Rapid Imaging of Microstructure using Spatially Resolved Acoustic Spectroscopy

Steve Sharples, Matt Clark, Wenqi Li, Mike Somekh

Applied Optics Group
School of Electrical & Electronic Engineering
University of Nottingham, U.K.
steve.sharples@nottingham.ac.uk

Applied Optics group
http://optics.eee.nottingham.ac.uk

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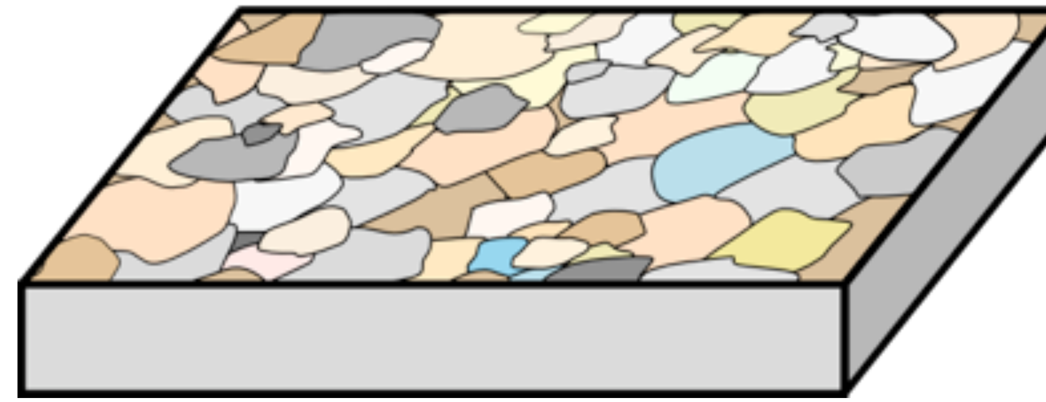
Aim: to image material microstructure

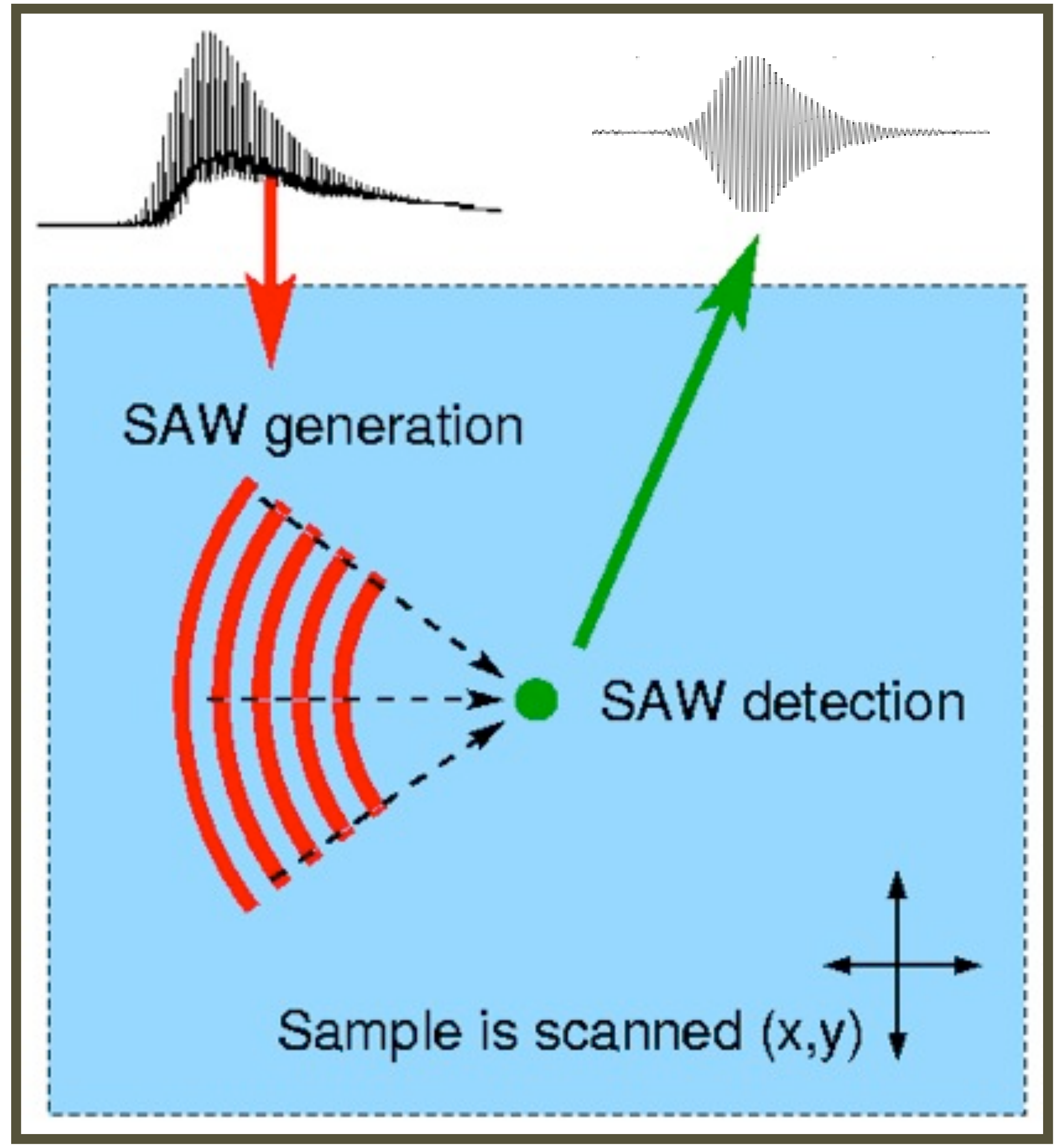
We would like to image the grain structure of industrially-relevant materials - titanium, aluminium etc.



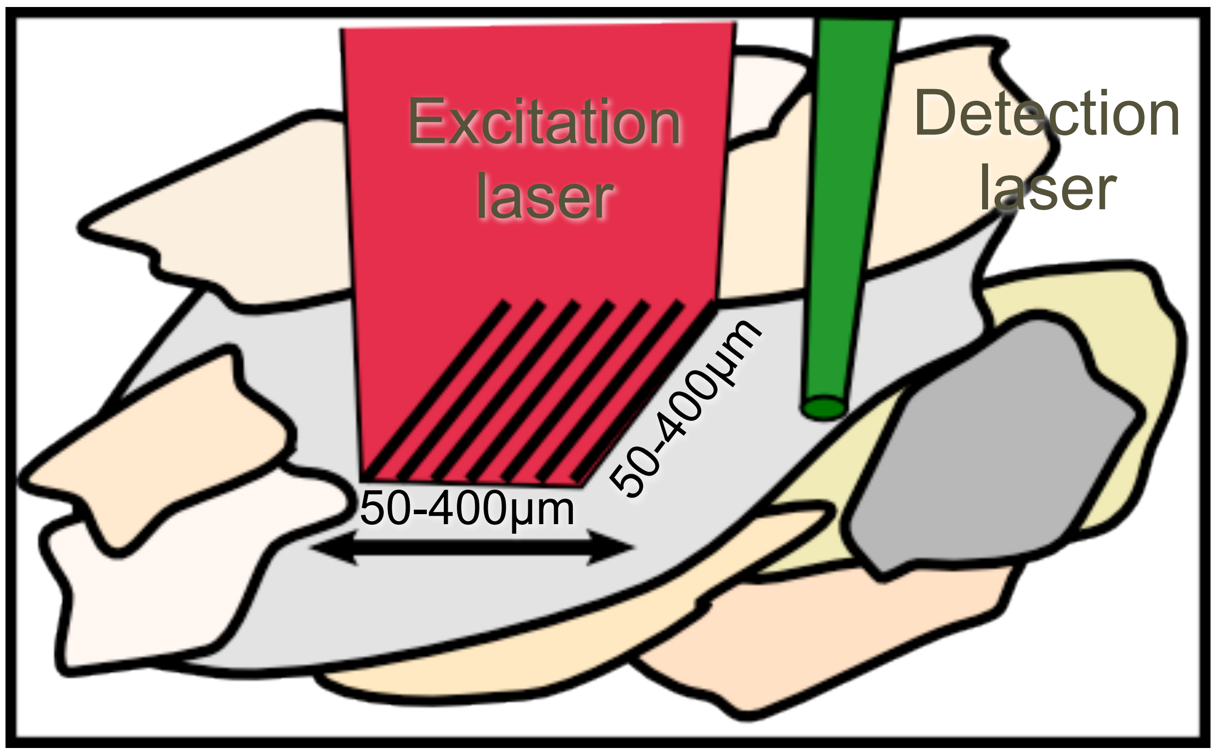
- Several important material properties are **structure sensitive:**
  - e.g. yield strength, fracture toughness, thermal conductivity
- These are all sensitive to microstructure parameters, such as:
  - Mean grain size
    - Degree of randomness, of both size and orientation
    - Clusters of grains all oriented in the same direction
  - Distribution and volume fraction of second phase particles
- We can use SAW phase velocity - which varies with grain orientation - as contrast mechanism

