Spatially Resolved Acoustic Spectroscopy (SRAS)

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With enormous help from
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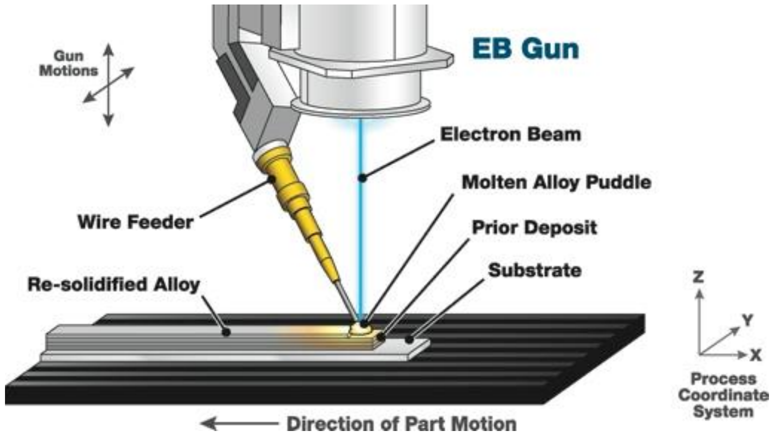
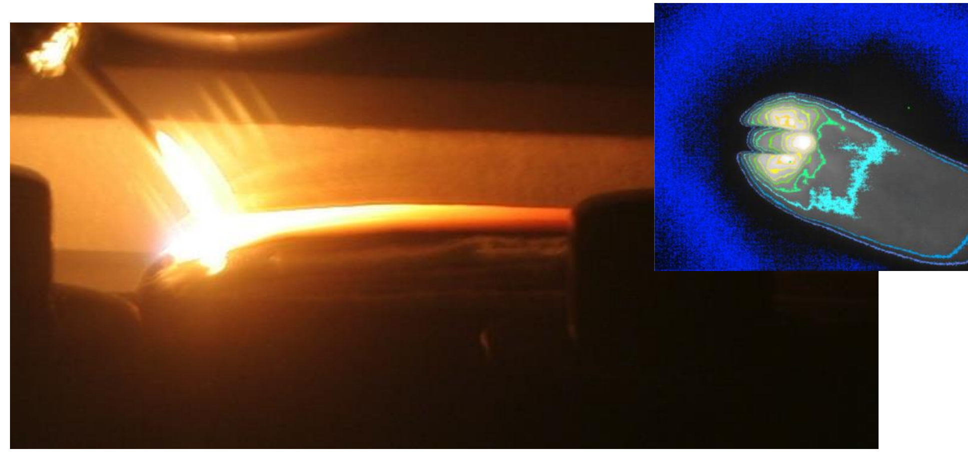
IOWA STATE UNIVERSITY

OPTICS & PHOTONICS
UNIVERSITY OF NOTTINGHAM

University of Nottingham
UK | CHINA | MALAYSIA

Motivation and overview - I



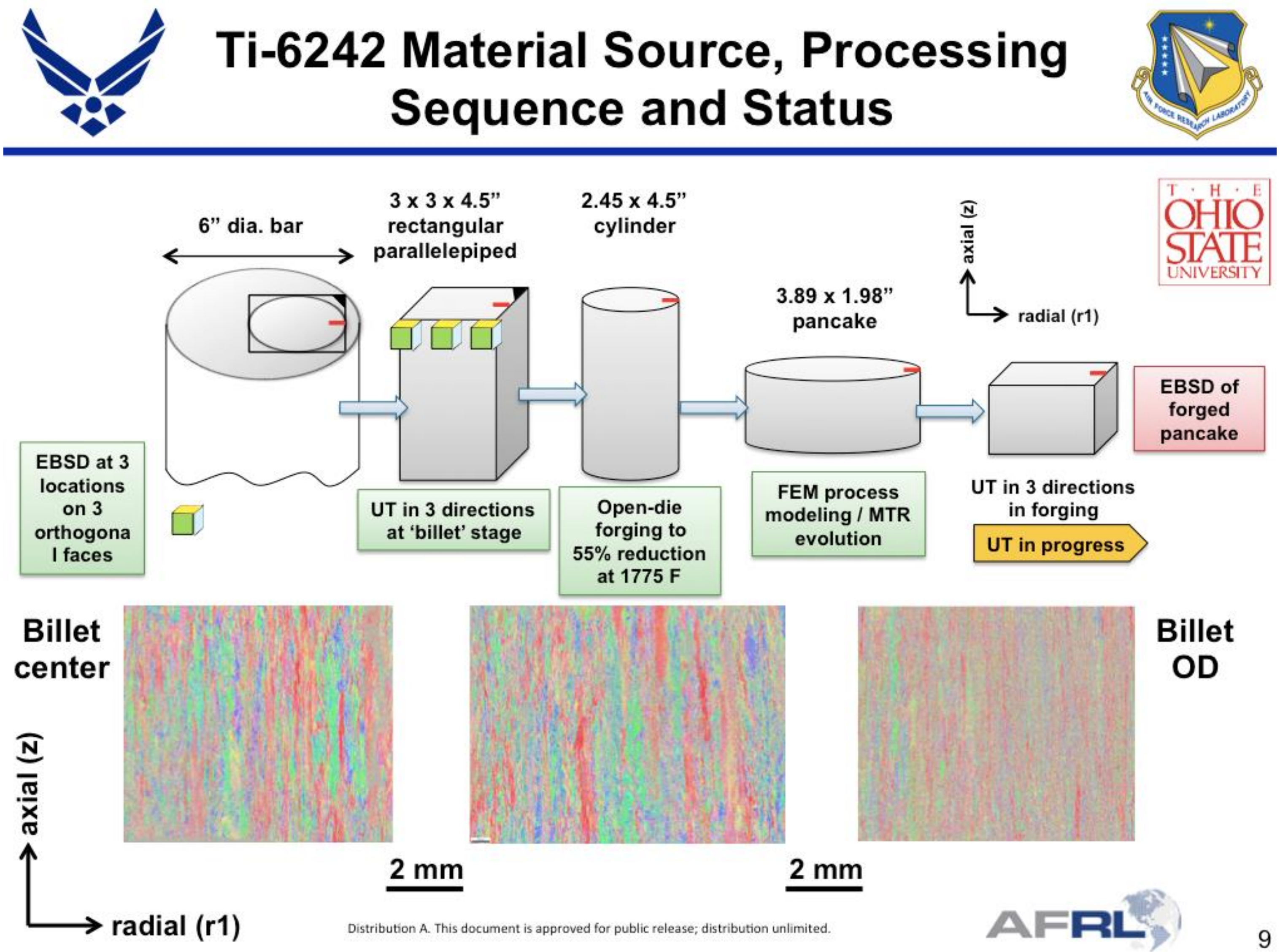


2012 AeroMat presentation: “F-35 Direct Manufacturing: Material Qualification Results” June 20, 2012

Motivation and overview - I

Motivation and overview - II

Data and slide: Adam Pilchak (AFRL)



Motivation and overview - II

The need:

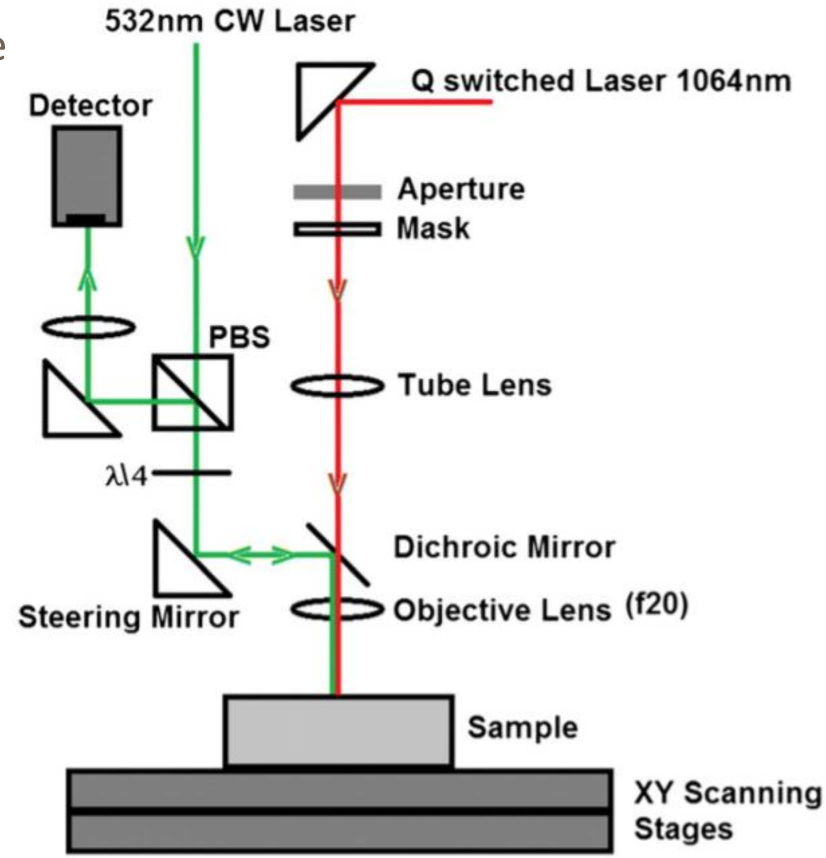
- **Rapidly analyze crystal orientations at the ‘mesoscale’.**

- *Here, I define mesoscale as what lies beyond the nanometer and micrometer length scales.*
- *One possibility would involve the use of surface acoustic waves.*
- *An investigation of this led to work coming out of one research group at the University of Nottingham – the Optics and Photonics group.*
- *They had pioneered <u>SRAS</u> (Spatially Resolved Acoustic Spectroscopy)*

- **Possible future extensions: enhance NDE modeling with known answers of material state**

SRAS (Spatial Resolved Acoustic Spectroscopy)

- Laser generated and detected SAWs (Surface Acoustic Waves)
  - Texture and orientation
- Q-Switched Laser provides pulse to generate SAW packet on surface
  - Packet velocity: ~7,000mph
- Continuous Wave (CW) Laser detects distortions in the surface as the wave packet disperses.
  - Distortions: ~5-15nm
- Distortion is detected by simple analog segmented photodiode detector.



"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

Spatially resolved acoustic spectroscopy (SRAS): texture and microstructure characterisation

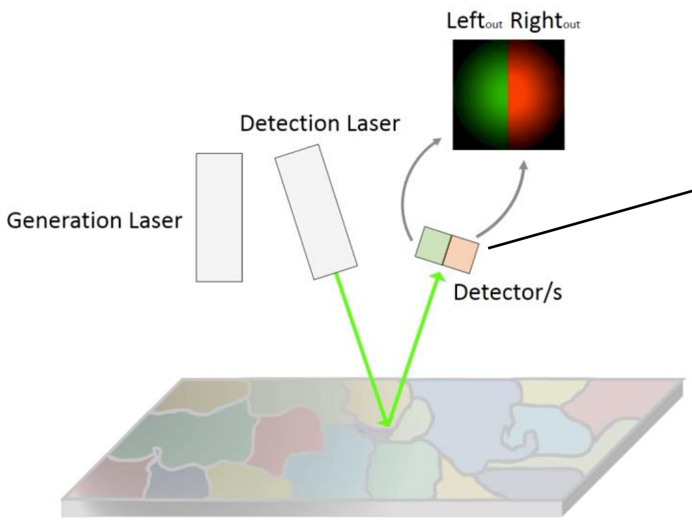
Wenqi Li, Rikesh Patel, Richard Smith, Matthias Hirsch, Matt Clark, Adam Clare and Steve Sharples

Optics & Photonics Group, Faculty of Engineering, University of Nottingham, UK.

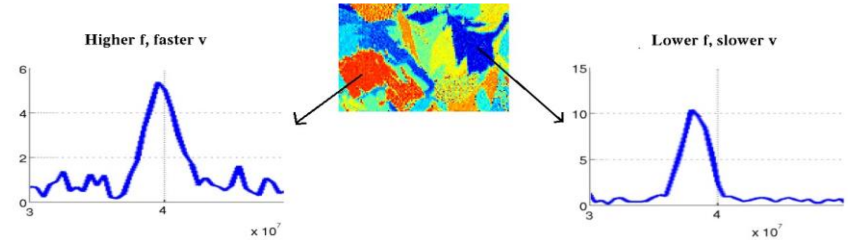
QNDE Workshop 2017, Provo, Utah, US

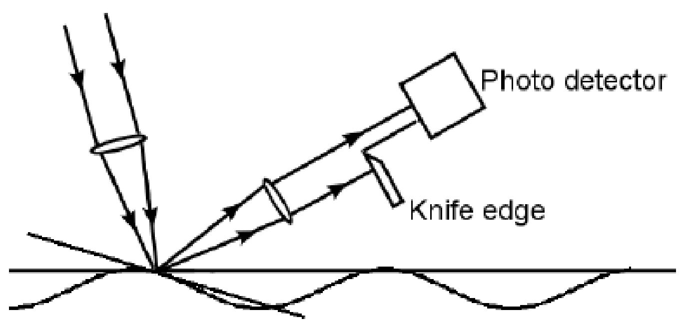
SRAS Theory

- **The size of this grating patch defines your resolution:**
- **The direction of the lines defines the direction of wave propagation**
- ***v* = *fλ***



Frequency → Velocity

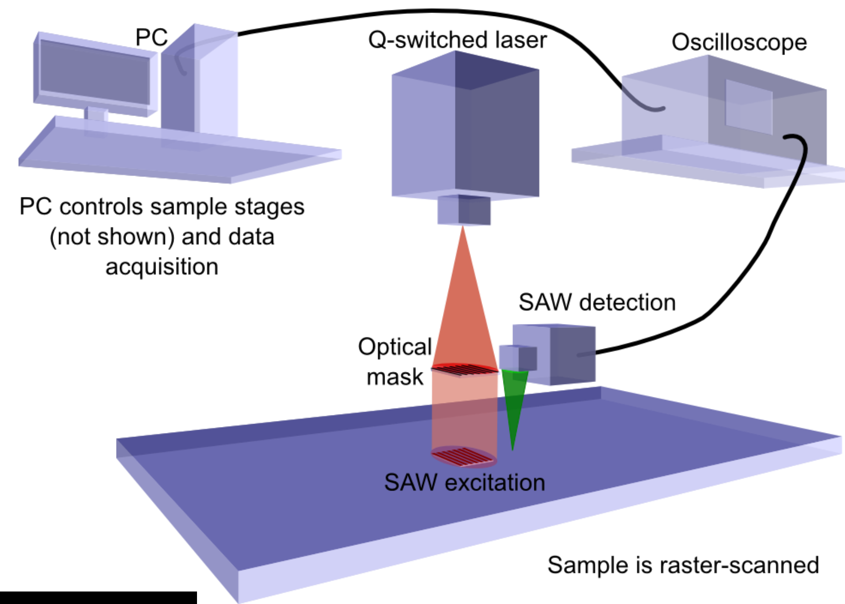




(Patent No.: GB2441953, 2009)

