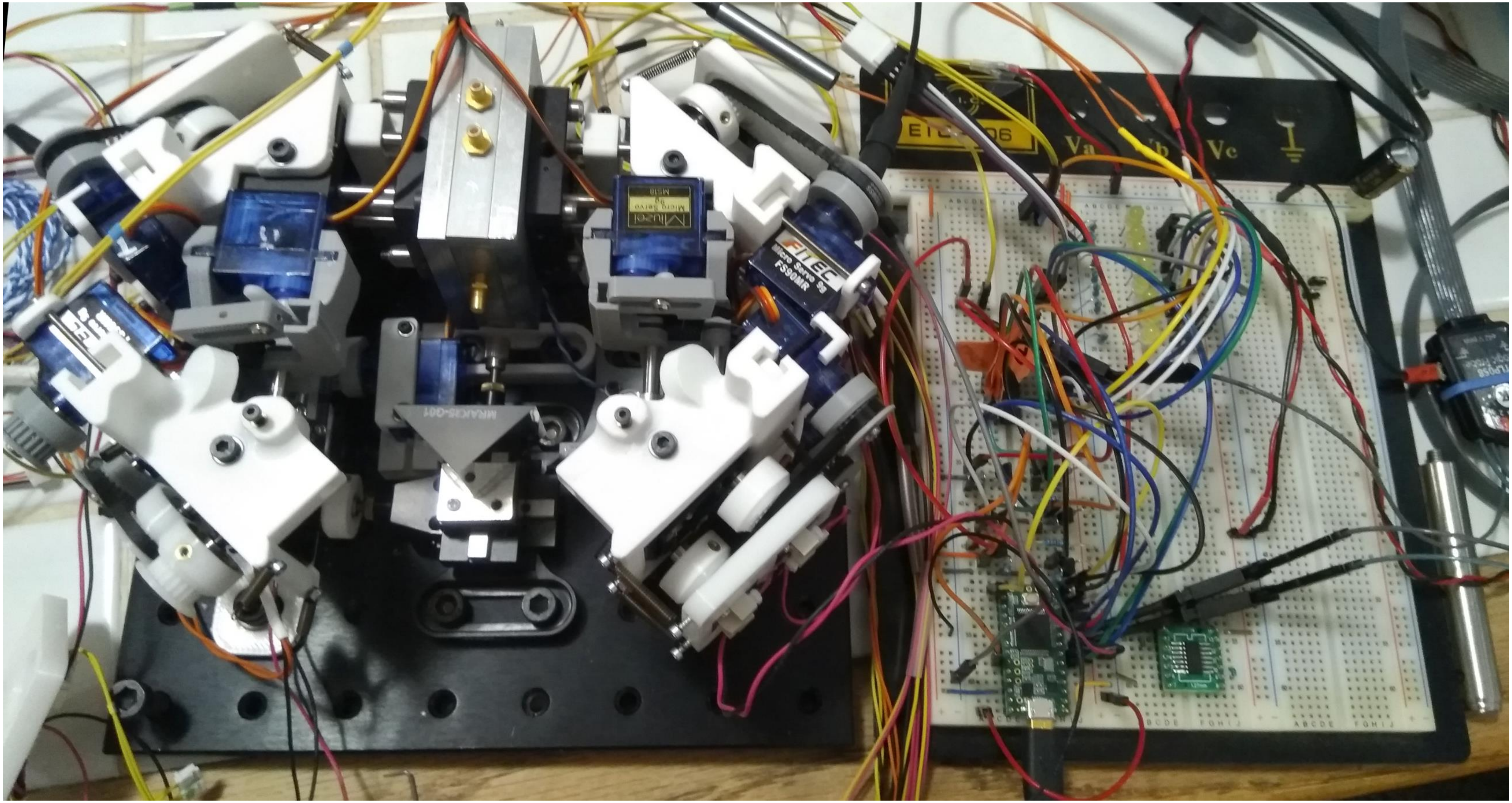

GEN3 4Ch Muxer




GEN3 MCU Controller

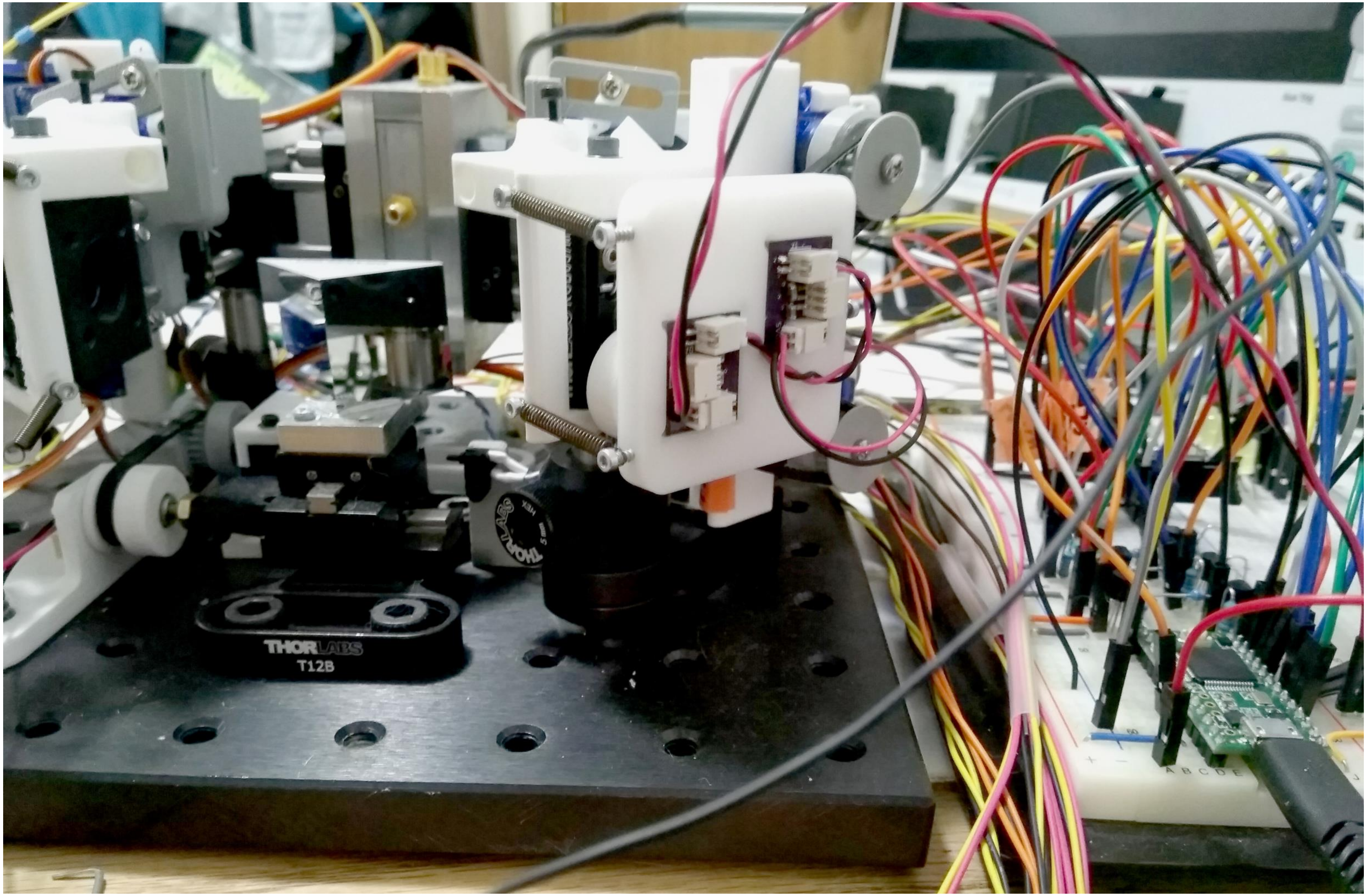
# Detector Progress

GEN3 Development Board



# Detector Progress

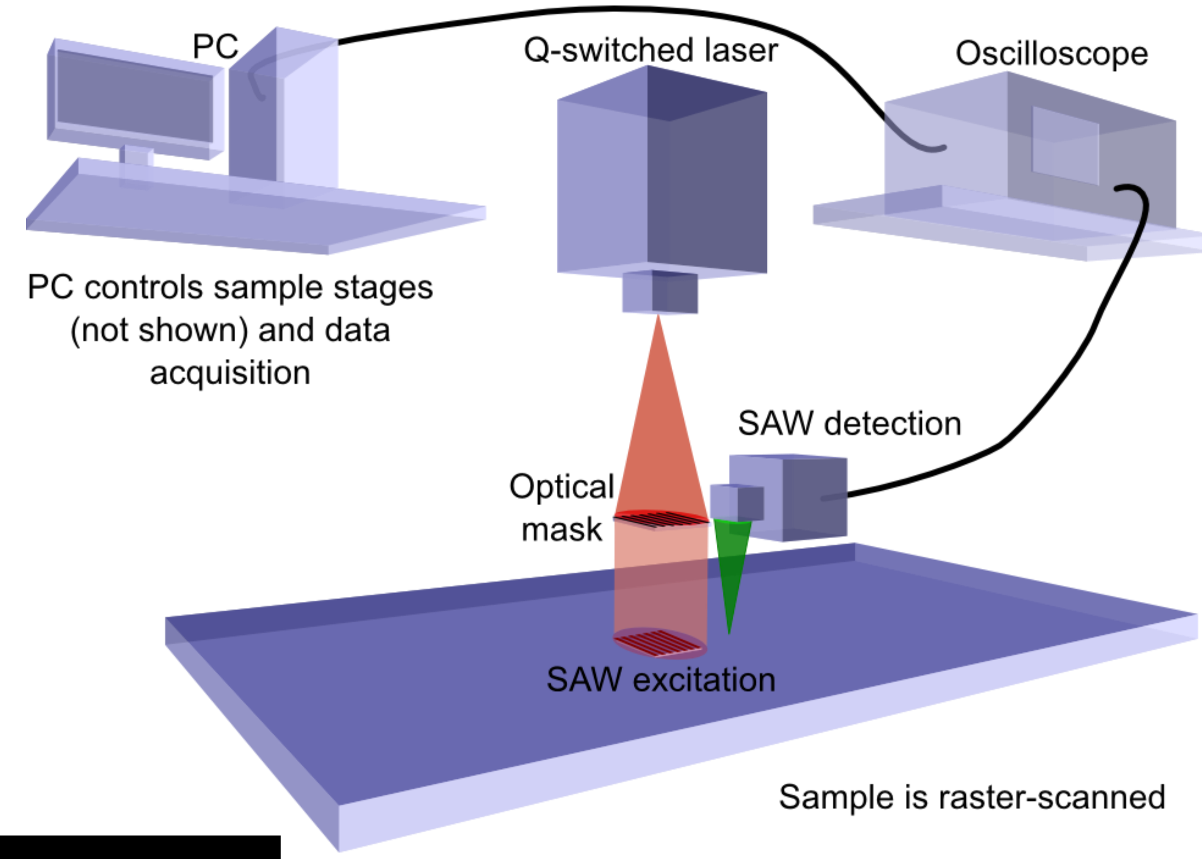