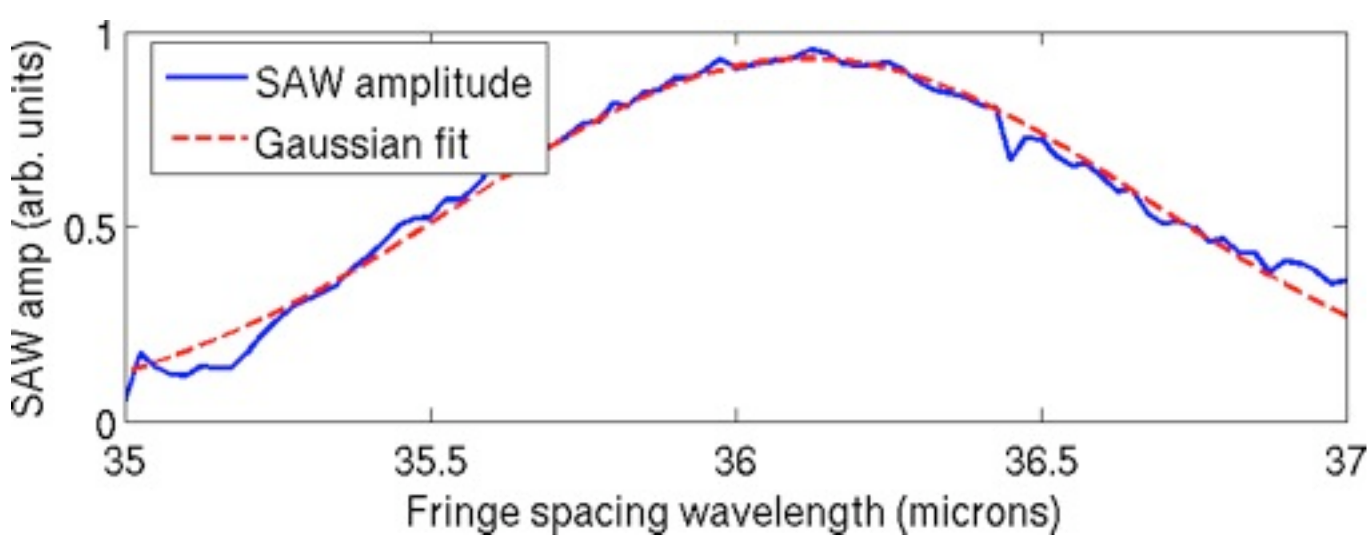
Laser ultrasound background... Current system: O-SAM

- Pulsed laser source
  - Fundamental frequency 82MHz
  - Repetition rate 1kHz
- Spread out the light
  - Multiple lines
    - lower power density
    - no damage
- Focus the SAWs
  - Higher amplitudes
    - easier and faster detection
- Multiple line source:
  - **Generation efficiency depends on how well you match the line spacing to the SAW wavelength**



SRAS: spatially resolved acoustic spectroscopy





- Fixed excitation frequency (82 or 164 or 328MHz)
- To find phase velocity of material in the area of excitation, we vary the fringe spacing of the excitation source
- When the fringe spacing matches the SAW wavelength, we get the best signal

$$v = f\lambda$$

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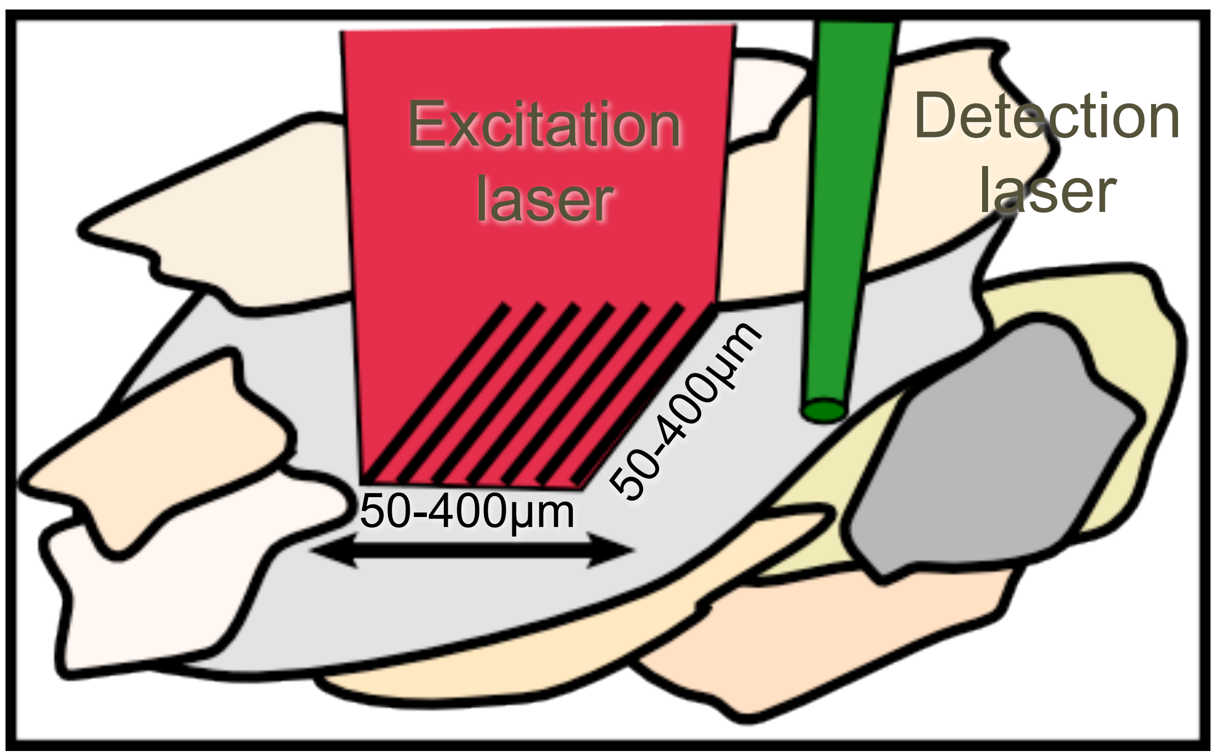
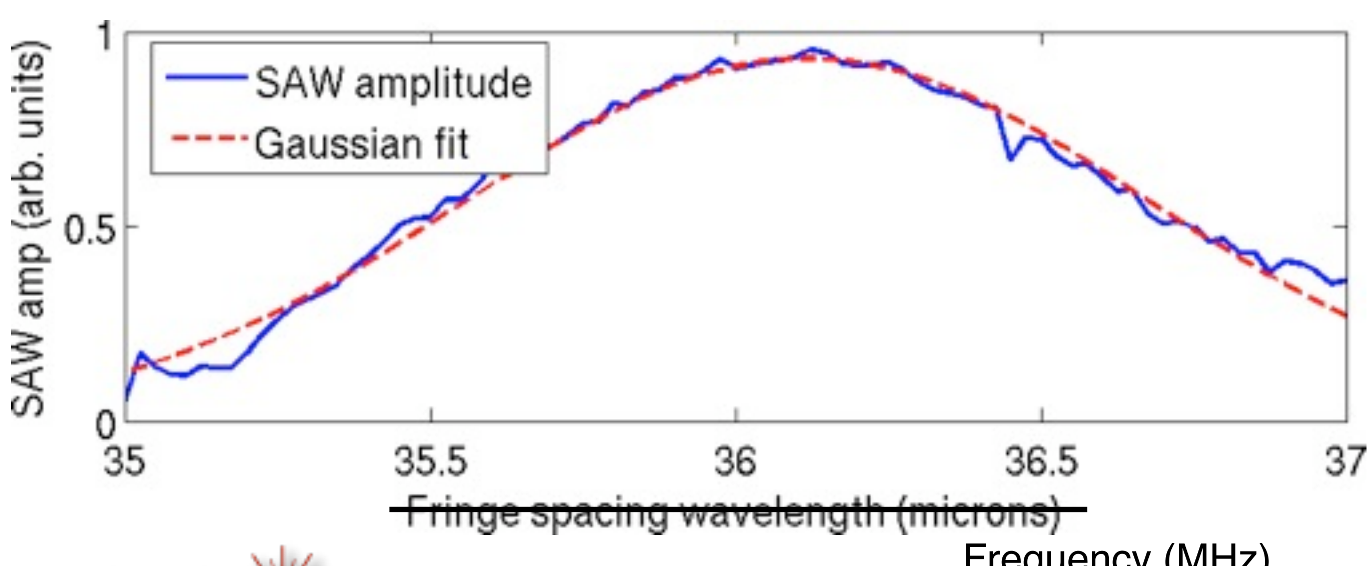
SRAS: spatially resolved acoustic spectroscopy