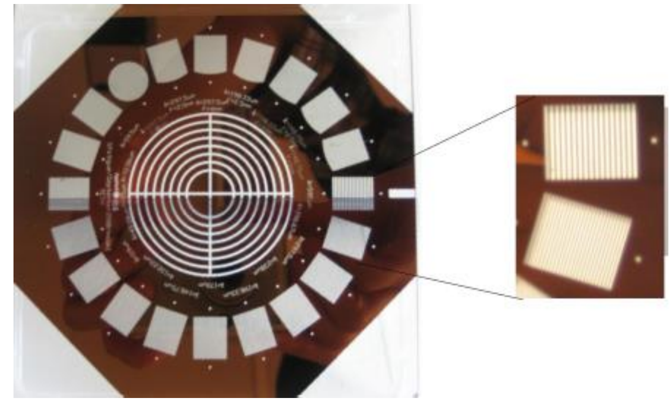
SRAS Instrument

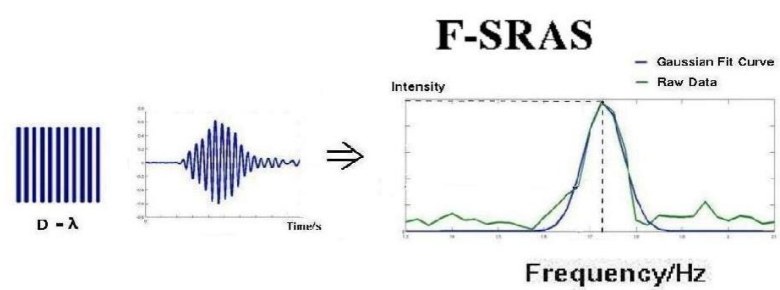
- At each point generate SAWs using *laser* and a *grating* – fixed acoustic wavelength
- Detect the SAWs with another laser
- Find the peak of the frequency spectrum of the detected waves
- Calculate the velocity using $v = f\lambda$



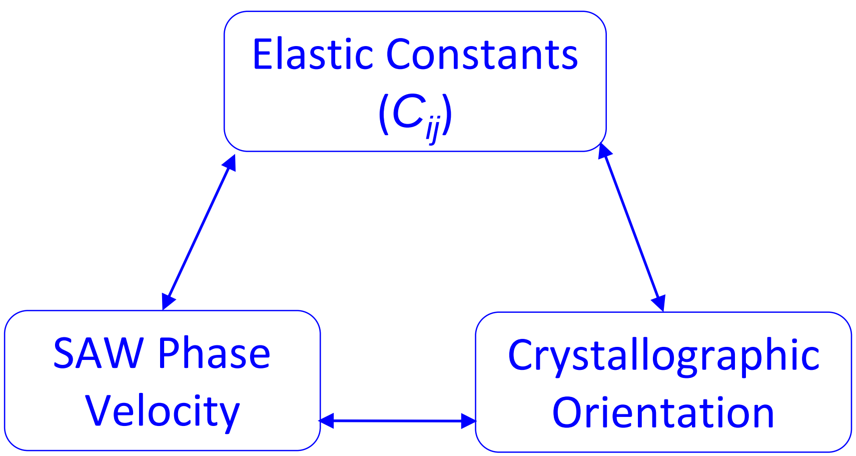
Orientation Determination

- *$v = f\lambda$*
  - *λ is the fringe spacing of the mask*
    - *Mask is glass coated with Cr*
    - *Grating acts as a filter.*
  - *f is the peak frequency from the experiment.*
    - *Velocity measured*
    - *FFT, interpret frequency domain to determine peak*





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



EASY:
- Calculating the elastic constants
- Predicting SAW Phase Velocity

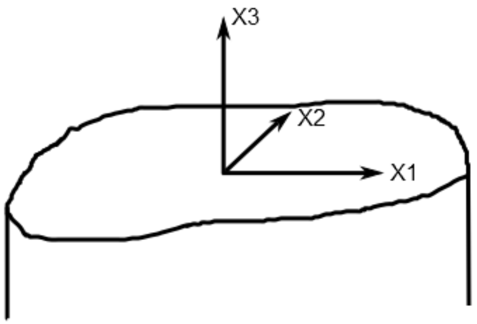
HARD:
- Calculating crystallographic orientation

SOLUTION:
Predict SAW velocity, index against solutions

Predict SAW Velocities

Wave equation:

$$\rho\frac{\partial^2 u_j}{\partial t^2} = \frac{\partial T_{ij}}{\partial x_i},\ (i,j=1,2,3)$$



Boundary condition:

$$T_{3j} = c_{3jkl}\partial u_k/\partial x_l = 0,\ \text{for } j=1,2,3.$$

Solution of the wave equation:

$$u_i = \sum_{n=1}^{3} C_n \alpha_i^{(n)} \exp[-j\beta l_3^{(n)} x_3] \exp[j(\omega t - \beta l_1 x_1 - \beta l_2 x_2)]$$

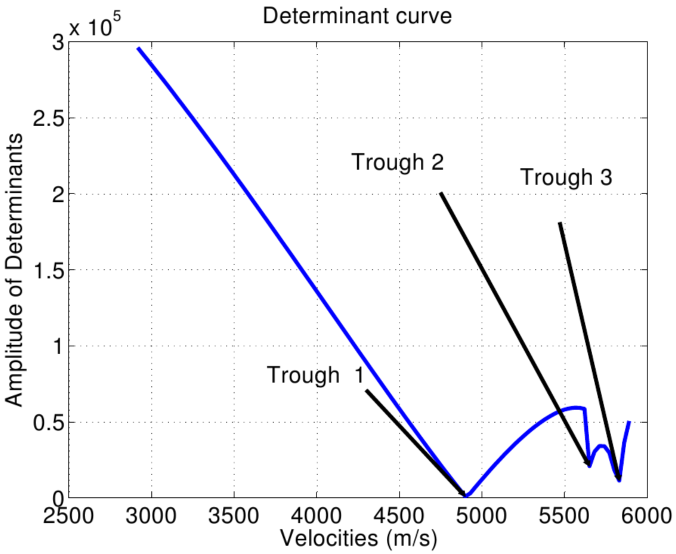
Determinant of the boundary condition:

$$d_{mn} = c_{m3kl}\alpha_k^{(n)} l_l^{(n)} = 0,\ \text{with } l_1^{(n)} \equiv l_1,\ l_2^{(n)} \equiv l_2.$$

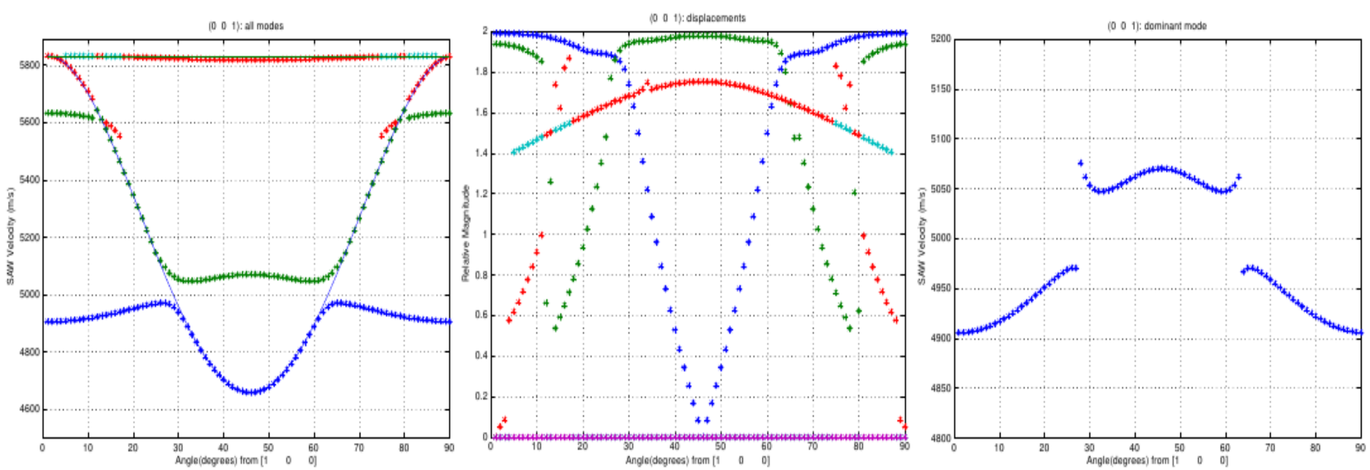
Methods adopted from:

- Li, W., Thesis, Laser ultrasonic method for determination of crystallographic orientation of large grain metals by spatially resolved acoustic spectroscopy (SRAS), University of Nottingham, 2012
- Farnell, G.W., Properties of Elastic Surface Waves, *Physical Acoustics, 6* (1970): 109-166
- Viktorov, I.A., Rayleigh and Lamb Waves: Physical Theory and Applications, Trans. From Russian. Plenum Press, 1967

Predict SAW Velocities

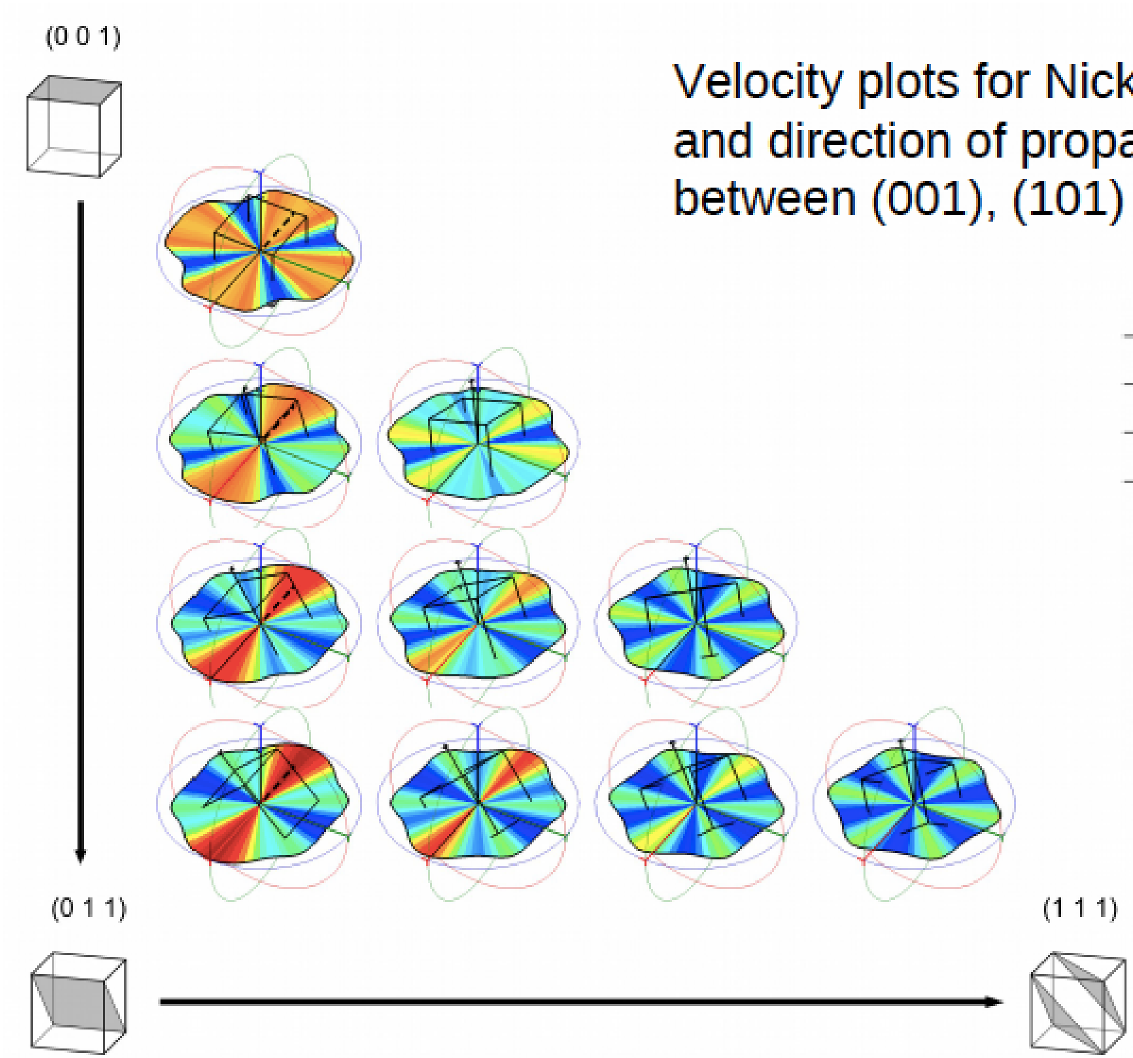


- The determinant of the boundary condition has been calculated at a specific velocity
- The curve of the determinant is plotted as a function of the velocity
- Troughs of the curve correspond to the wave modes
- The ‘dominant’ mode is selected according to the out-of-plane displacement

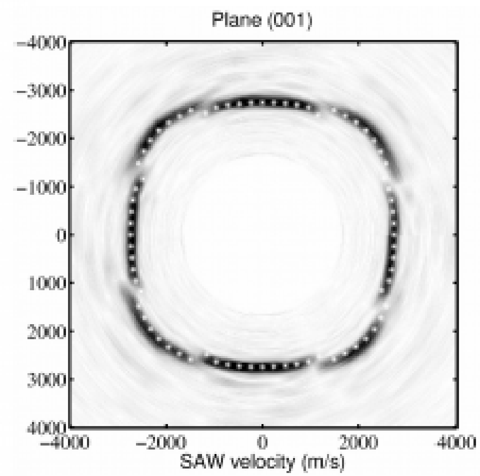


Orientation Determination in practice

(1) Orientation imaging - forward model

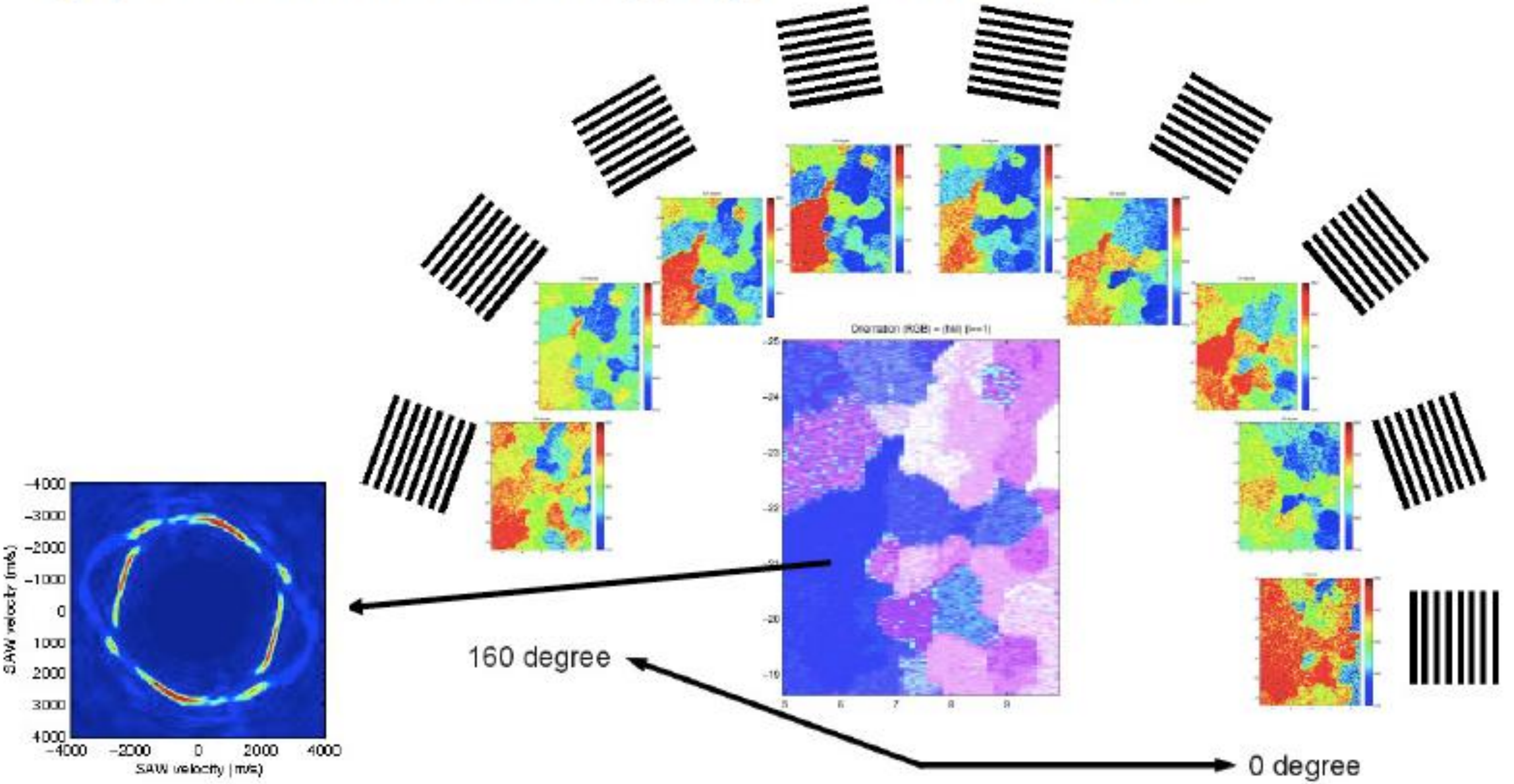


Velocity plots for Nickel vs orientation and direction of propagation for planes between (001), (101) and (111)