GEN3 Development Board

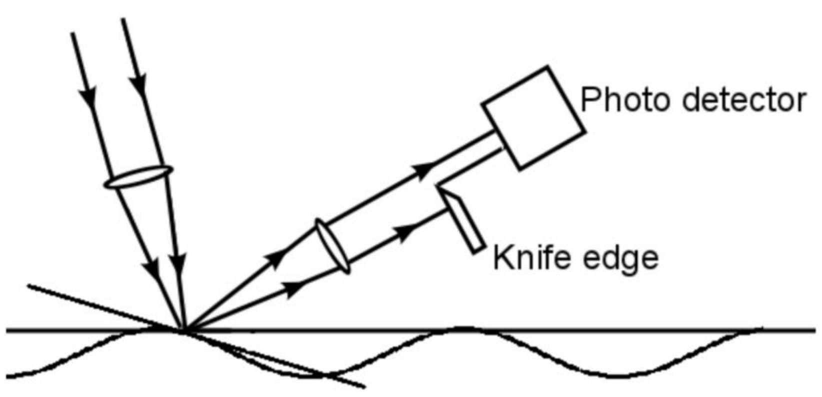


# Extras

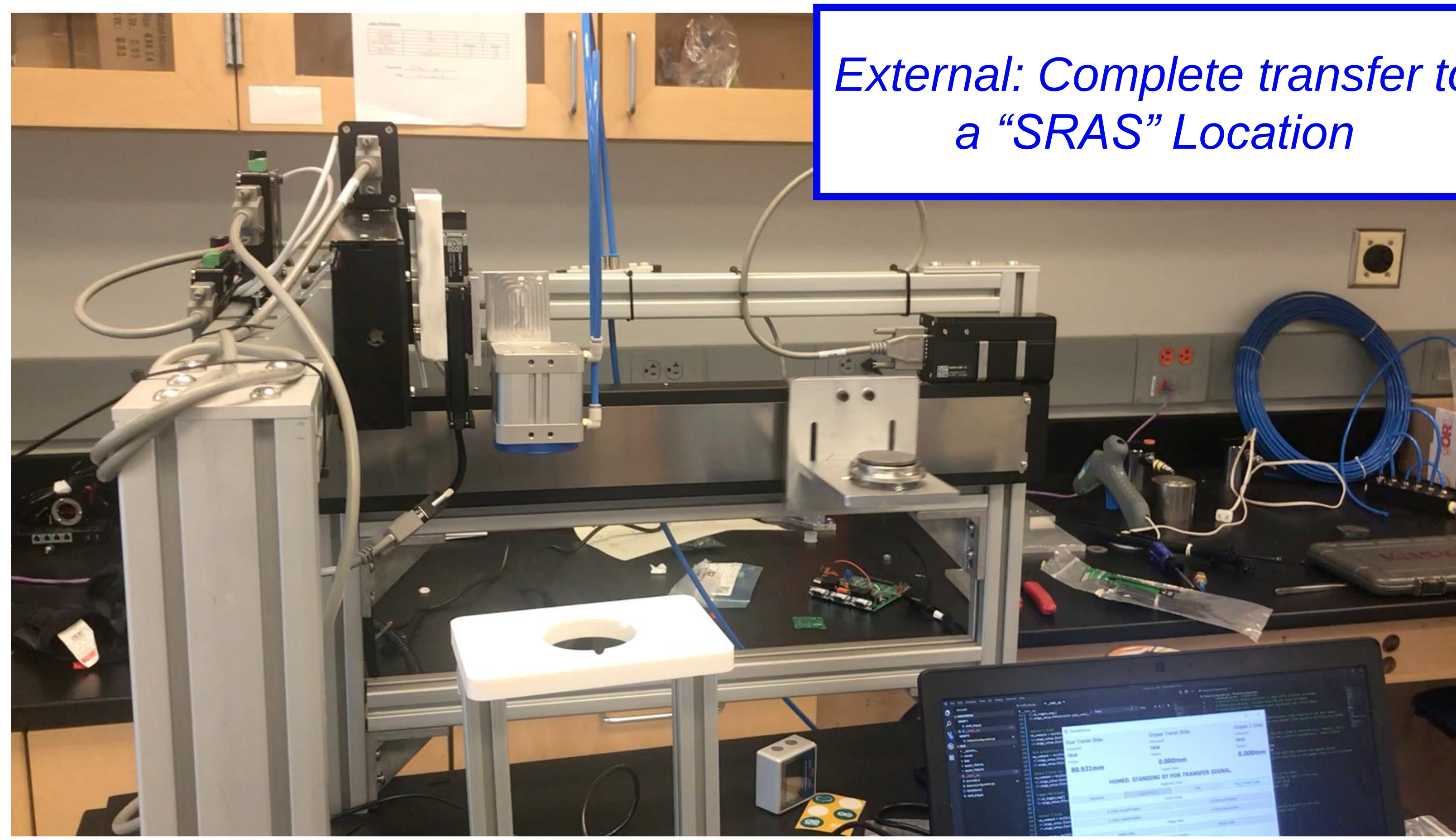
# SRAS Instrument

- At each point generate SAWs using *laser* and a *grating* – fixed acoustic wavelength
- Detect the SAWs with another laser
- Find the peak of the frequency spectrum of the detected waves
- Calculate the velocity using $v = f\lambda$



# Automated robot transfer system



*External: Complete transfer to a "SRAS" Location*

*Below: Internal (no drop-off) with code. Precision of location.*


***Possibility: Expansion for other "drop off" sites. Ultrasound? X-Ray? SEM?***