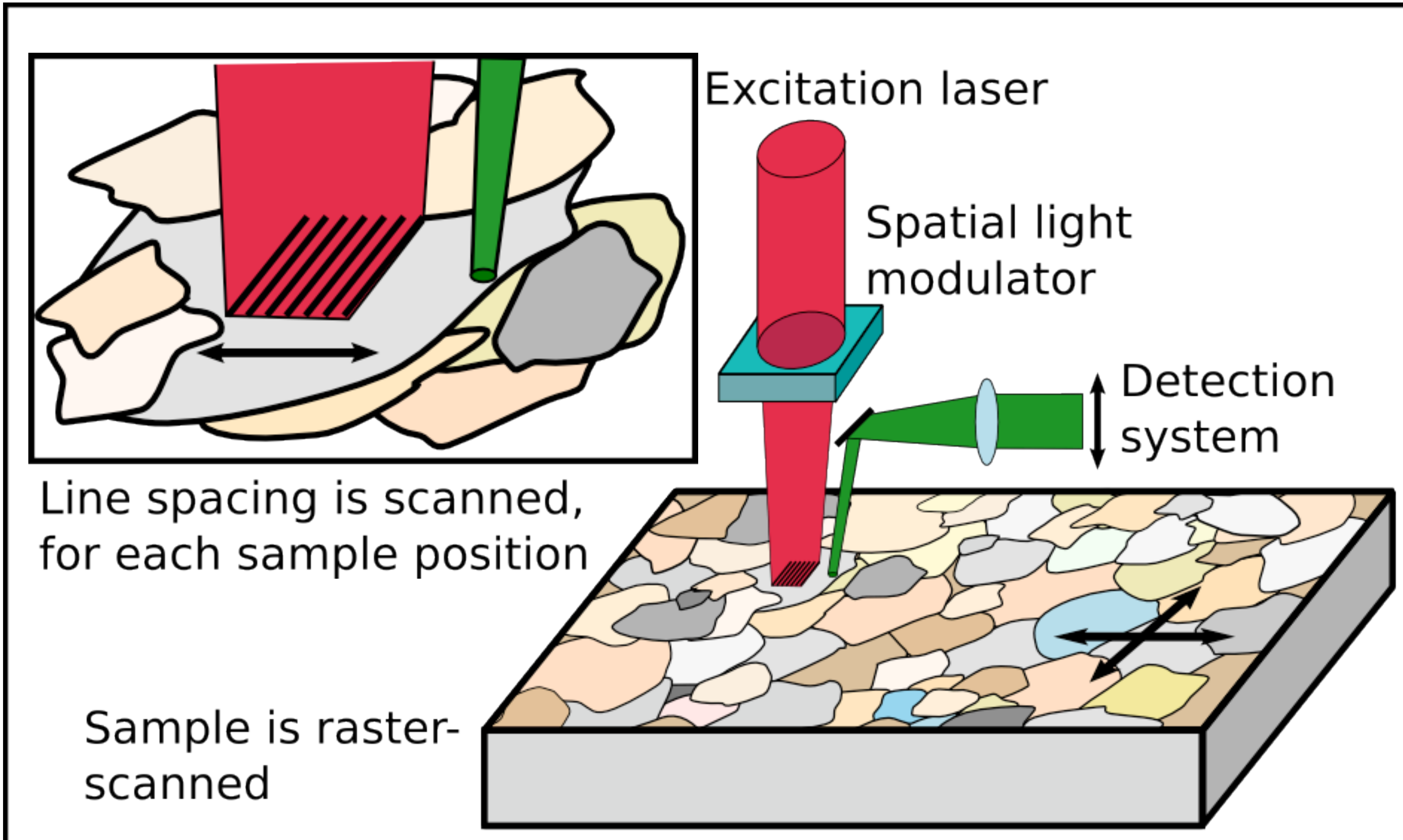




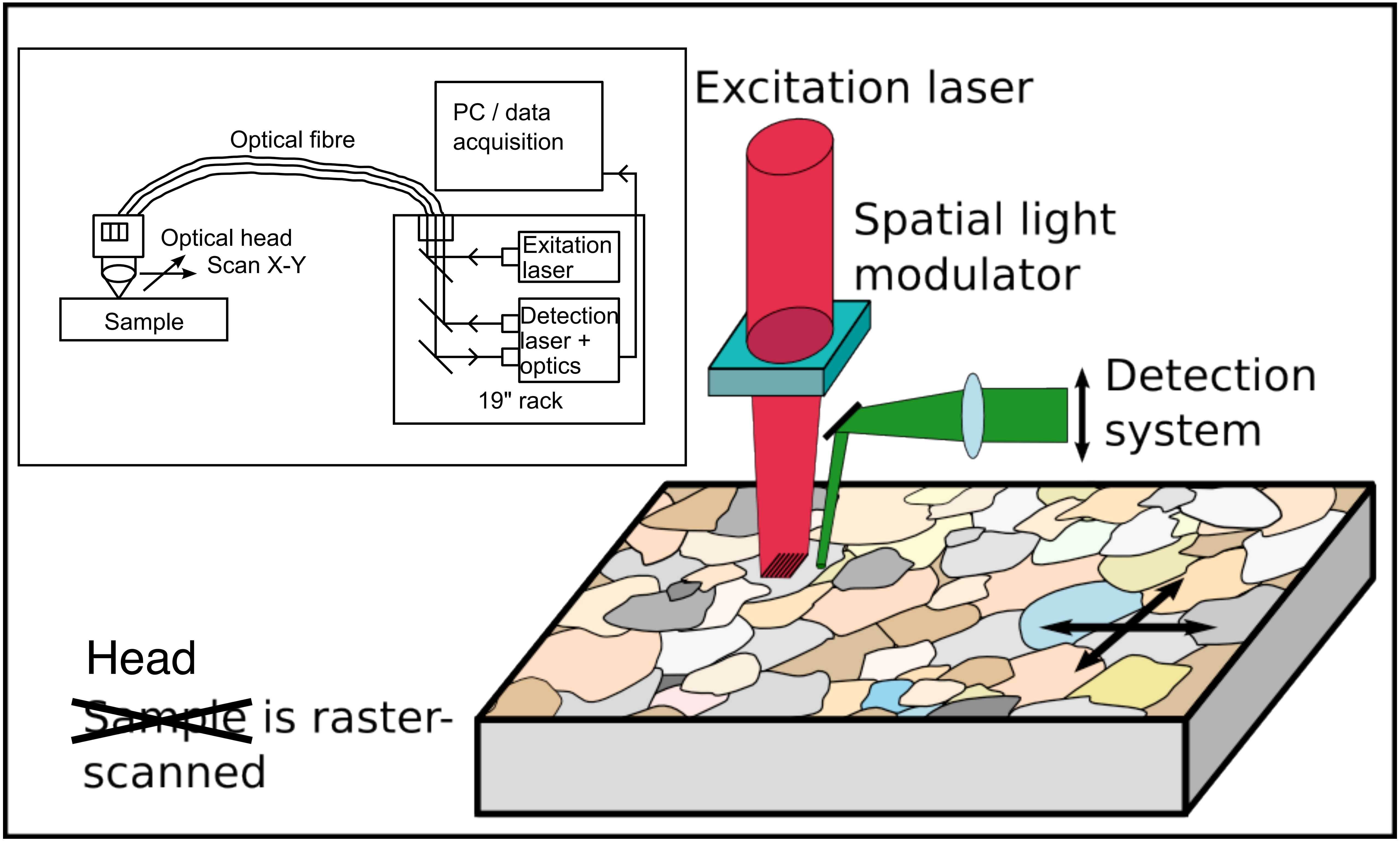
- Alternatively...
- Broad excitation frequency (over several hundred MHz)
- To find phase velocity of material in the area of excitation, we keep the fringe spacing of the excitation source fixed
- Measure the peak frequency of the detected waves... same formula:

$$v = f\lambda$$

System schematic



System schematic

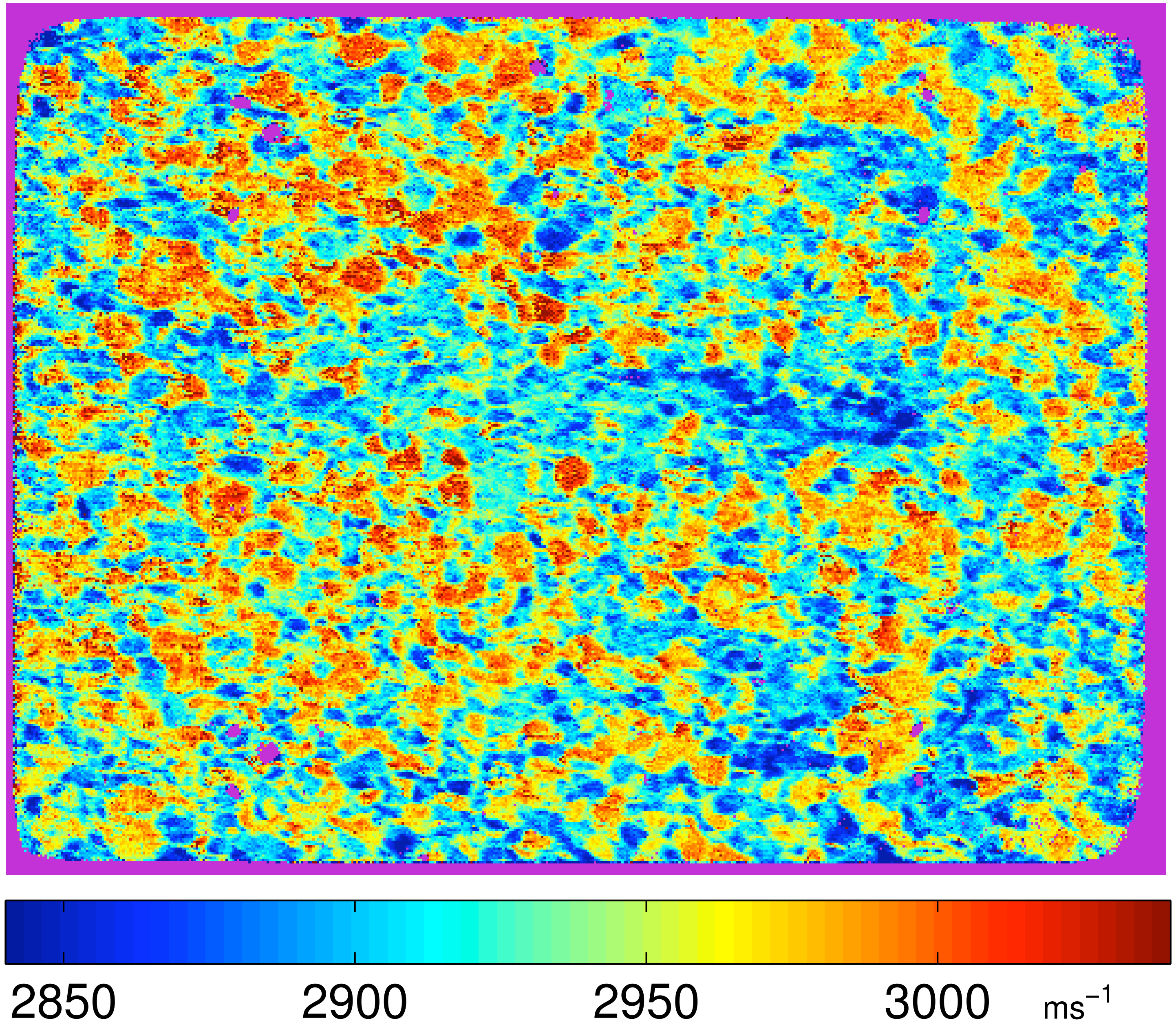


SRAS capabilities

- Lateral (spatial) resolution determined by SLM image size
  - Current spatial resolution is approximately 25μm
- Velocity resolution determined by signal/noise and number of fringes, if curve-fitting is used
  - On a good sample, the best velocity resolution is $\pm 1.5 ms^{-1}$ (approximately 0.03%)
- Scanning speed:
  - Current practical speed for great results: 10-20 points/sec
  - Up to ~100 points/sec in present configuration
  - Potential to go much higher than this