Orientation Determination in practice

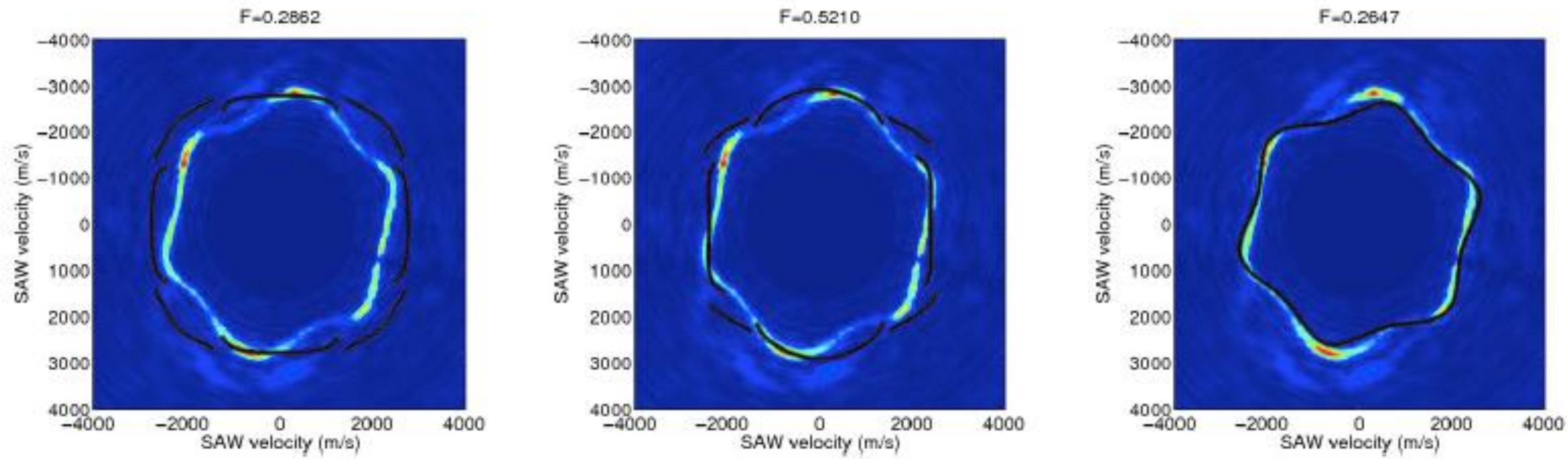
(2) Orientation imaging – Collect data



Orientation Determination in practice

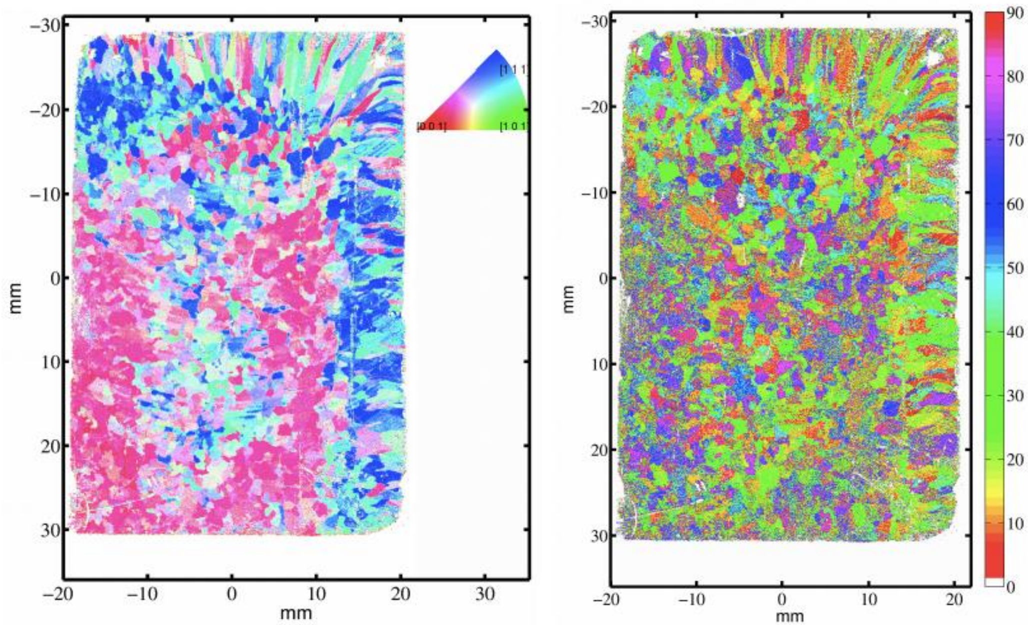
(3) Orientation imaging - fit to data

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

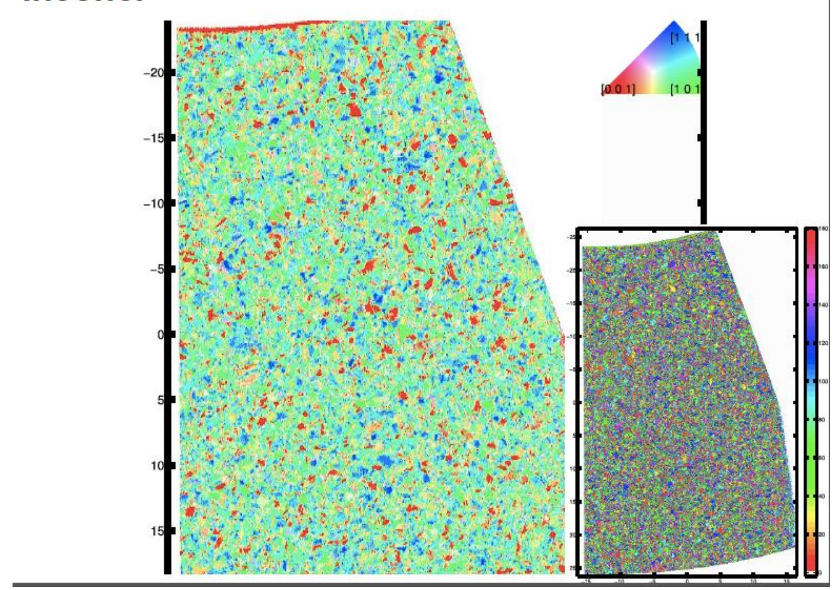


- The merit function is simply the sum of the amplitude under the black asterisks on the graph
- Repeat this procedure for all the combinations of plane and propagation direction

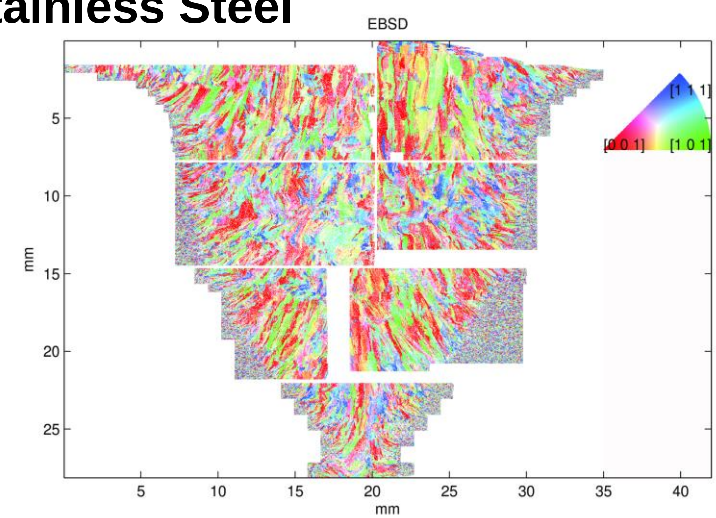
Large grain aluminium



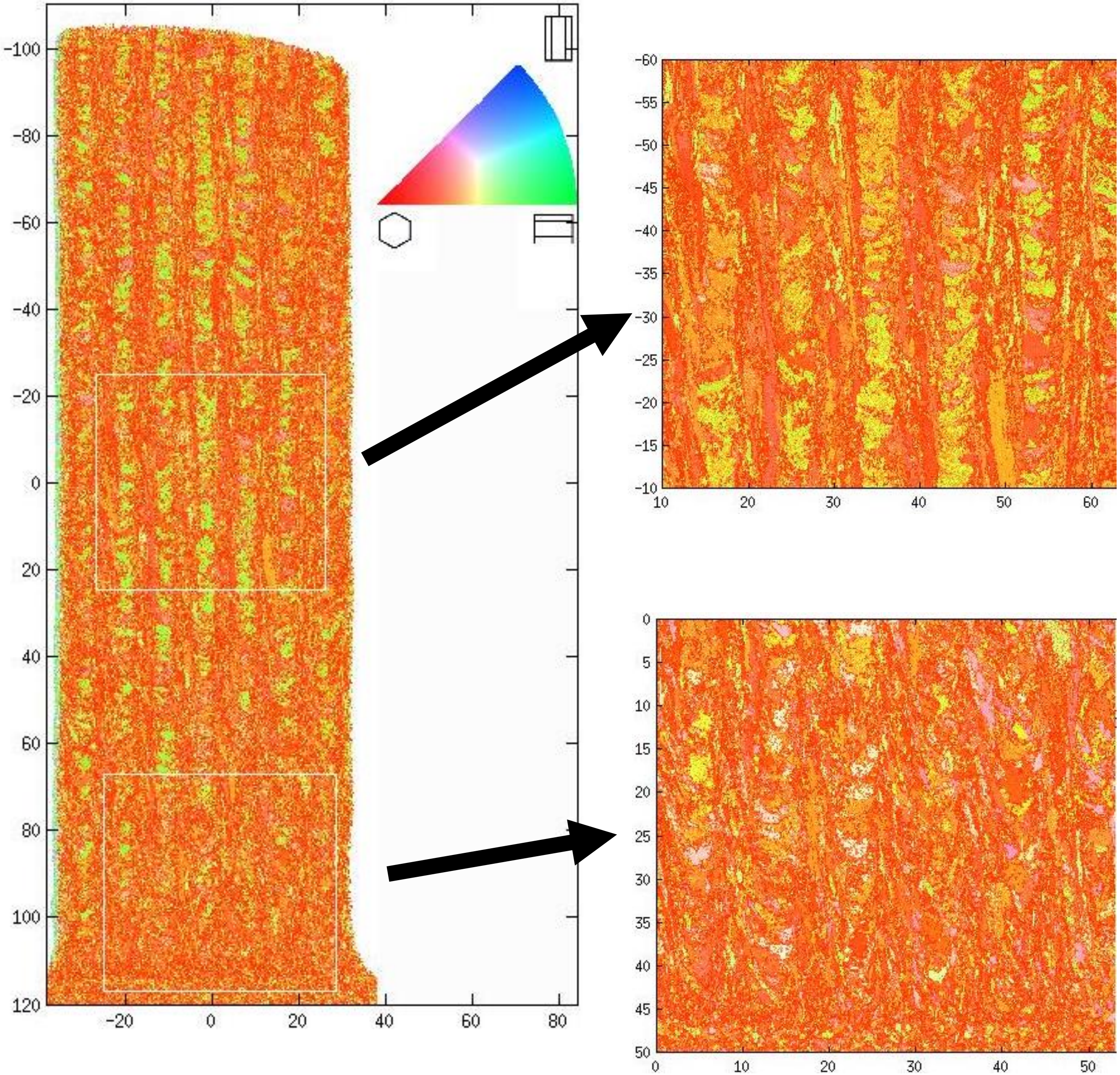
Inconel



Stainless Steel



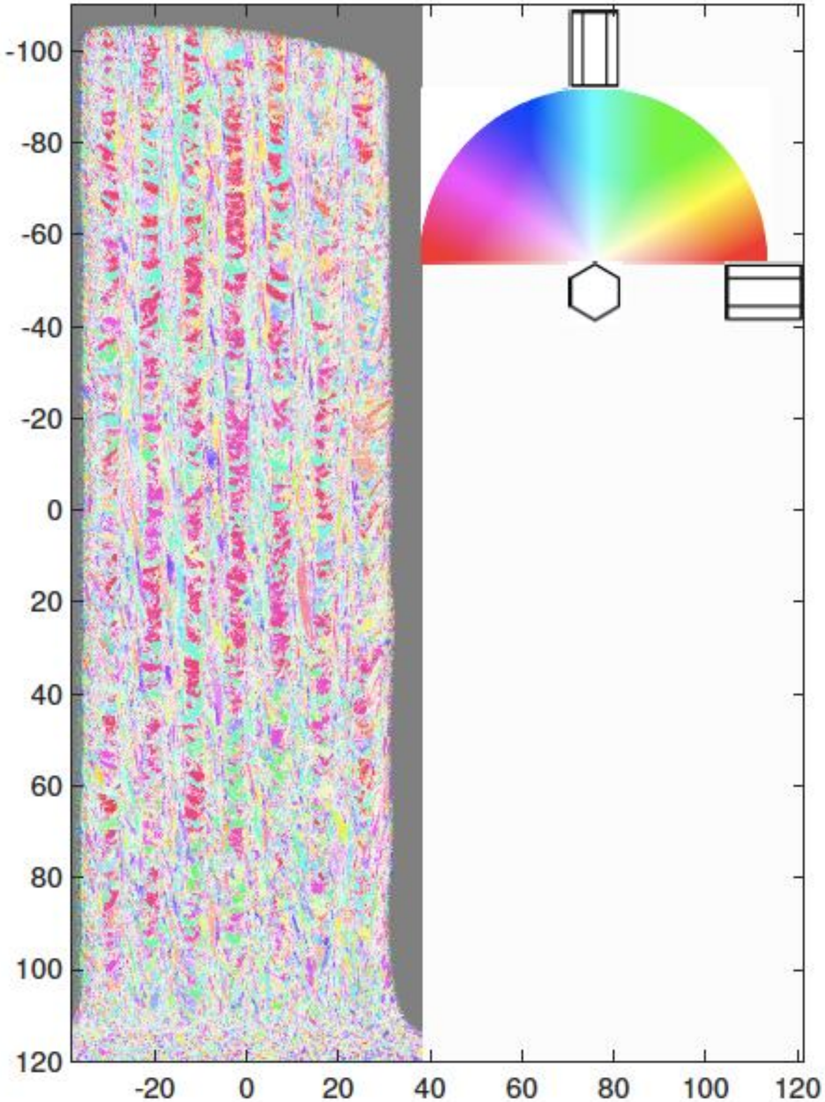
Hexagonal materials: SRAS on Ti 64

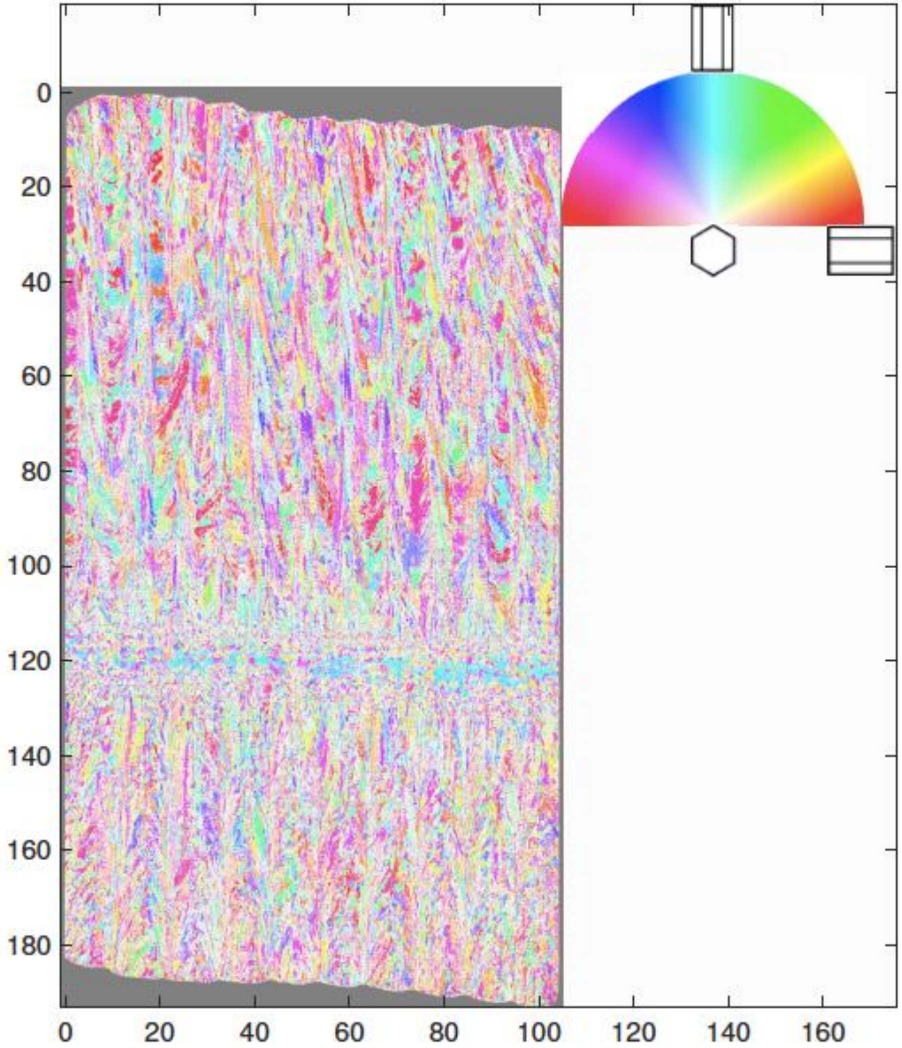


~14,500 mm^2

This scan was obtained in 16 hours.

A conventional SEM with EBSD, operating under “normal” modes, would take ~10 years of 24 hour operation to obtain this scan.

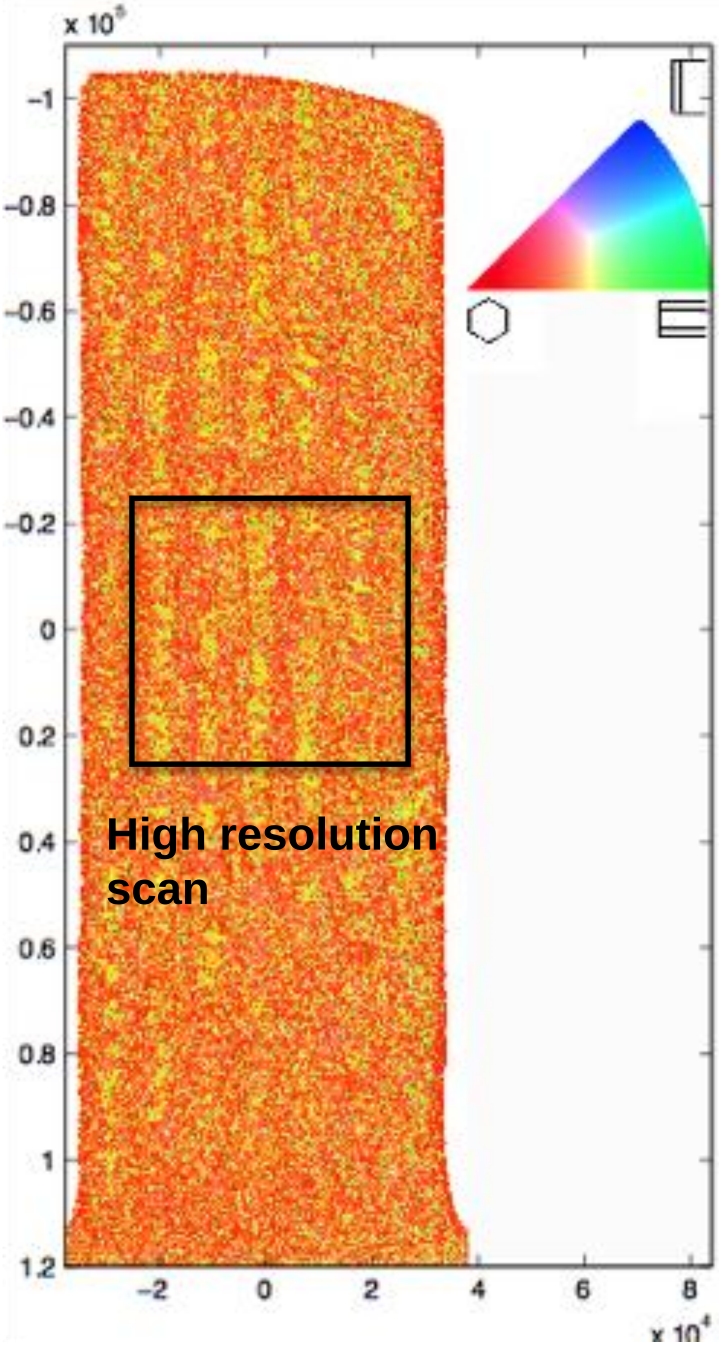


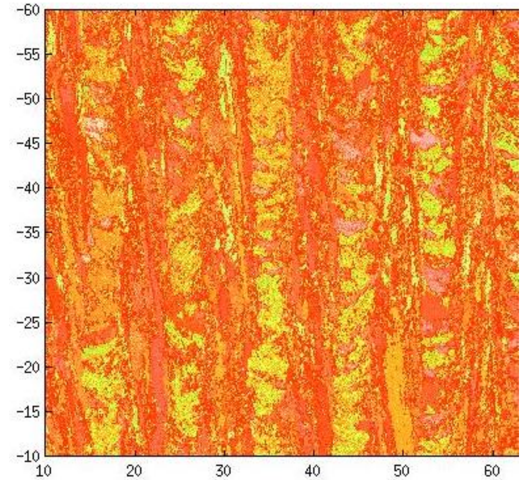


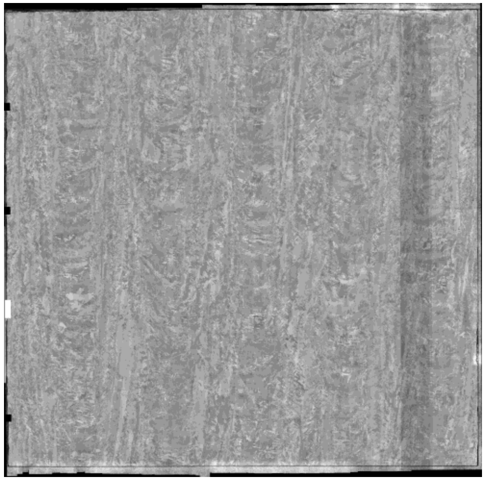
~35,000 mm2, collected in ~2.5 days*

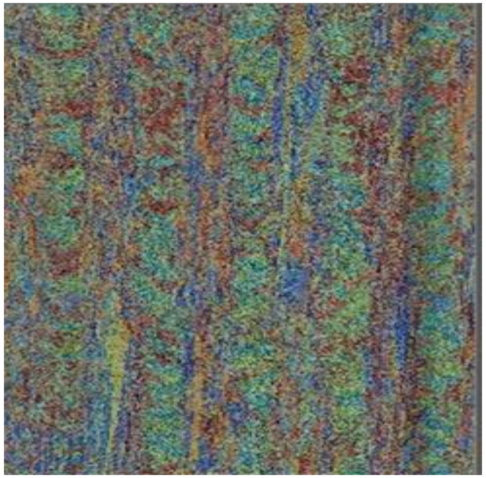
The system

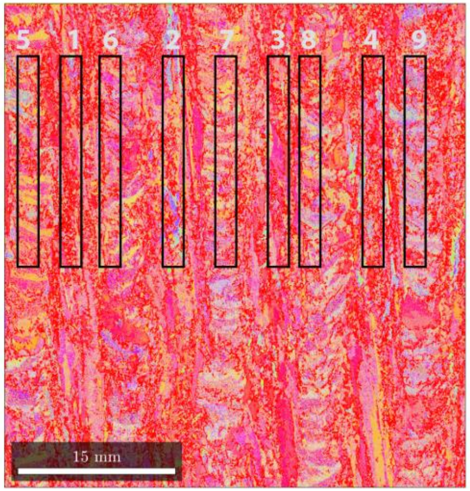
- Develop the first inverted SRAS system
  - Deal with varying focus issues with the existing SRAS system and a Robo-Met (Automated 3-legged pi-micrometer system)
- Integrate it into a system with an optical microscope
  - Microscope vendors…don't want to pass lasers through their optical lenses…so we have fully built our own
    - Possible future integration with other optics…
  - Will address a missing Bunge angle in some crystal systems
- Integrate it into a Robo.Met-3D platform
  - Provide large, mesoscale 3D orientation datasets…we are after cubic centimeters to cubic inches.
- Challenges:
  - Space!
  - Safety!
  - 2D to 3D
  - (and everything else we didn't think about for 7,000mph waves and 5nm displacements)



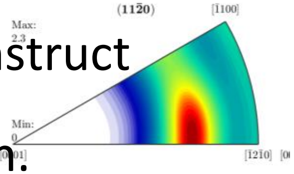


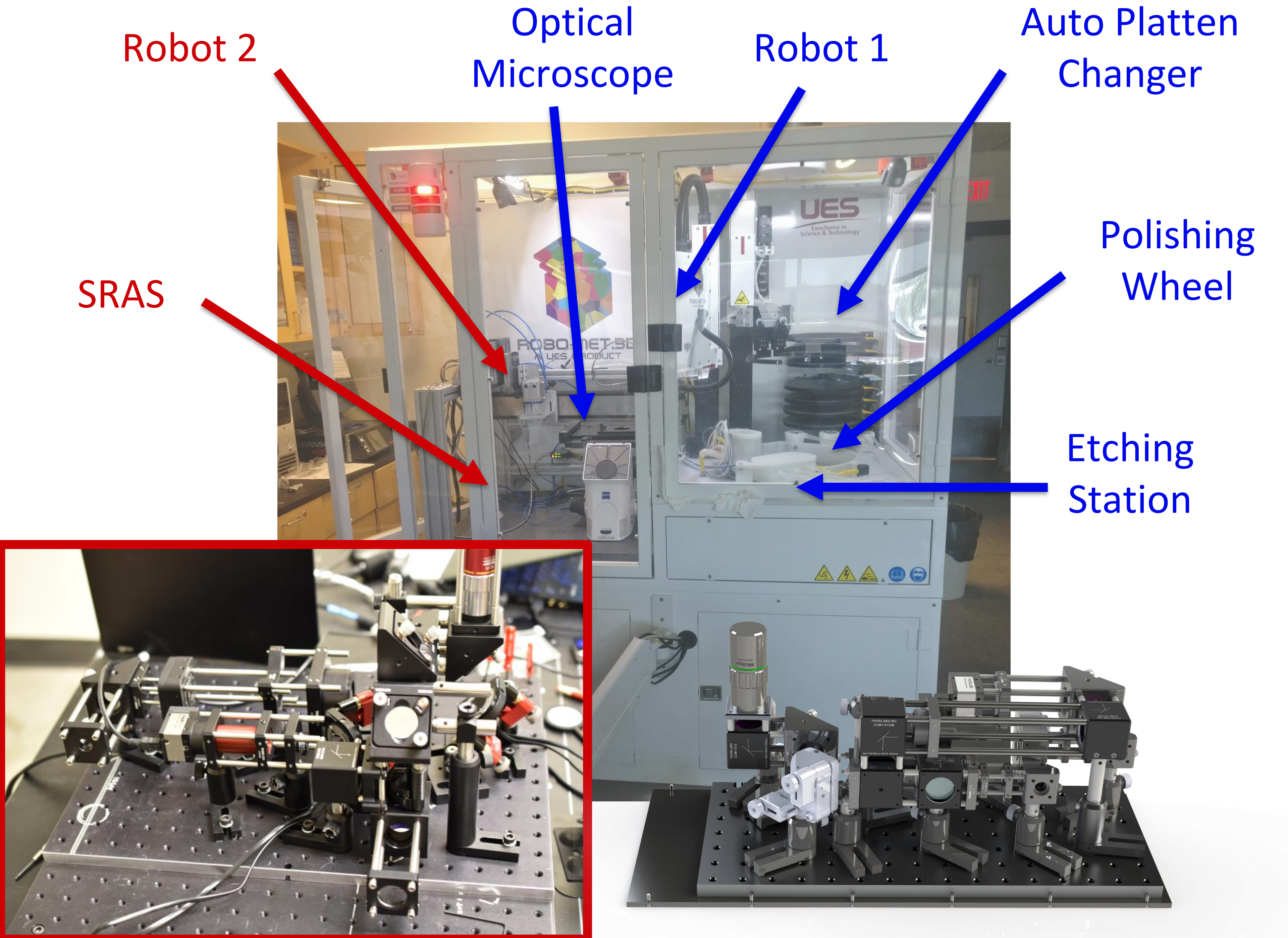






Ti-6Al-4V is a bit “messy” to reconstruct (lath normals are not planar).
The reconstruction has a deviation.