Grain clusters in titanium alloy

- 76x57mm velocity map of titanium alloy
- Colours represent SAW phase velocity in horizontal direction
- Dark blue region indicates cluster of grains of similar orientation
- Pixel size is 150μm
- Acquisition time was under 3 hours (approx 200,000 pixels)



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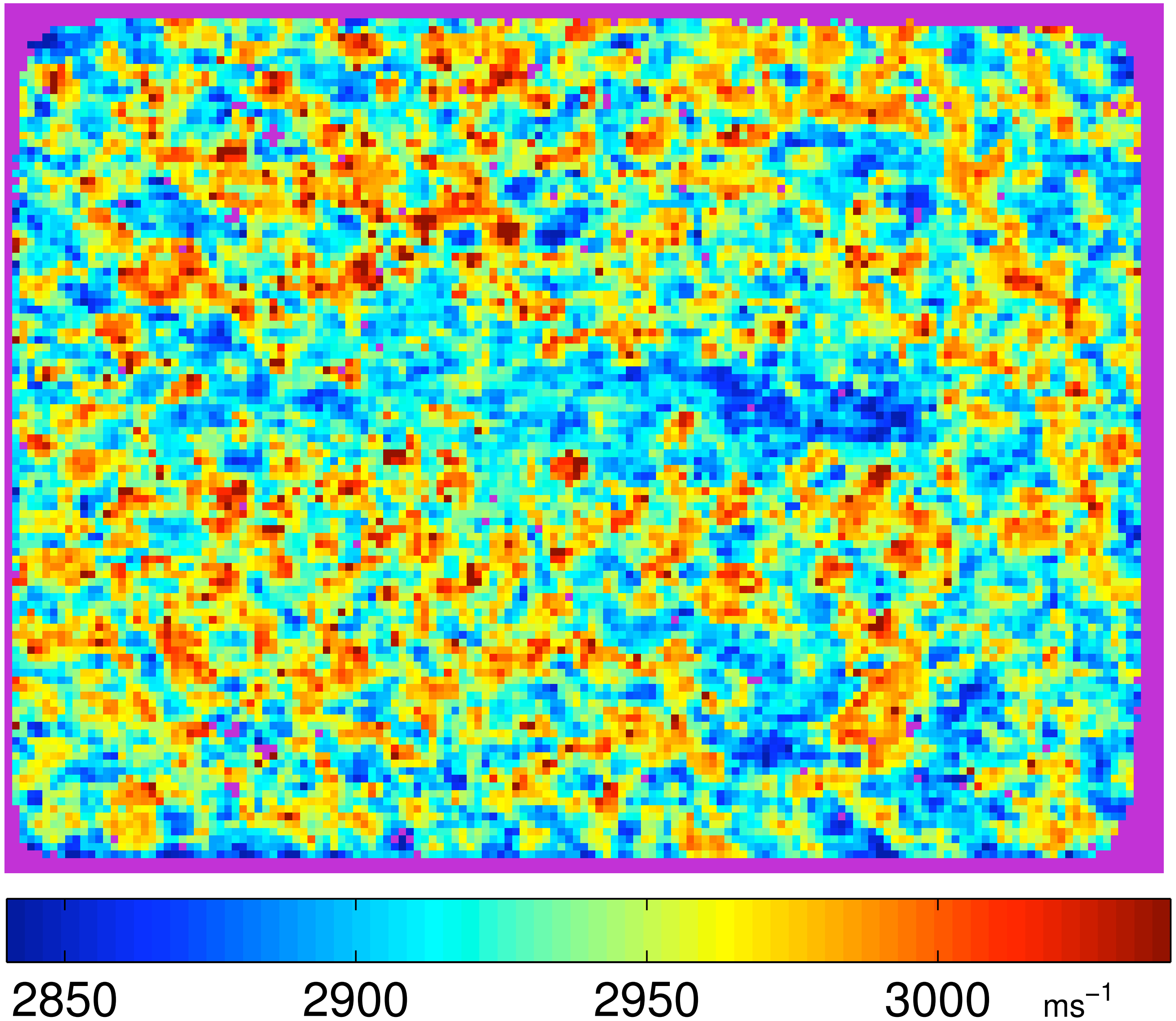
Grain clusters in titanium alloy

- 76x57mm velocity map of titanium alloy
- Colours represent SAW phase velocity in horizontal direction
- Dark blue region indicates cluster of grains of similar orientation
- Pixel size is 500µm
- Acquisition time was under 18 minutes (17,600 pixels)



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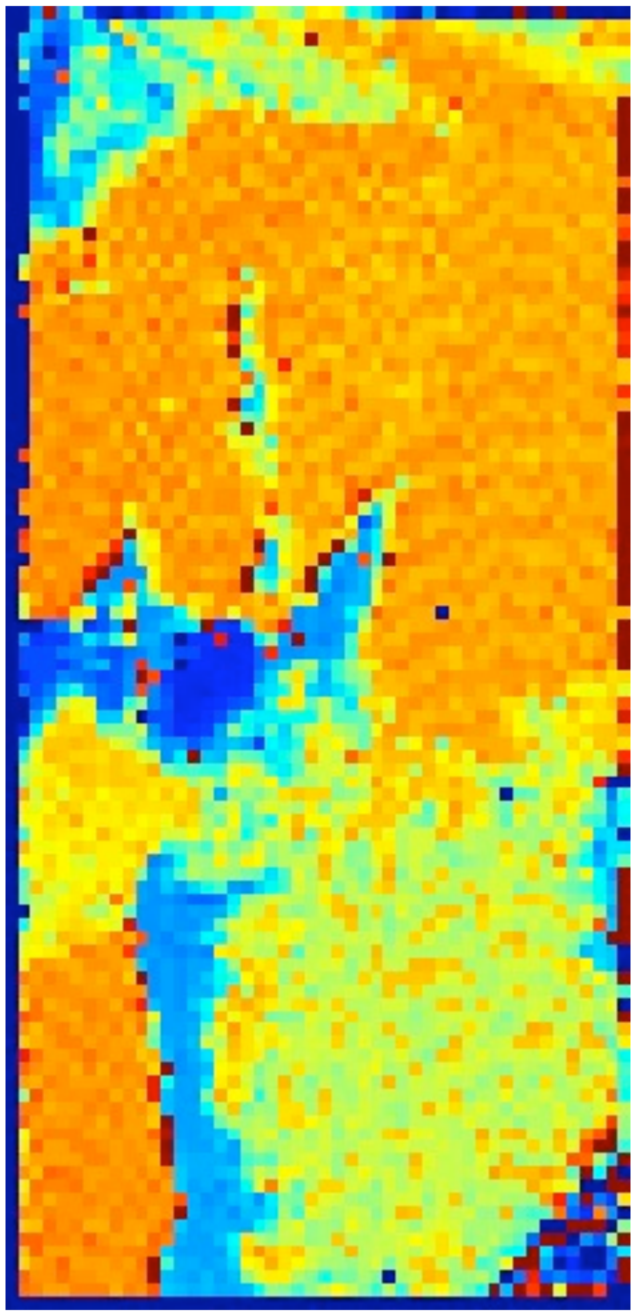
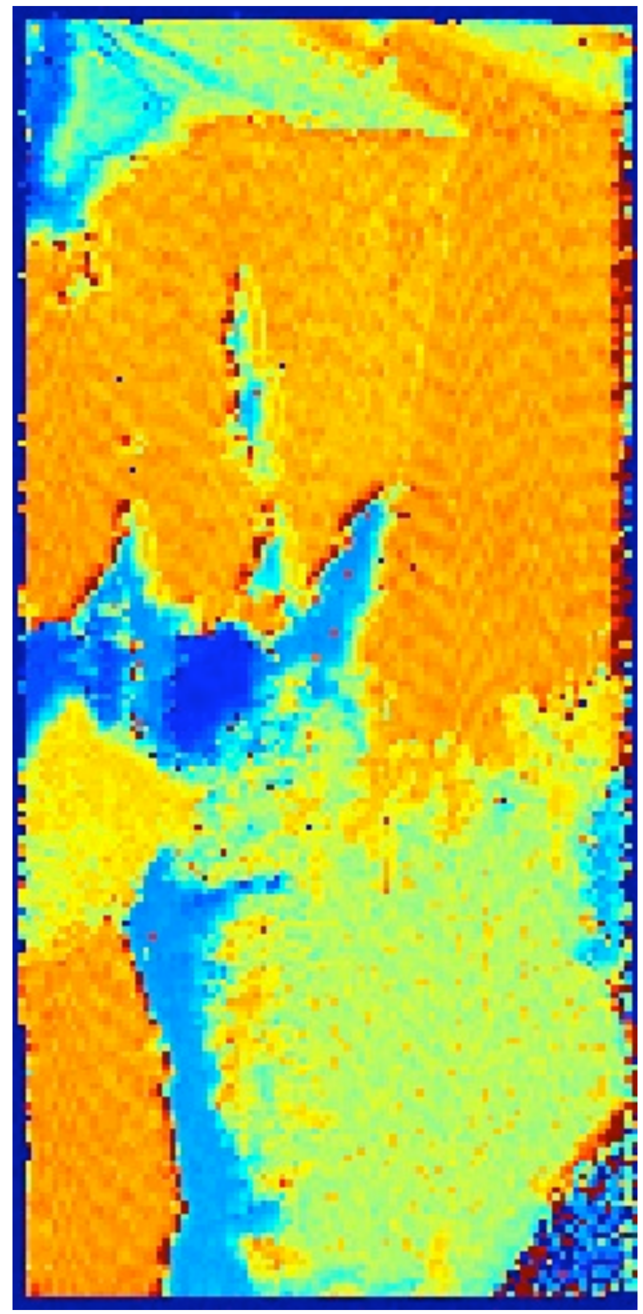
Demonstration of speed of system