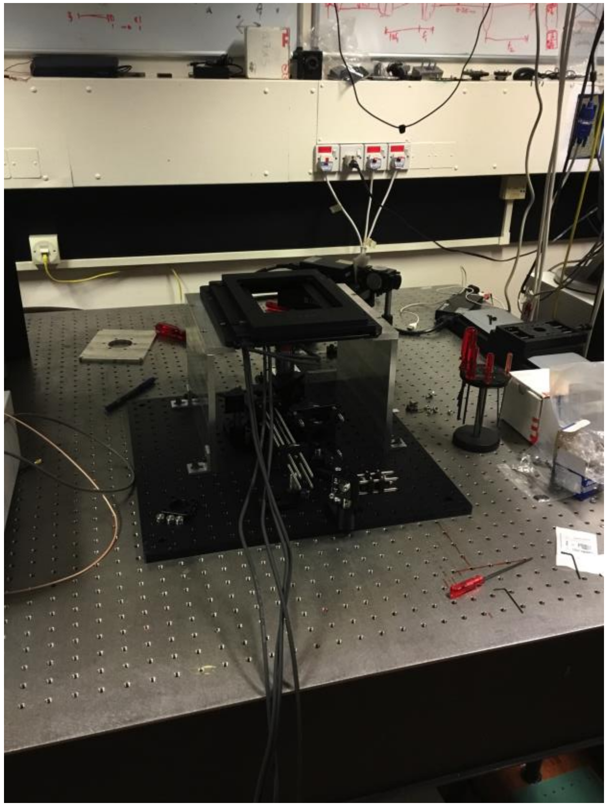


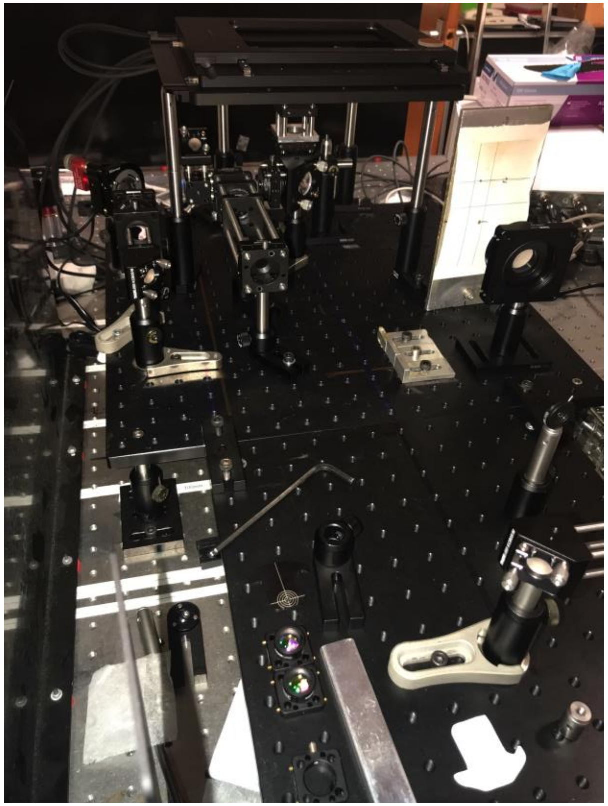

Robot 2
Optical Microscope
Robot 1
Auto Platten Changer
Polishing Wheel
SRAS
Etching Station
UES

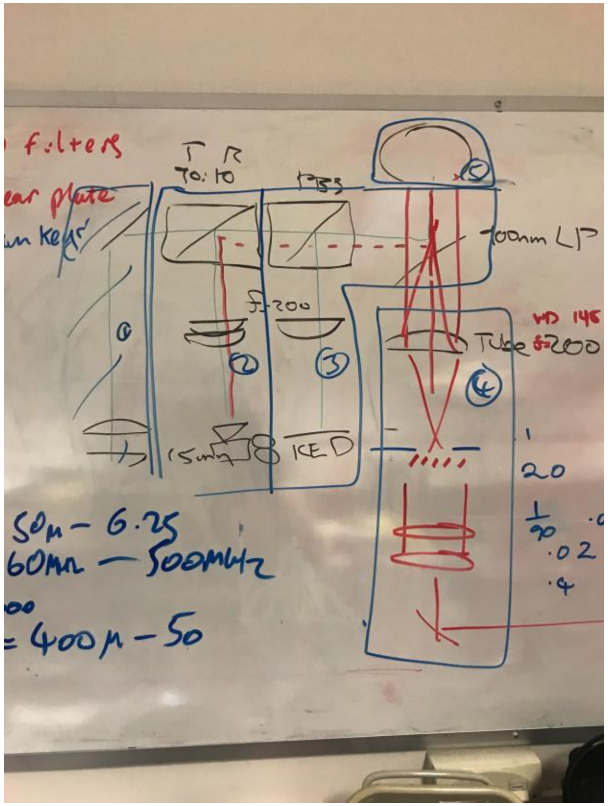
The integration

- We have been in very close communication with UES Inc. (Dayton, OH) on the system.
  - They have provided us with the system CAD “wrap” files so we can ensure integration.
  - They have provided a new software capability that will permit a “3rd party” ‘external’ analytical instrument to communicate with the Robo.Met software.
- We have been in very close contact with the University of Nottingham (4 trips so far to UK, 1 to US).
  - They are providing technical know-how
  - They are providing legacy codes
  - They are providing some hardware (the Cr-coated glass grating)

2nd trip to Nottingham in Sept. 2018 to work on system

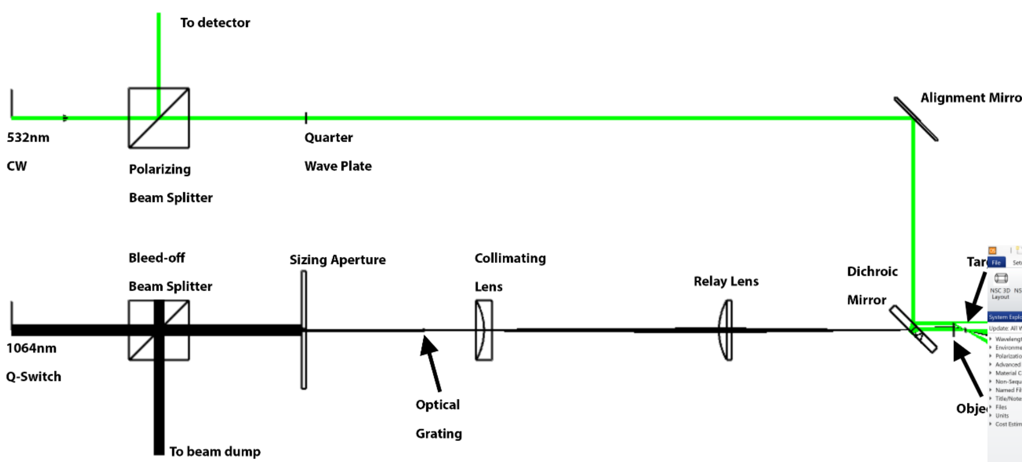


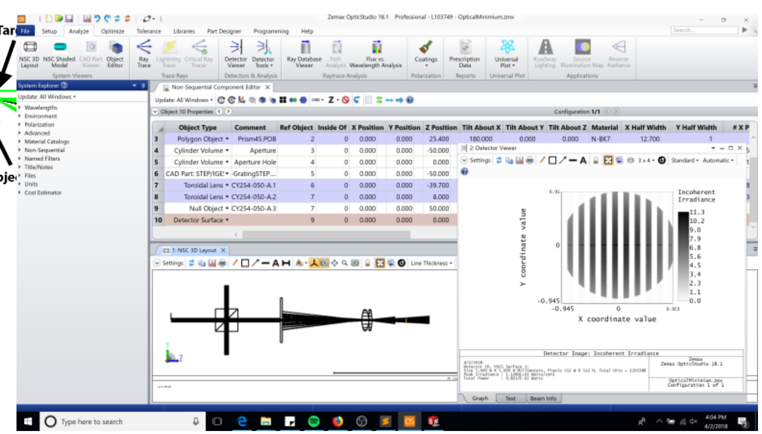




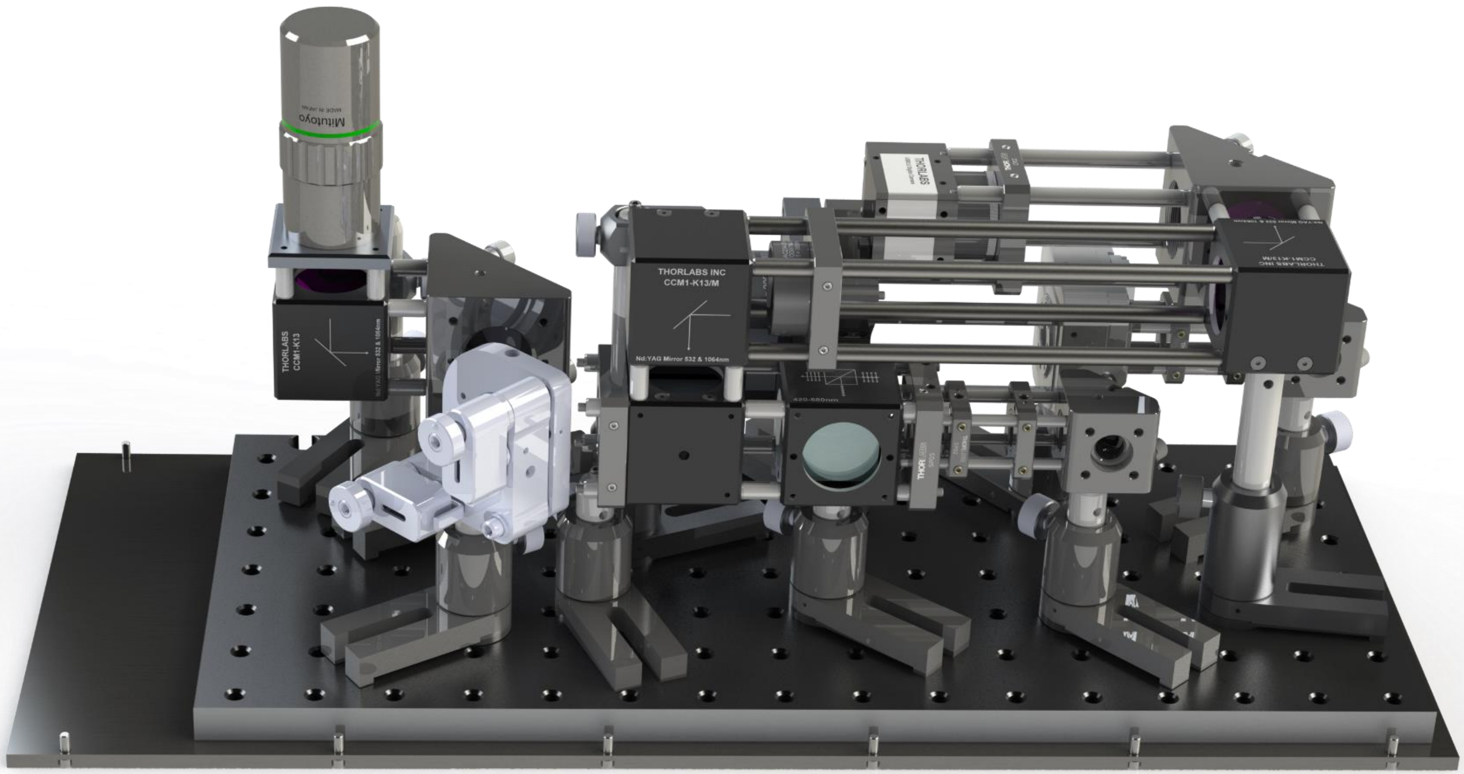
Design approach

- Using Zemax Optics Studio to simulate beam paths.
- Using Solid Works to ensure components fit into the very tight envelope.
- Integrated approach between these two packages.