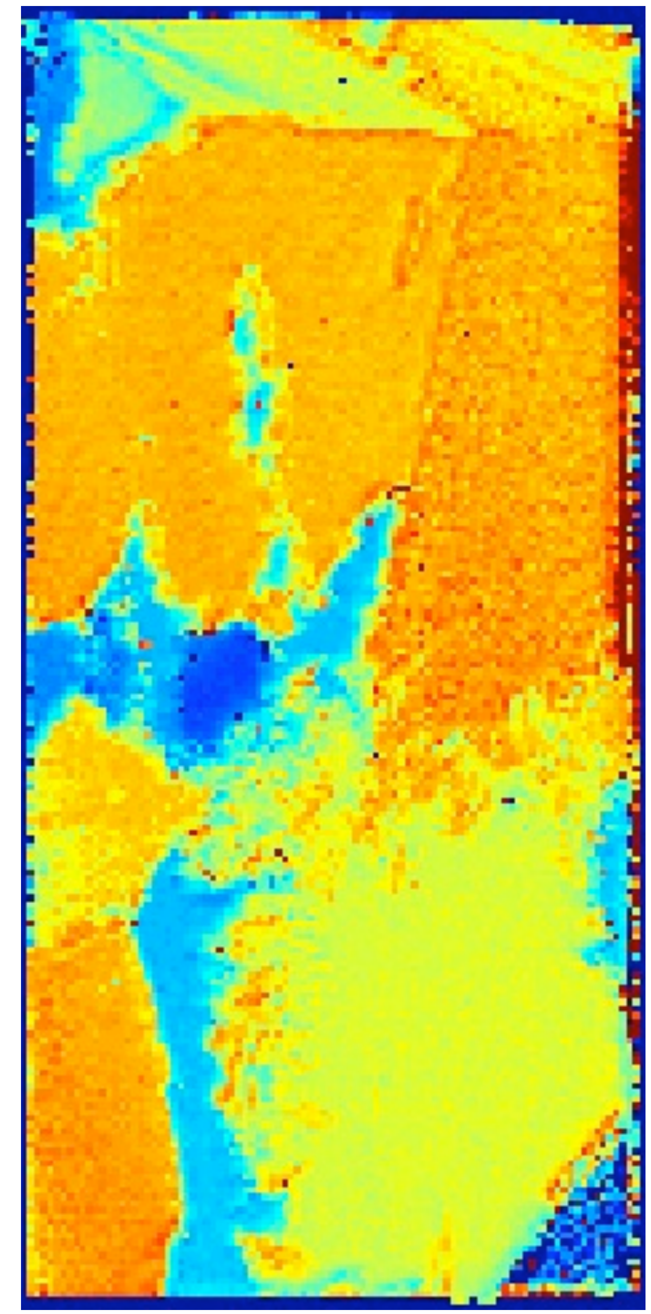
Less than 10 min



Less than 30 min



Less than 60 min



Sample size: 12.7x25.4mm, pixel size is 125µm

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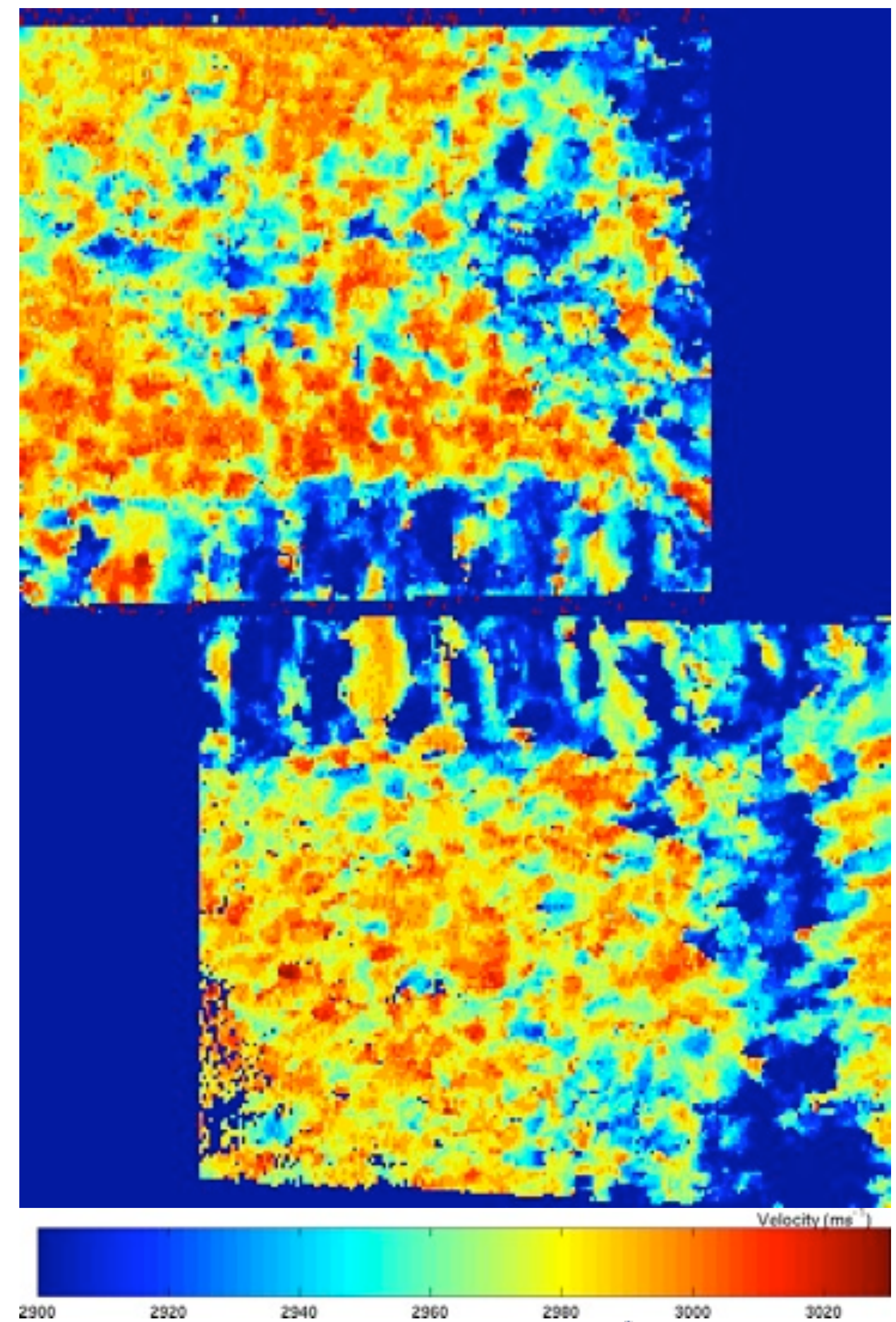
Aluminium

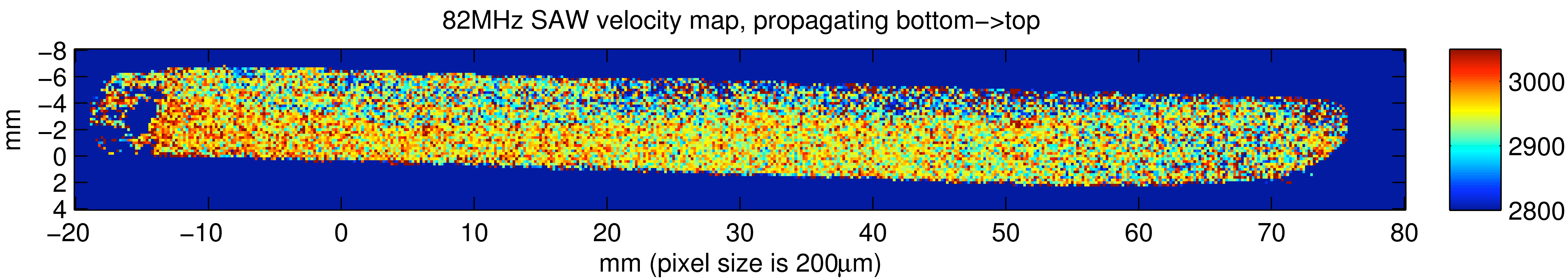
- Large-grained aluminium
- Two samples, each approximately 50x40mm
- Used to be part of the same block when cast
- Grains have preferential orientation where molten aluminium was stirred

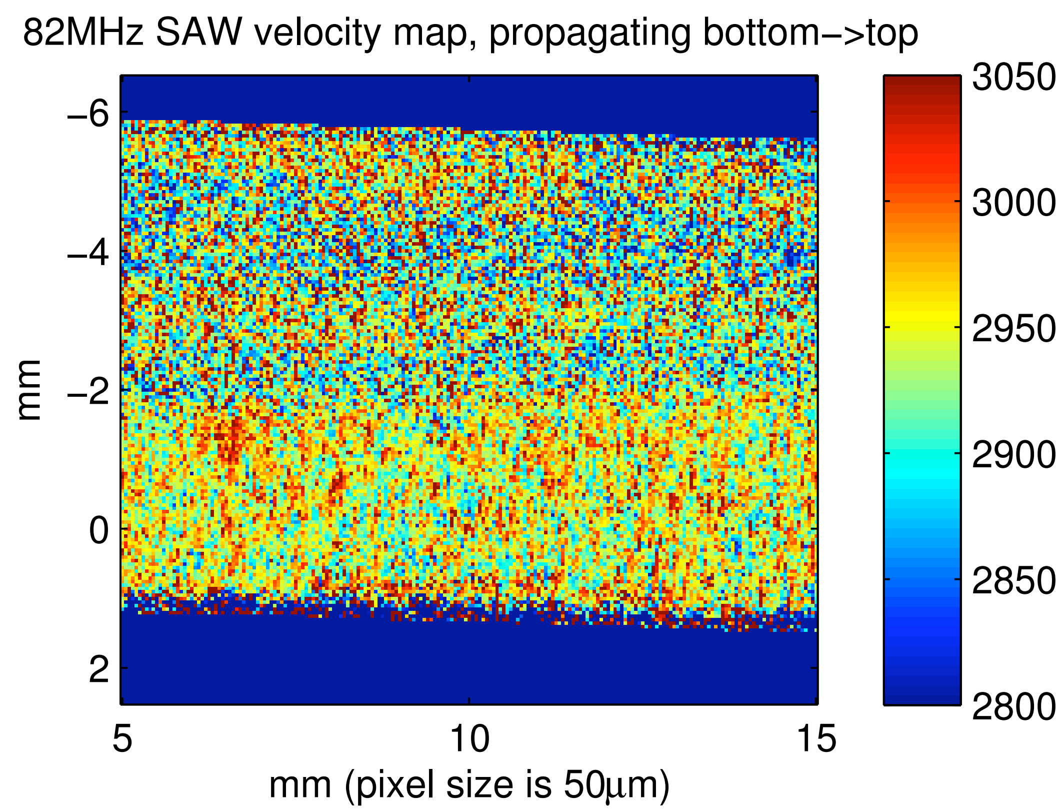


Iron and steel

- Iron stock with steel layer, tempered in the traditional way
- Archaeological interest in being able to test the thickness of steel plating non-destructively

Iron and steel





- SRAS velocity maps of the sample (iron at top, steel below)
- Note small grain size: lateral resolution ~200 microns
- SRAS as validation tool for bulk wave techniques to determine steel thickness

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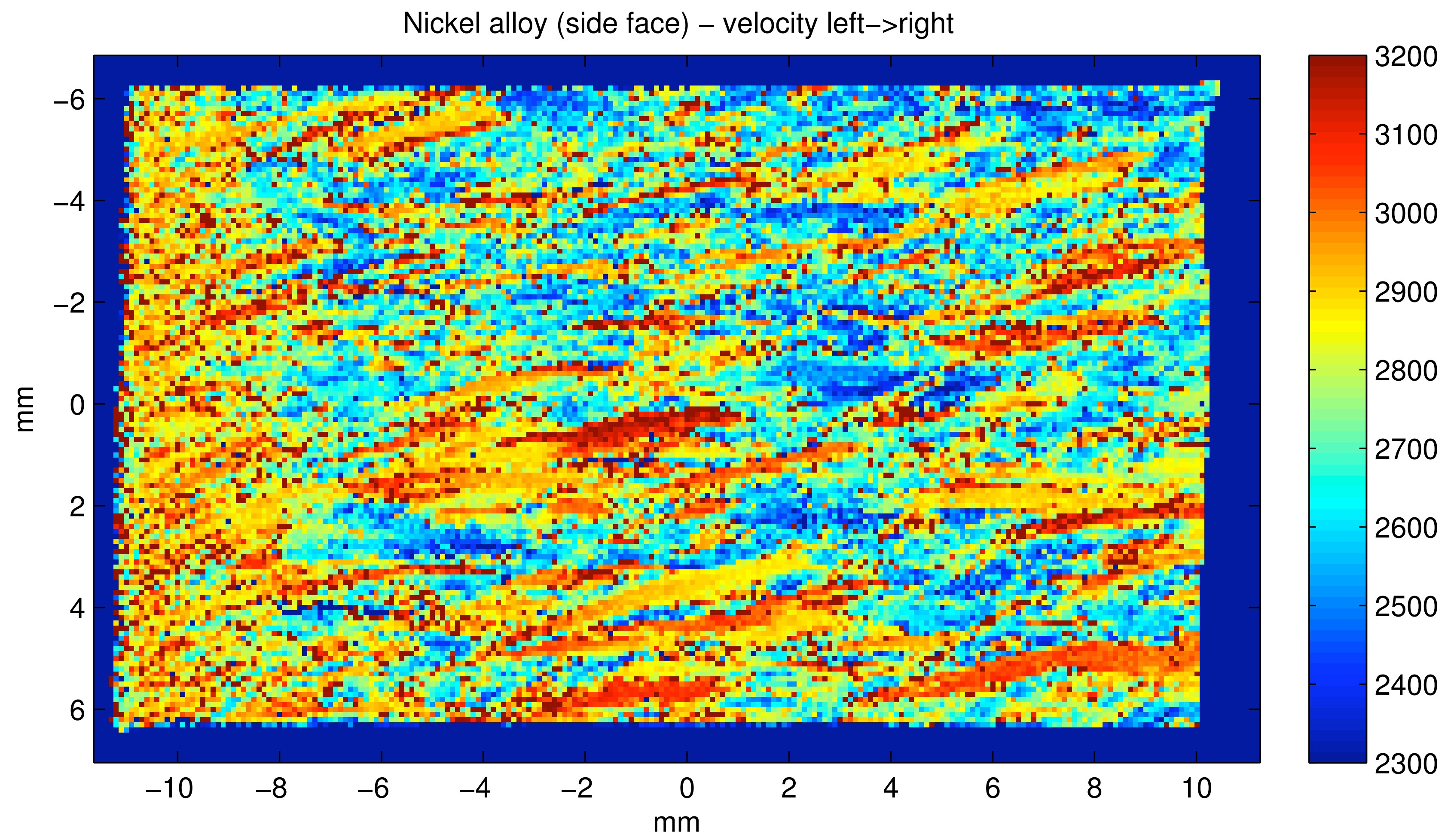
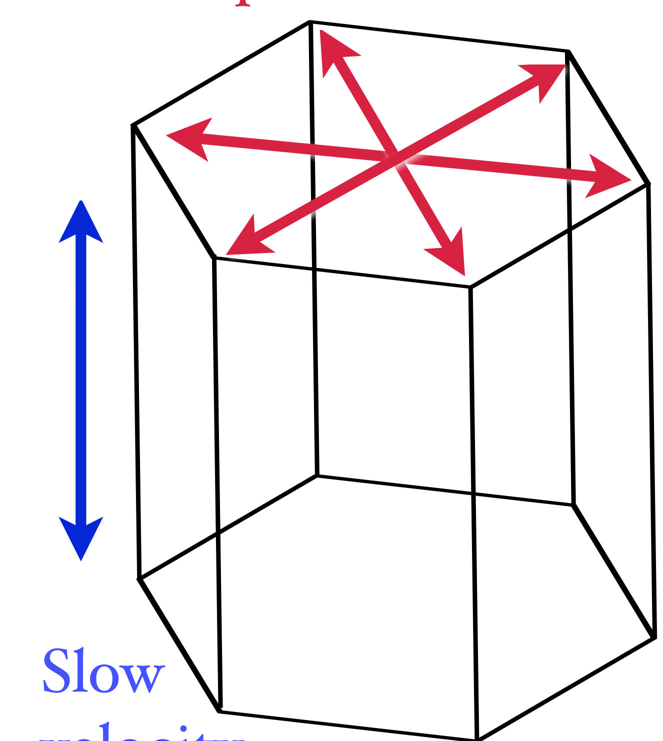
Nickel alloy

- Note velocity scale: very high degree of anisotropy
- SRAS is tolerant to acoustic aberration

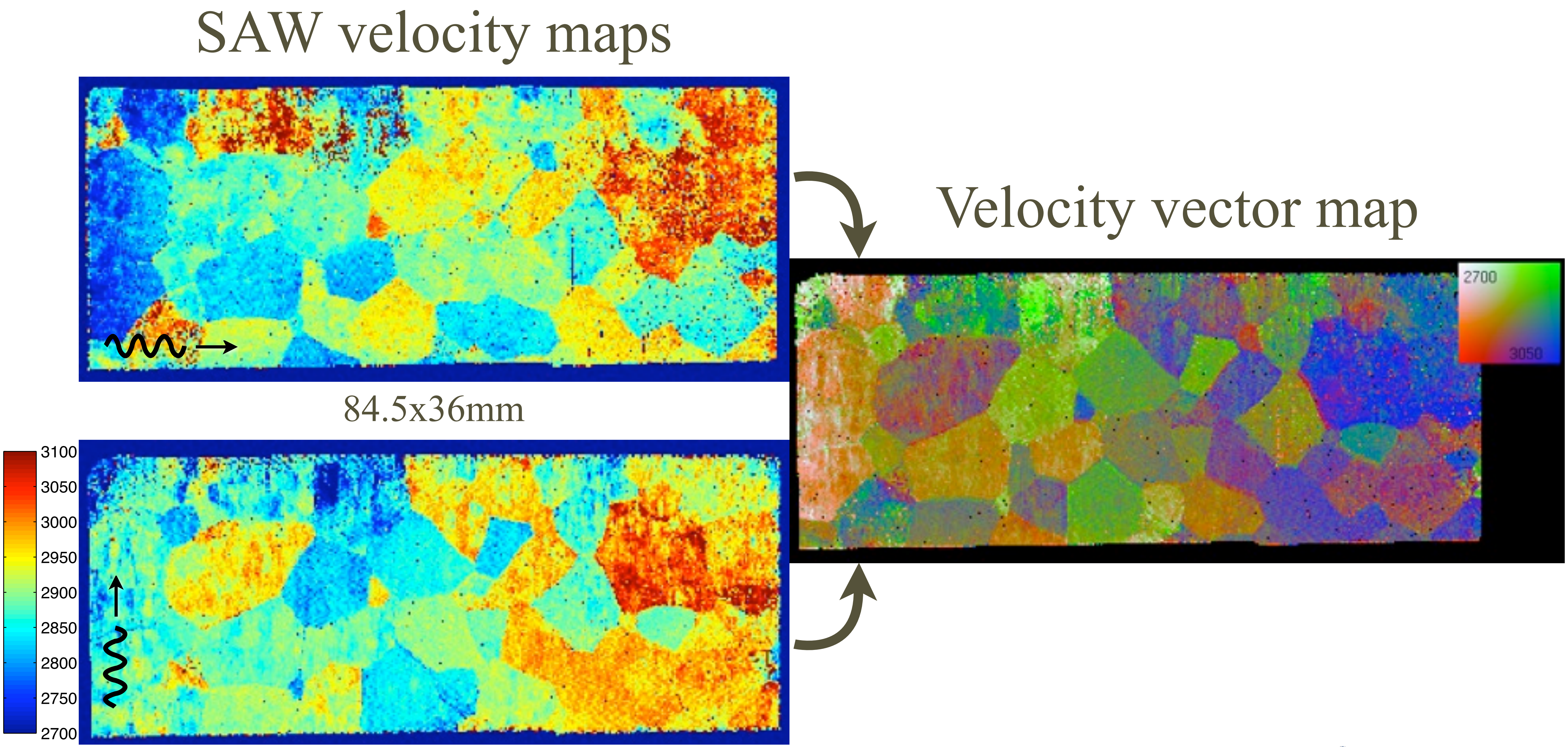


Grain orientation from velocity measurement in >1 direction

- Crystals are 3D in structure, e.g. titanium crystals can be:
  - hexagonal close packed (HCP) in the alpha phase
  - body cubic centred (BCC) in the beta phase
- Velocity can vary greatly (e.g. 50%) between parallel and perpendicular directions, relative to basal plane for certain materials
- By scanning at orthogonal angles, can get an idea of the angle of the basal plane