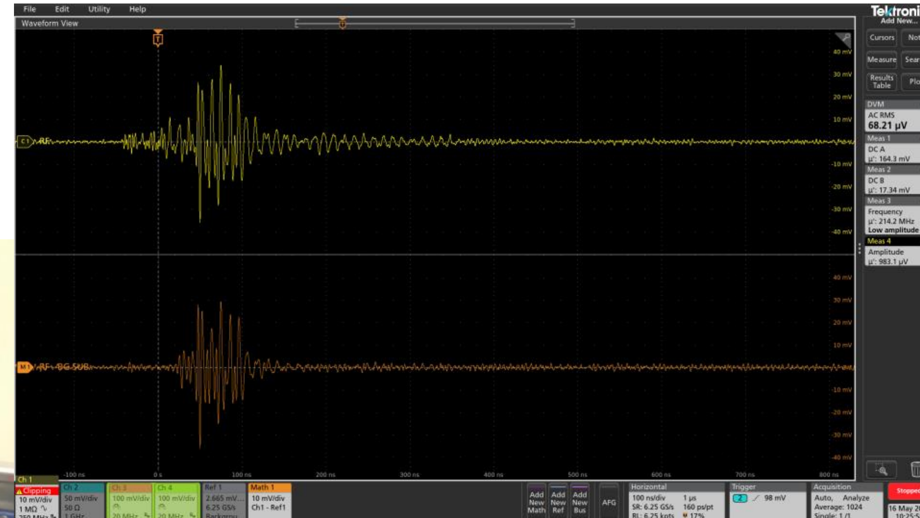


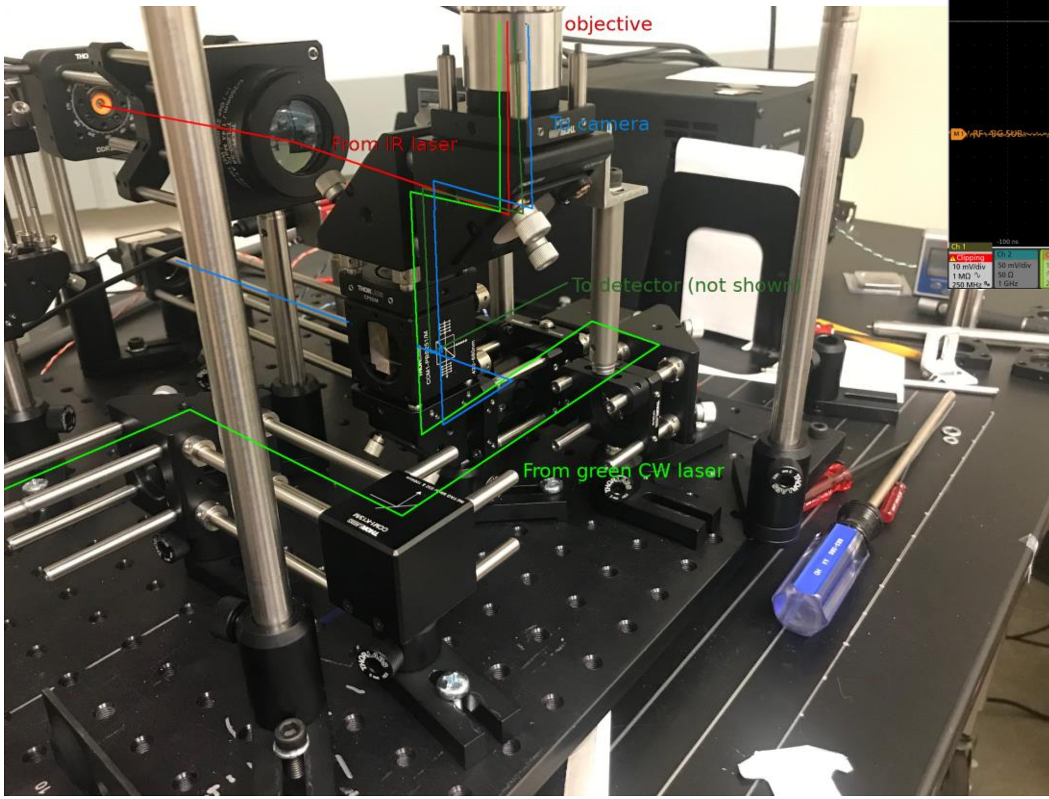


Robomet System – Views of design

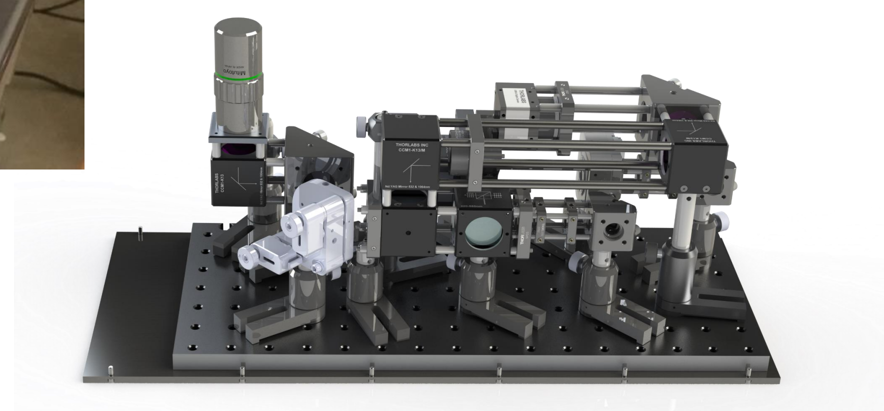


SRAS

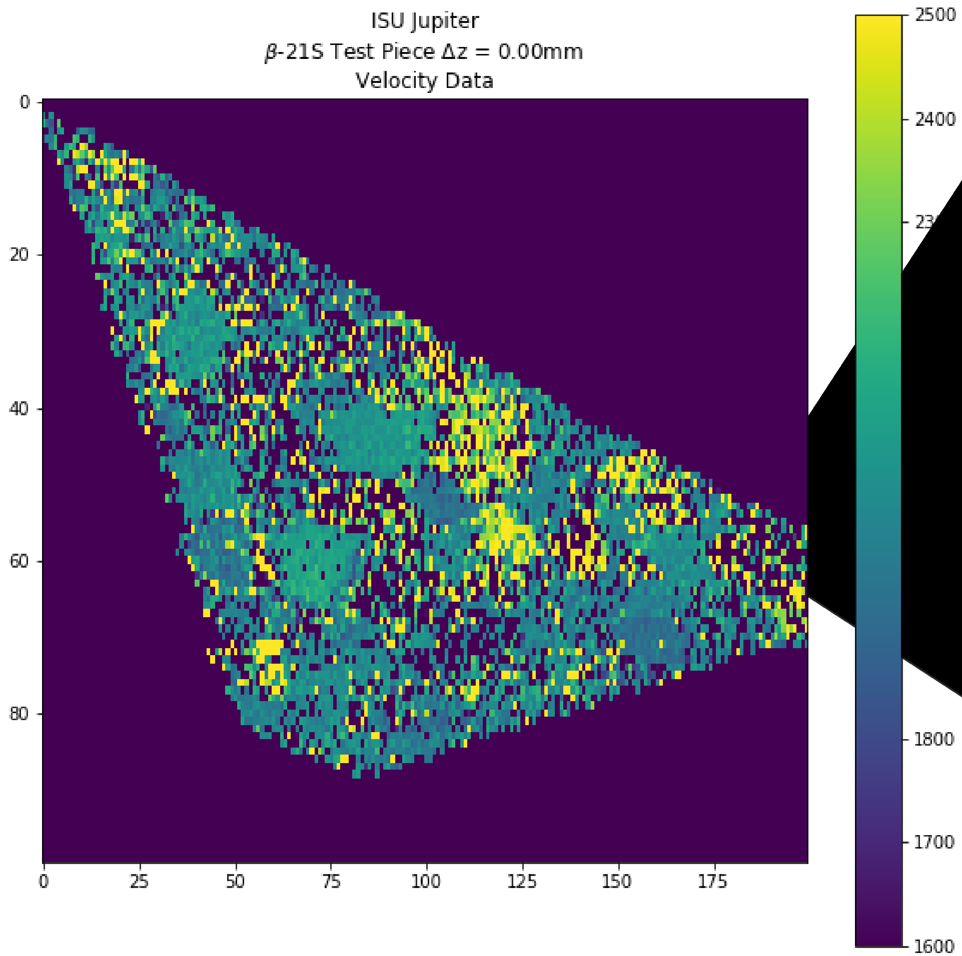


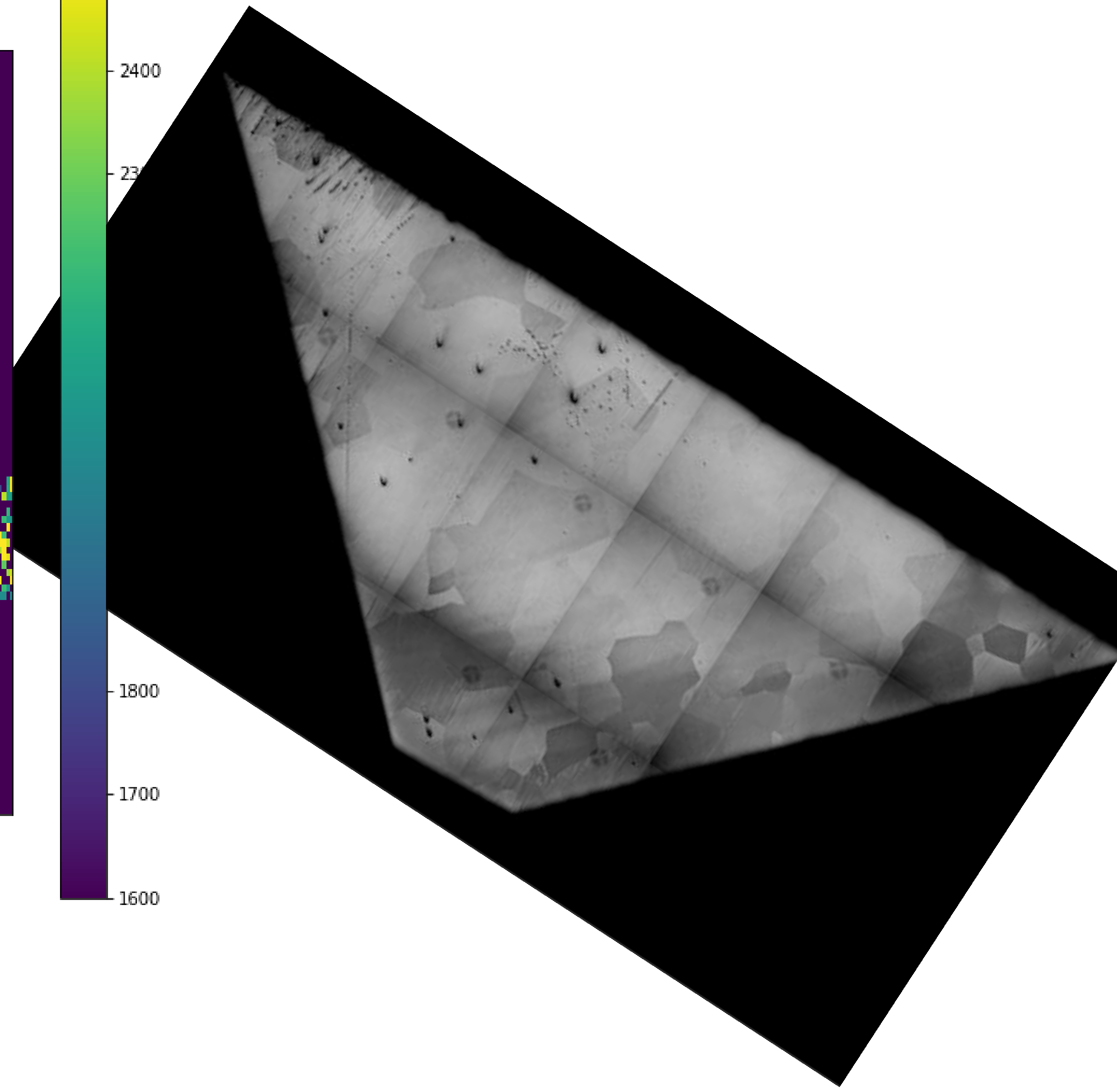


Amongst first SRAS-SAW waves in US



First results: beta 21S





Other progress

Code

- 9 legacy files written by multiple authors in MatLab (2011b) for the forward model
  - Has been written to Python (we feel the "need for speed")
  - We have not yet written the algorithms for slowness map to model mapping, but this is trivial compared to the other challenges we face…

THE CHALLENGES

Detectors…

- High-speed photodiodes. Need ~500 MHz (at least 250 MHz). No commercially available product (3 remain at Nottingham).
- No supplier is willing to make these detectors anymore, even if we throw $100k at them.
- *We have designed a new detector - but are still working to see if it will work (no one has done it)*

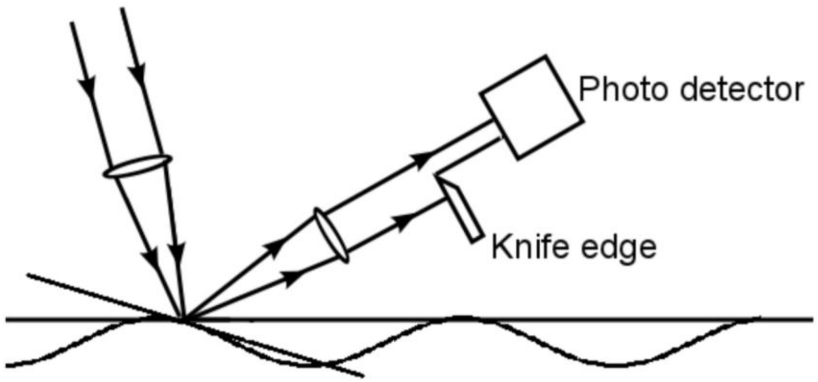
Data transfer

- High end oscilloscopes can obtain data quickly, but are generally poor in saving and streaming data efficiently. (1 of 3 oscilloscope manufactures declined to guarantee they could ever transfer data quickly, 2 said it was "probable")
- *We <u>have</u> (as of yesterday) beaten this with help from Tek (6x speed up)*

Detector Possibilities (preferred)

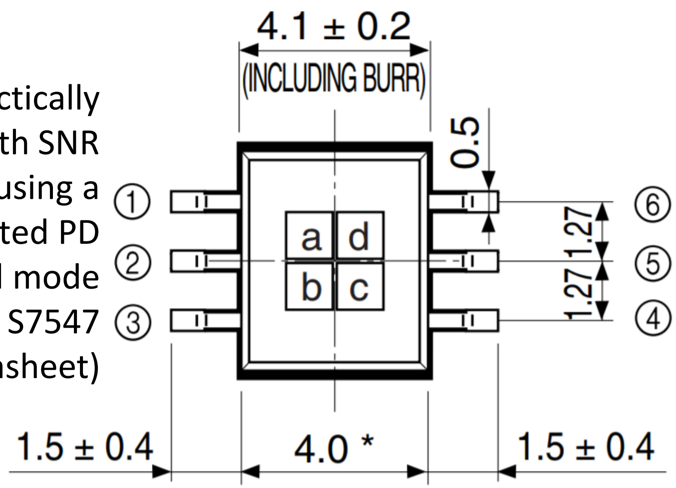
- Knife Edge / Segmented PD Detection

Pros	Cons
High Speed (>2.5kS/s)	Sensitive to alignment
Relatively Cheap (<$1k/det)	Hard to source high-speed parts, parts may be nonexistent
Single-laser	
No carrier injection required	



Li, Wenqi, “Laser ultrasonic method for determination of crystallographic orientation of large grain metals by spatially resolved acoustic spectroscopy.” PhD Thesis, Univ of Nottingham

“Knife edge” is practically achieved along with SNR boost by using a segmented PD in differential mode (Hamamatsu S7547 Datasheet)



Detector Possibilities (Alternative)

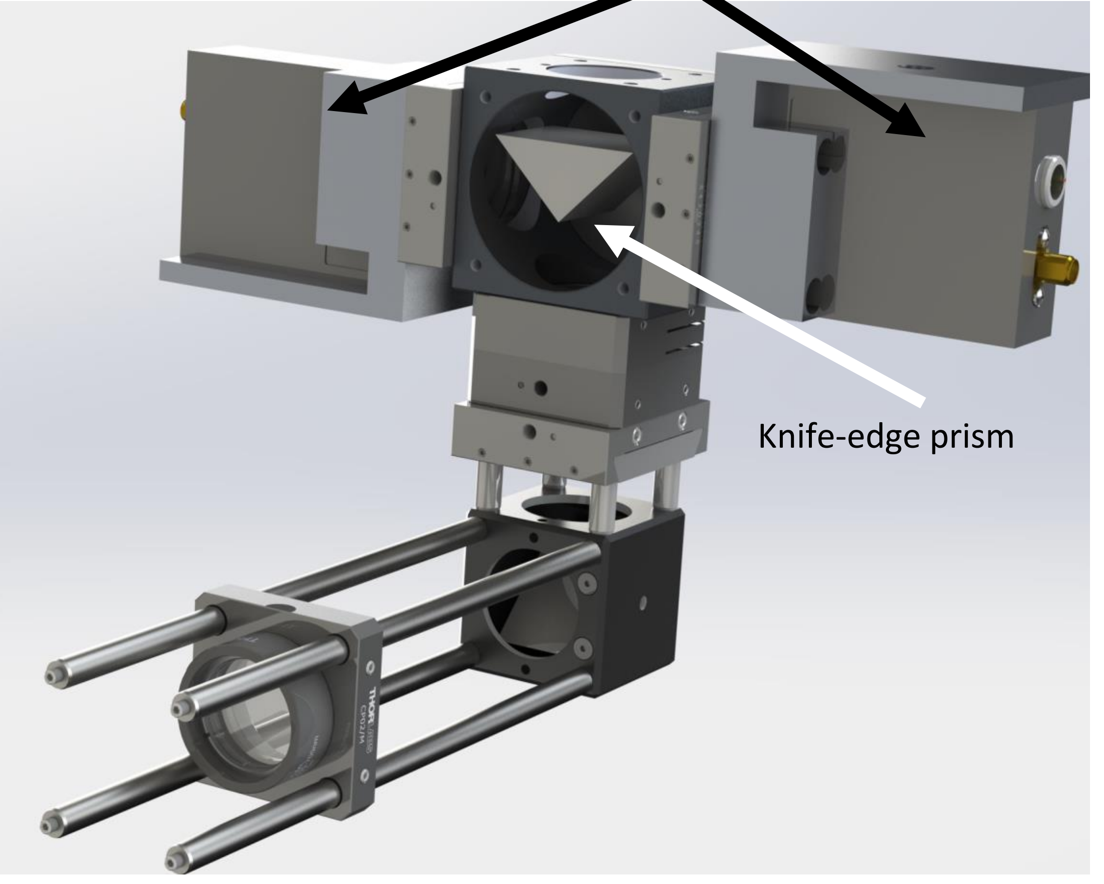
- Another possibility (EDMA-II) uses a knife-edge prism along with two high-speed PD detectors to achieve similar signal as the differential method developed by UoN.