Ti-6246: velocity vector map



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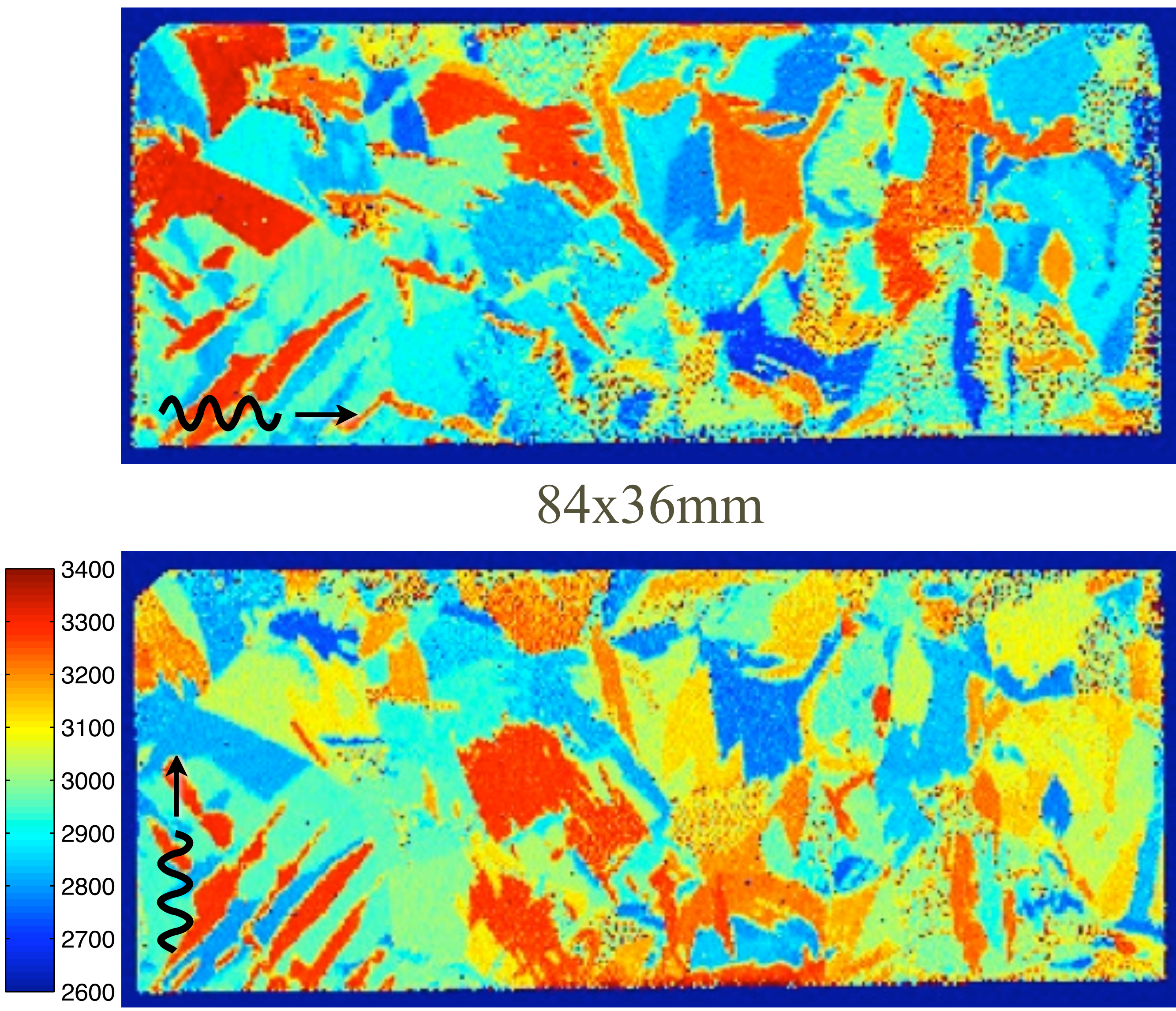
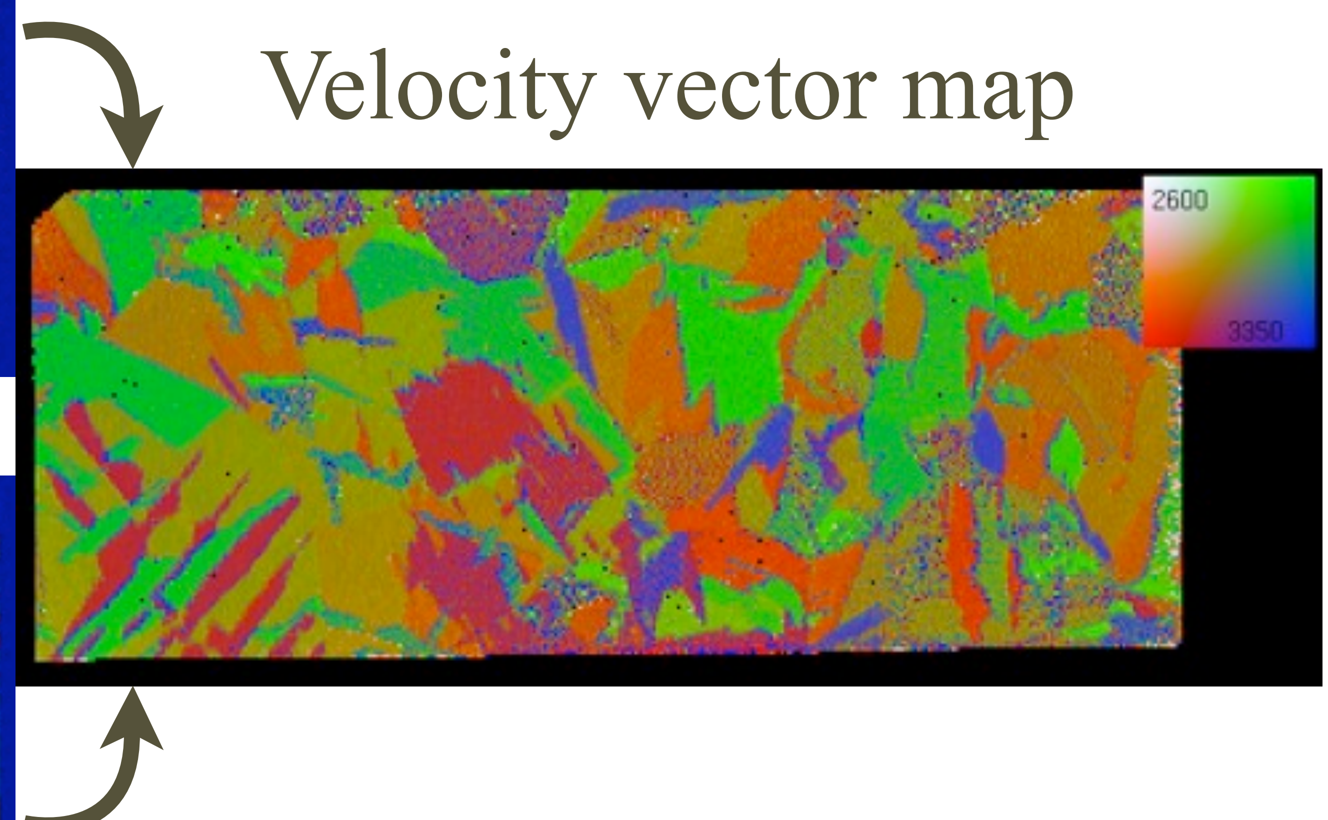
Ti-685: velocity vector map