- This method is too large to be included in the integrated Robo.Met

- EMDA Volume: ~500x250x250mm

  Robo.Met Build Volume: ~360x175x160mm

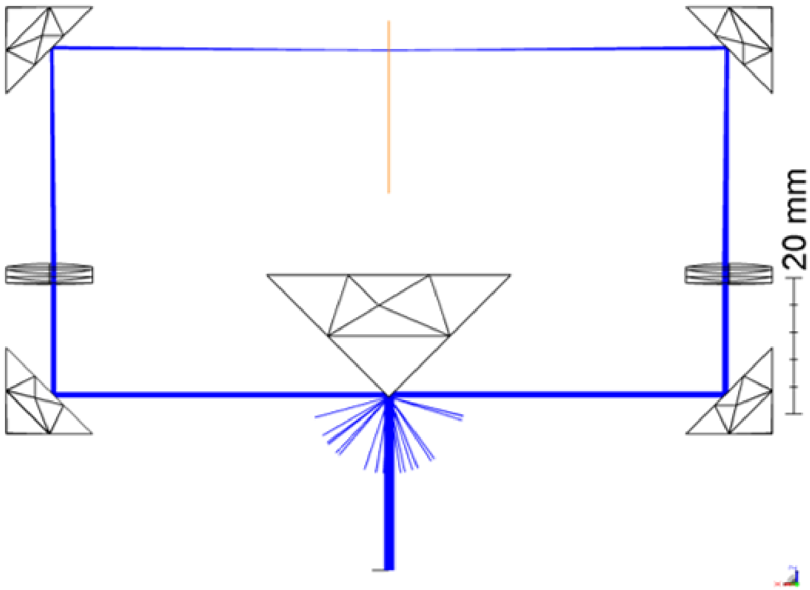
We are still exploring exploring this. Depends upon whether the next design works or not.

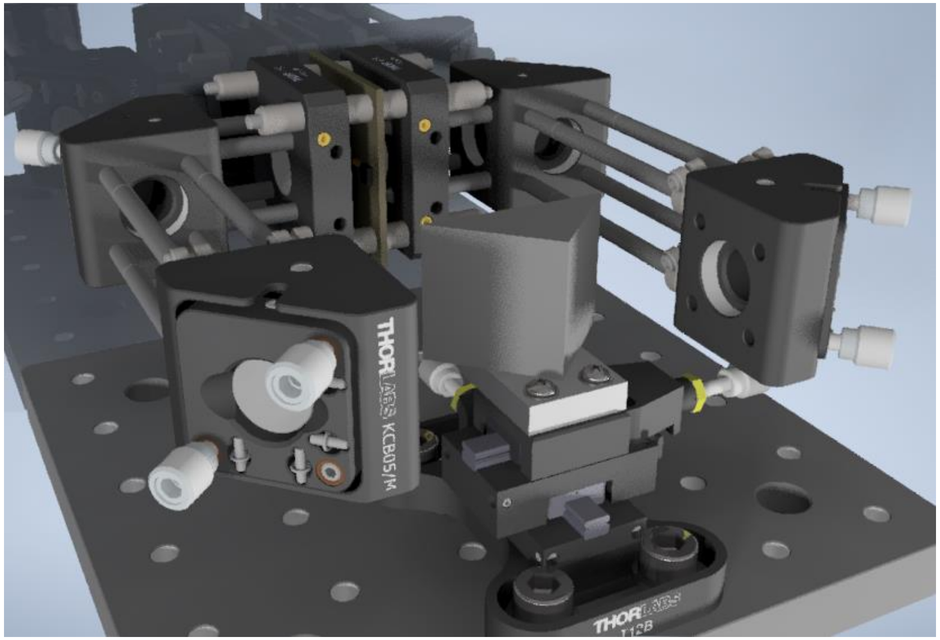


Detector Possibilities (Alternative)

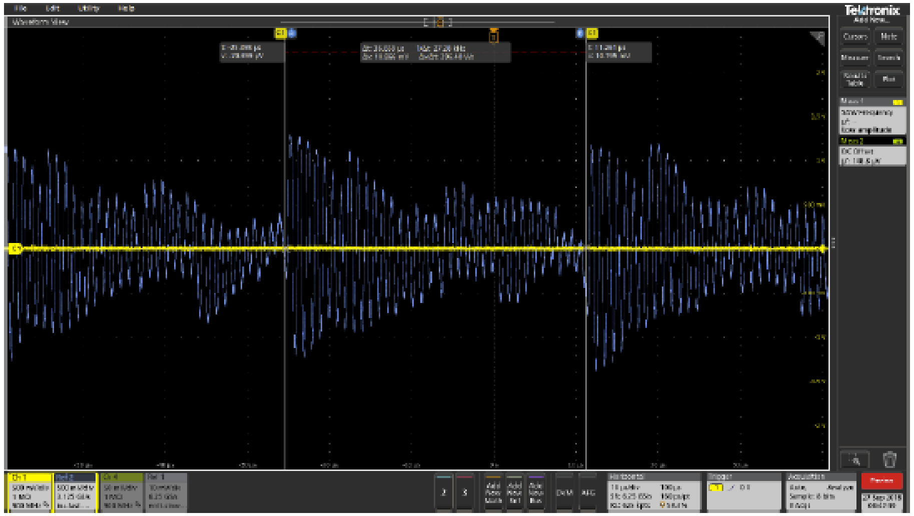
JANUS

Janus is slightly bigger than the Nottingham Detector, but has available components.

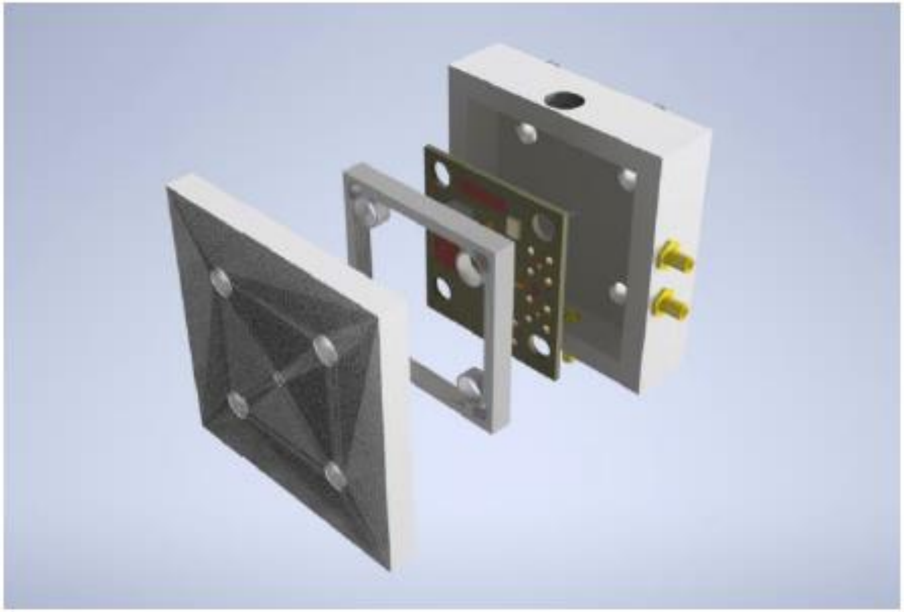




First signals (noisy, can’t get real signal with this!)

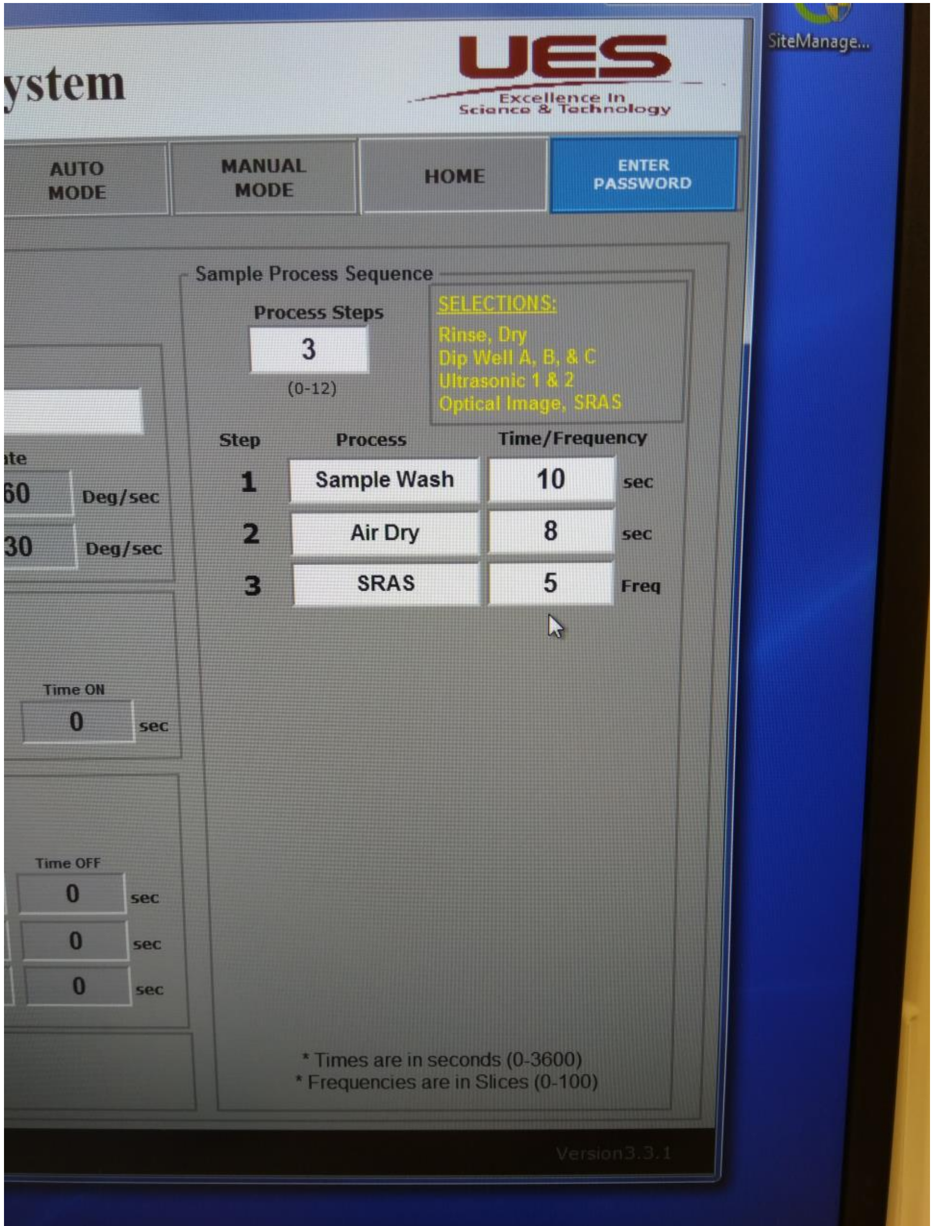
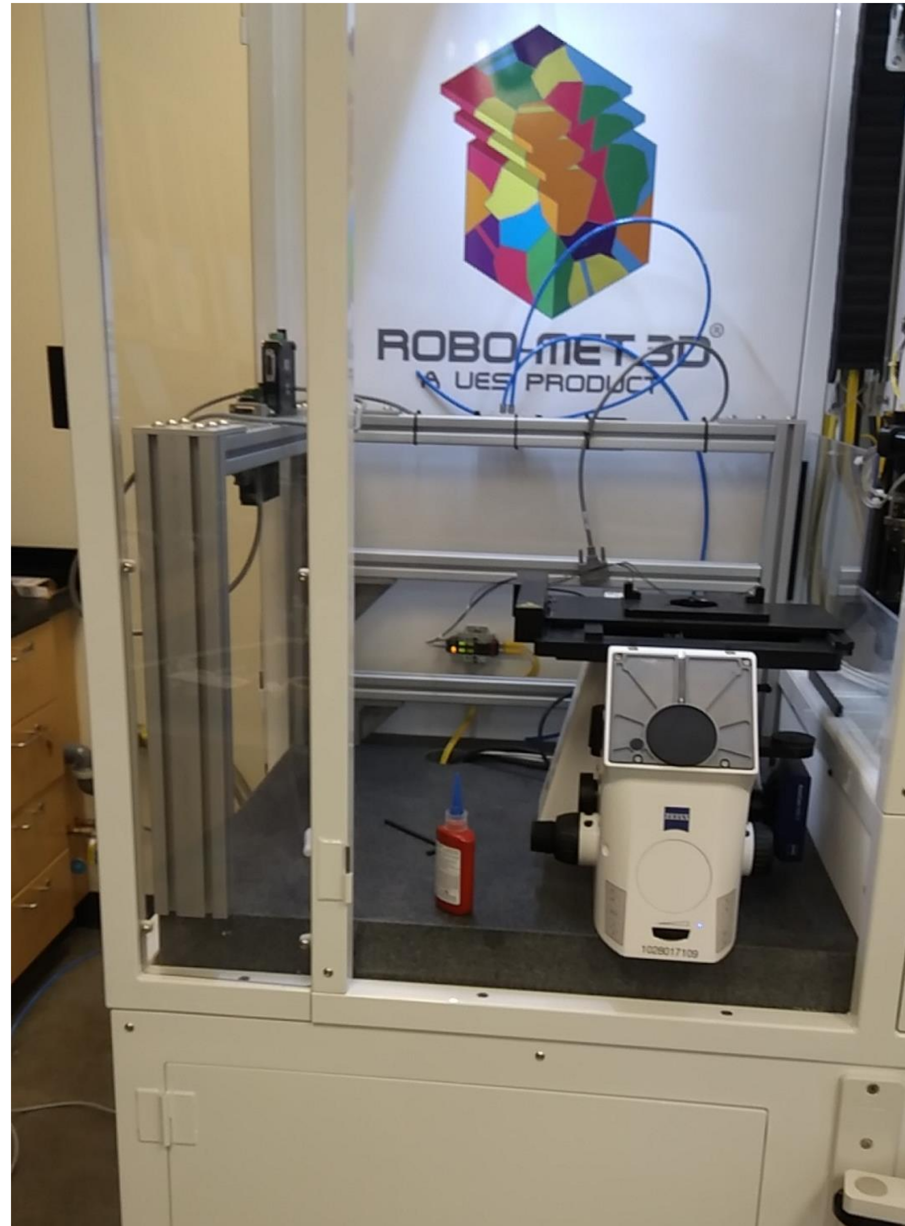


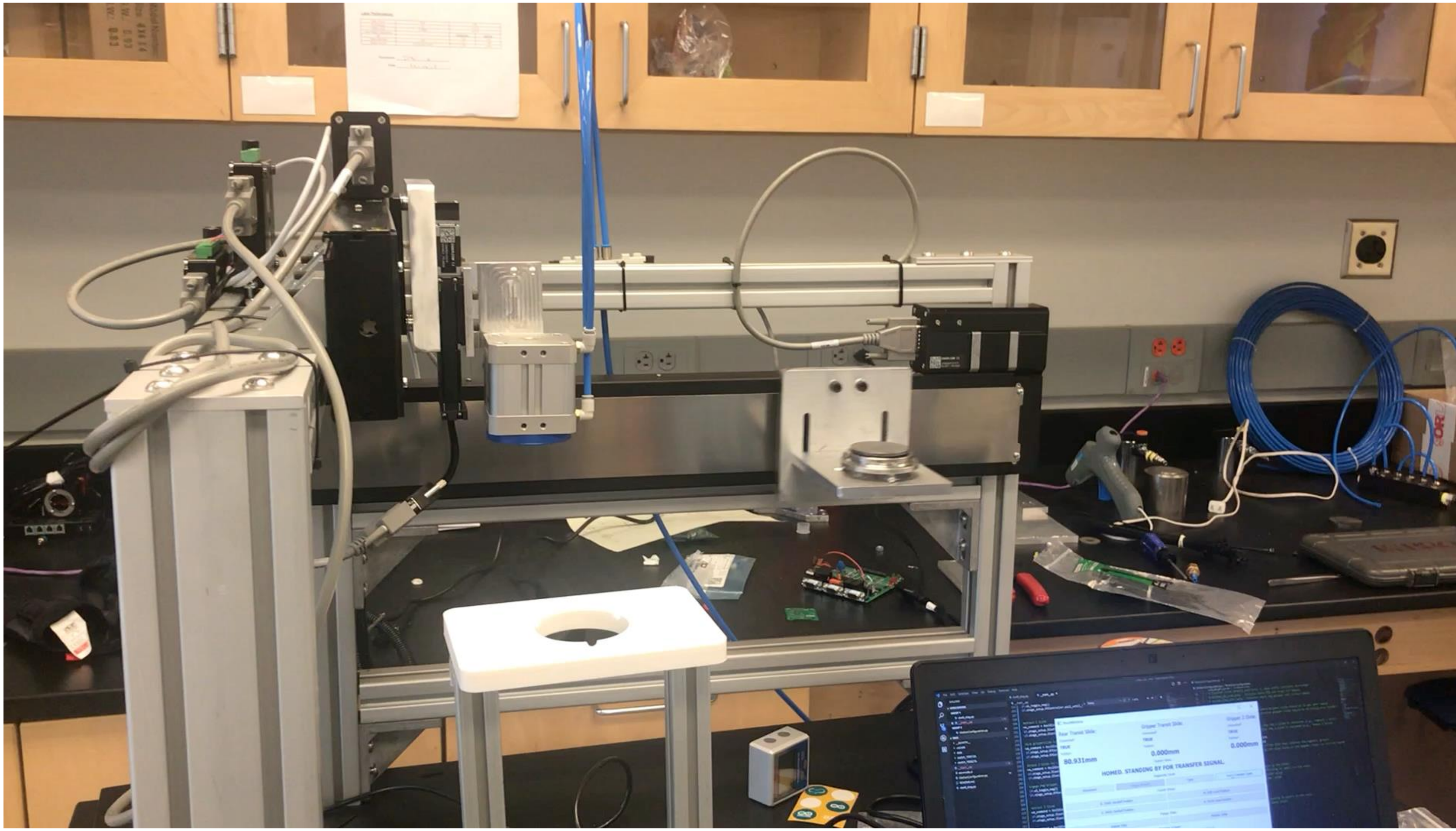
Noise from switch mode power supplies of the lasers.

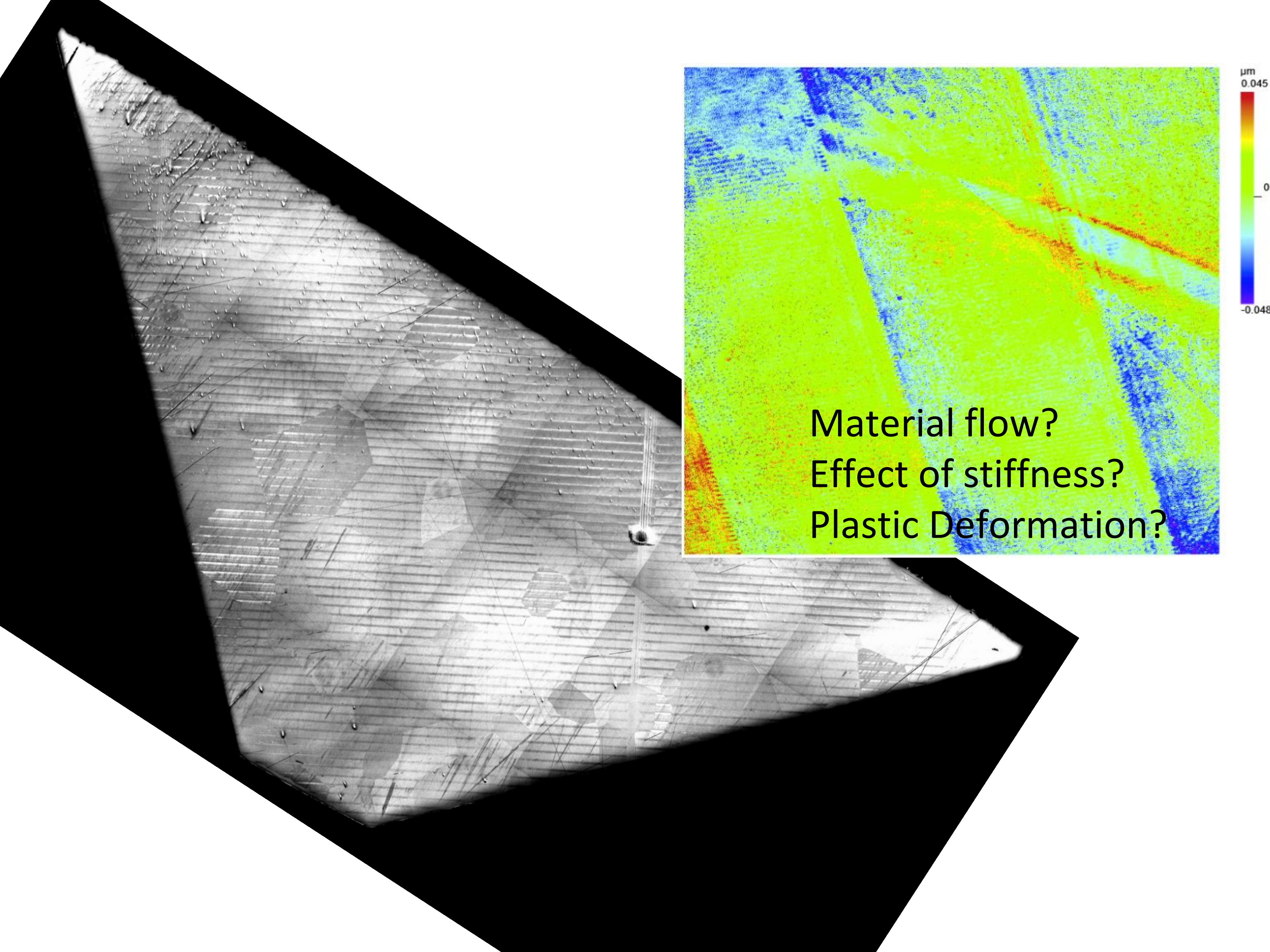


Moving to:

- Low-noise power supply
- Pi filters
- Secondary shielding


ystem
UES
Excellence In Science & Technology
AUTO MODE
MANUAL MODE
HOME
ENTER PASSWORD
Sample Process Sequence
Process Steps
3
(0-12)
SELECTIONS:
Rinse, Dry
Dip Well A, B, & C
Ultrasonic 1 & 2
Optical Image, SRAS
Step
Process
Time/Frequency
1 Sample Wash 10 sec
2 Air Dry 8 sec
3 SRAS 5 Freq
60 Deg/sec
30 Deg/sec
Time ON
0 sec
Time OFF
0 sec
0 sec
0 sec
* Times are in seconds (0-3600)
* Frequencies are in Slices (0-100)
SiteManage...

ROBO-MET.3D
A UES PRODUCT


Rear Transit Slide:
TRUE
80.931mm
Gripper Transit Slide:
TRUE
0.000mm
0.000mm
HOMED. STANDING BY FOR TRANSFER SIGNAL.


µm
0.045
0
-0.048
Material flow?
Effect of stiffness?
Plastic Deformation?

SRAS - Some interesting possibilities

- Improved resolution

- Any effect of an external variable on C_{ij}
  - Composition (evidence of this fluctuation)
  - Temperature
  - Defects

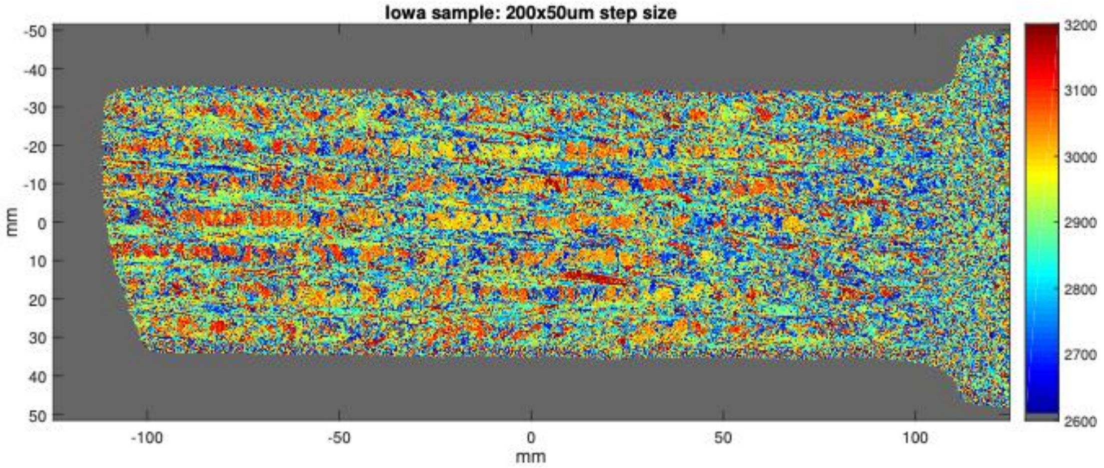
- Possibility of time resolved experiments
  - Some similar work on radiation effects

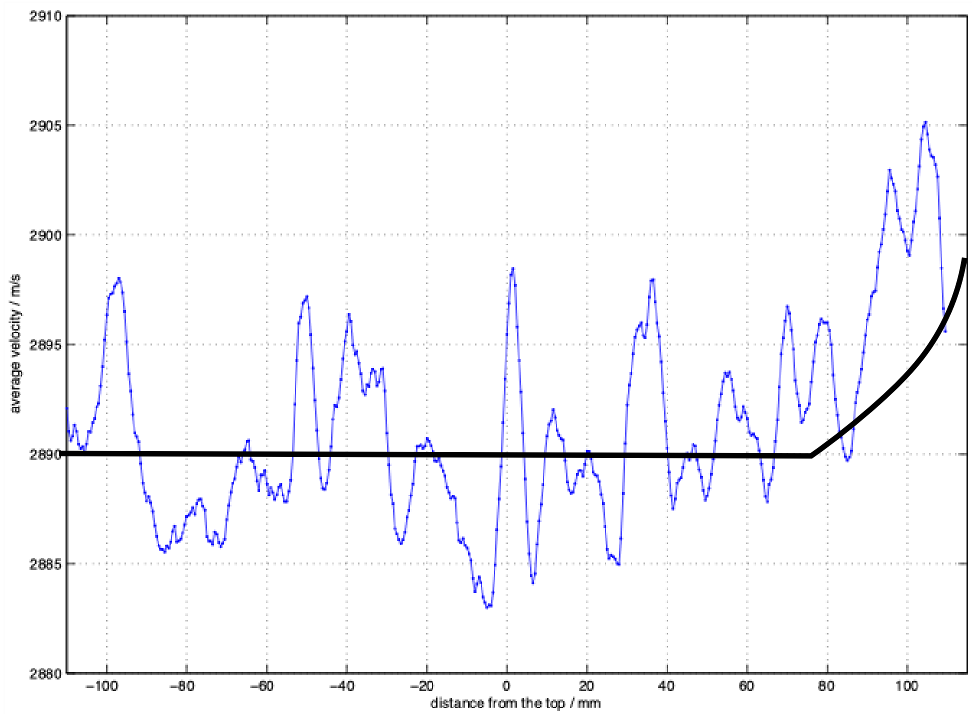
Where we are going – I (Limitations)

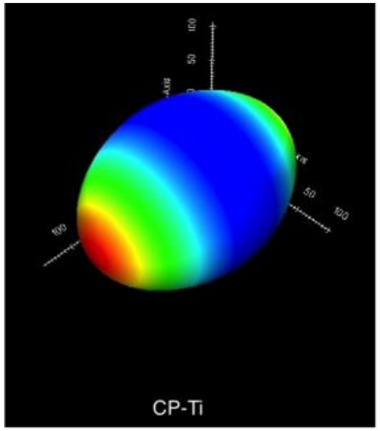
- A limitation of SRAS is resolution.
  - Currently, it is a stretch to reach 20 microns.
  - For large grained materials, this isn't an issue (especially when integrating optical microscope datasets)
  - But, wouldn't it be nice if it were better?

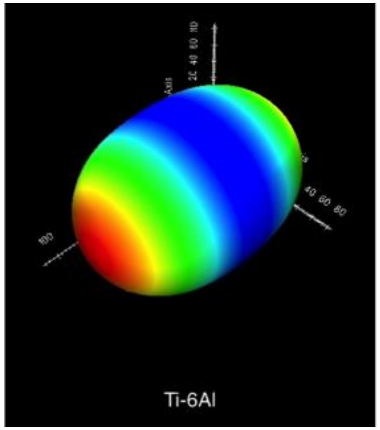
- Supersecret result

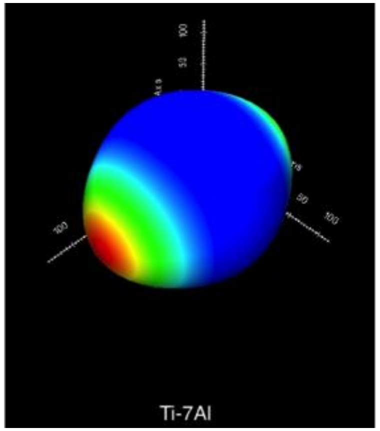
Example: Chemistry











Where we are going – III (tech transfer)

- Ensuring this research reaches a wider audience
  - We entered discussions with Nottingham.
  - We have formed a business through ISU’s “Startup Factory” – which follows the Stanford model of lean start-ups.
  - In October 2018, we completed an exclusive and world wide agreement for the patent for SRAS related systems.
  - We have a first customer and a first SBIR (complex structures, non-flat surfaces).
  - Hopefully, we can leverage into multiple CANFSA projects (the first will be texture in Ti forgings!)

If you ever visit Nottingham…