SAW velocity maps



84x36mm

Velocity vector map



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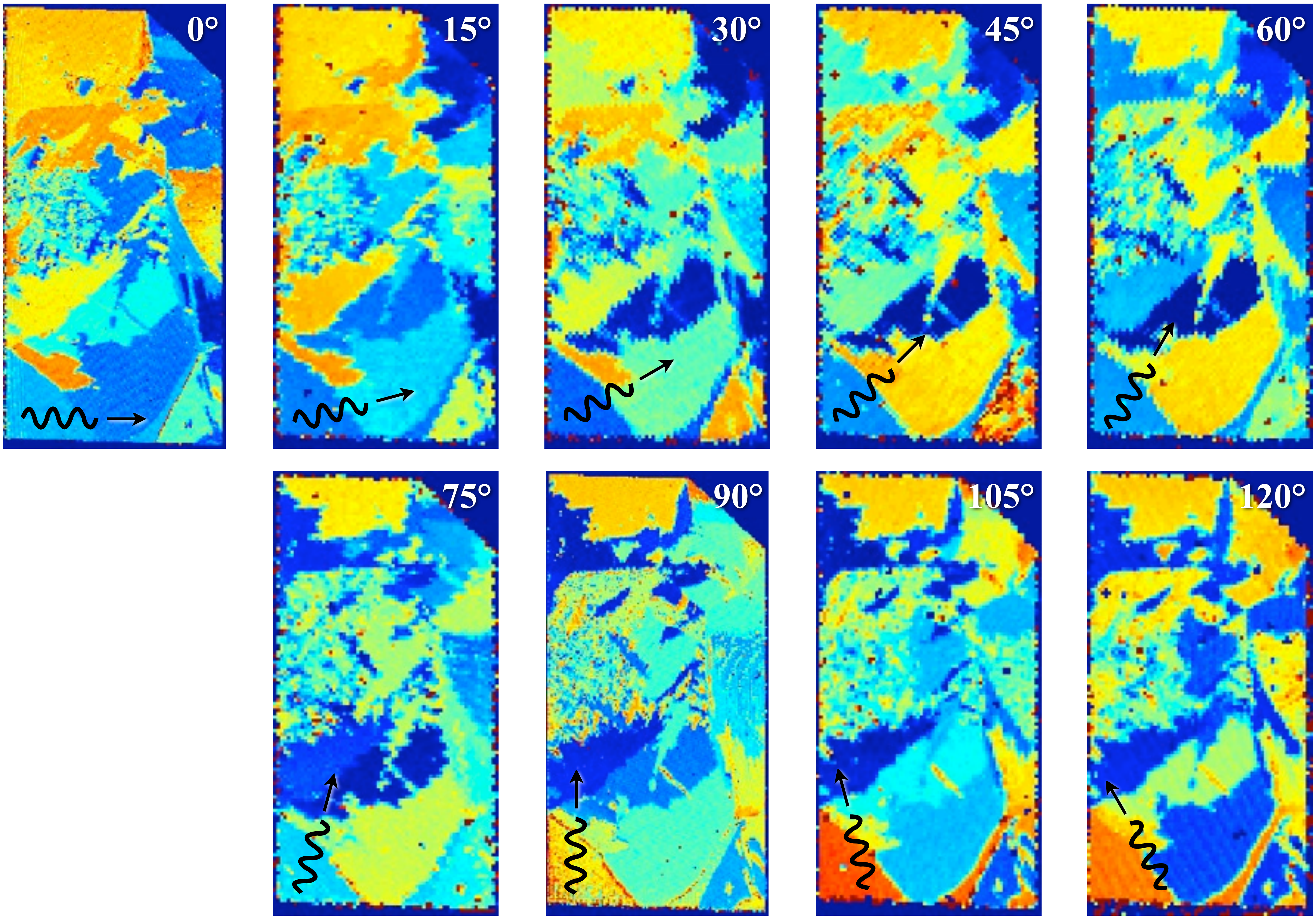
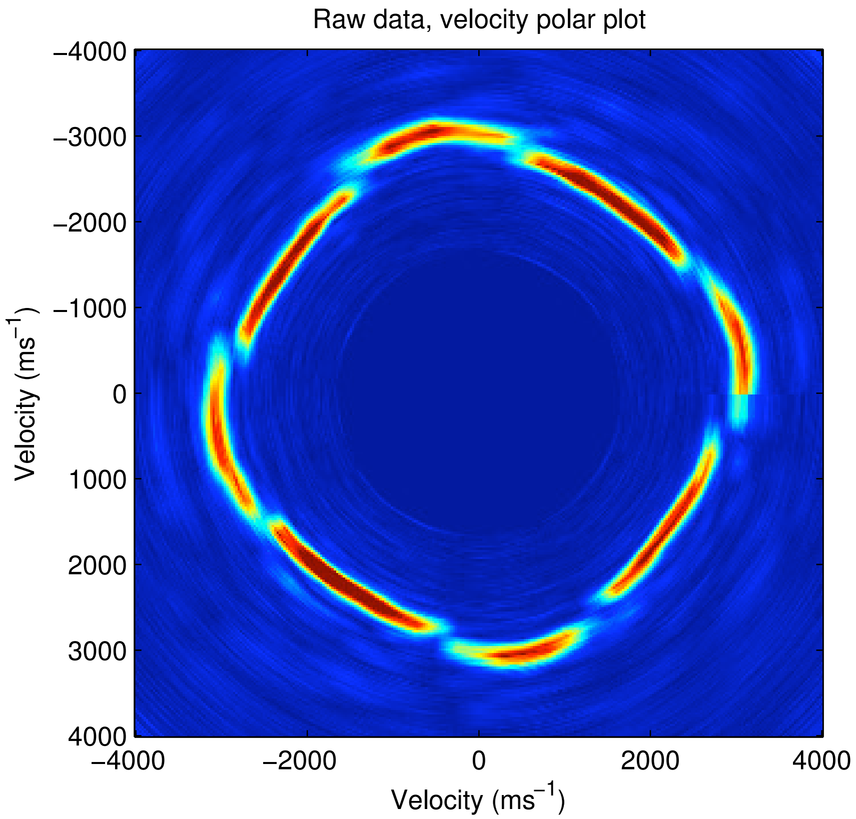
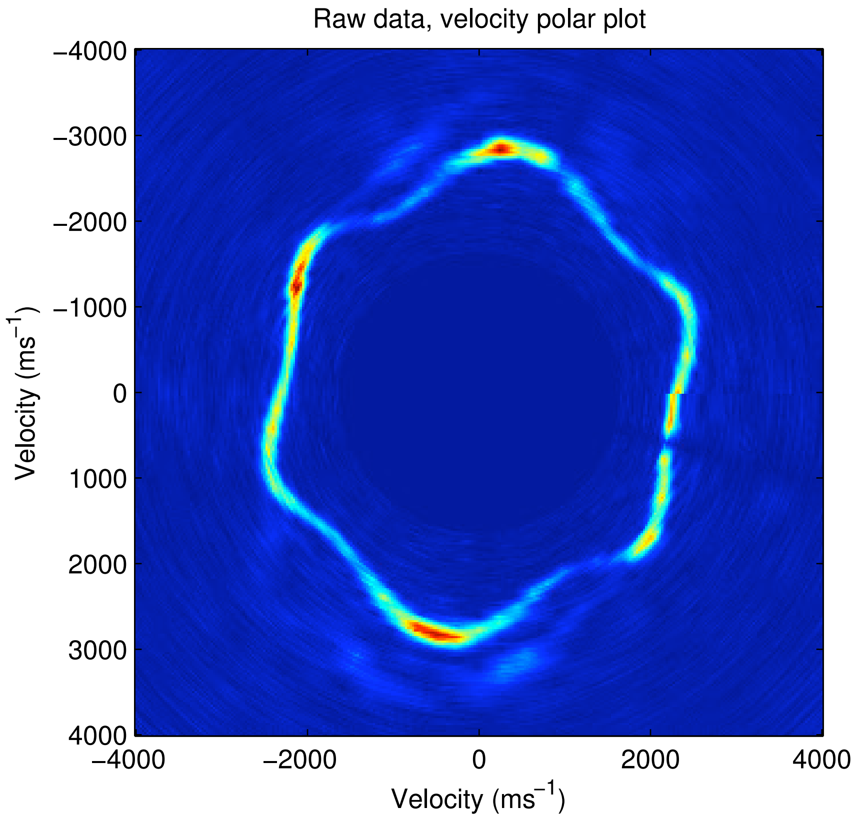
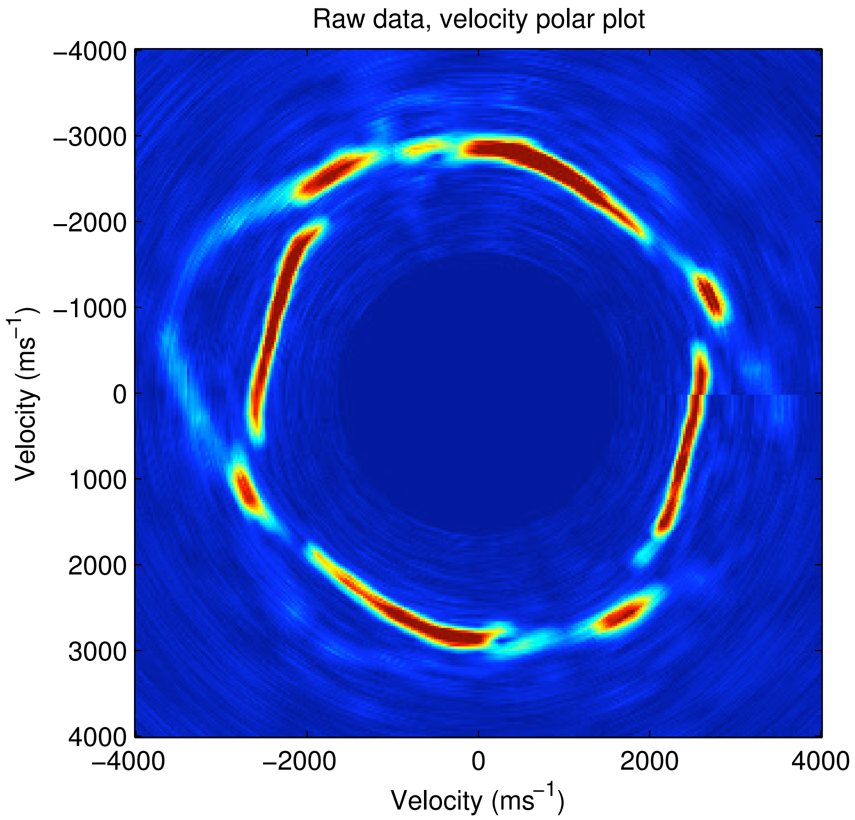
Propagation in multiple directions



Propagation in all directions

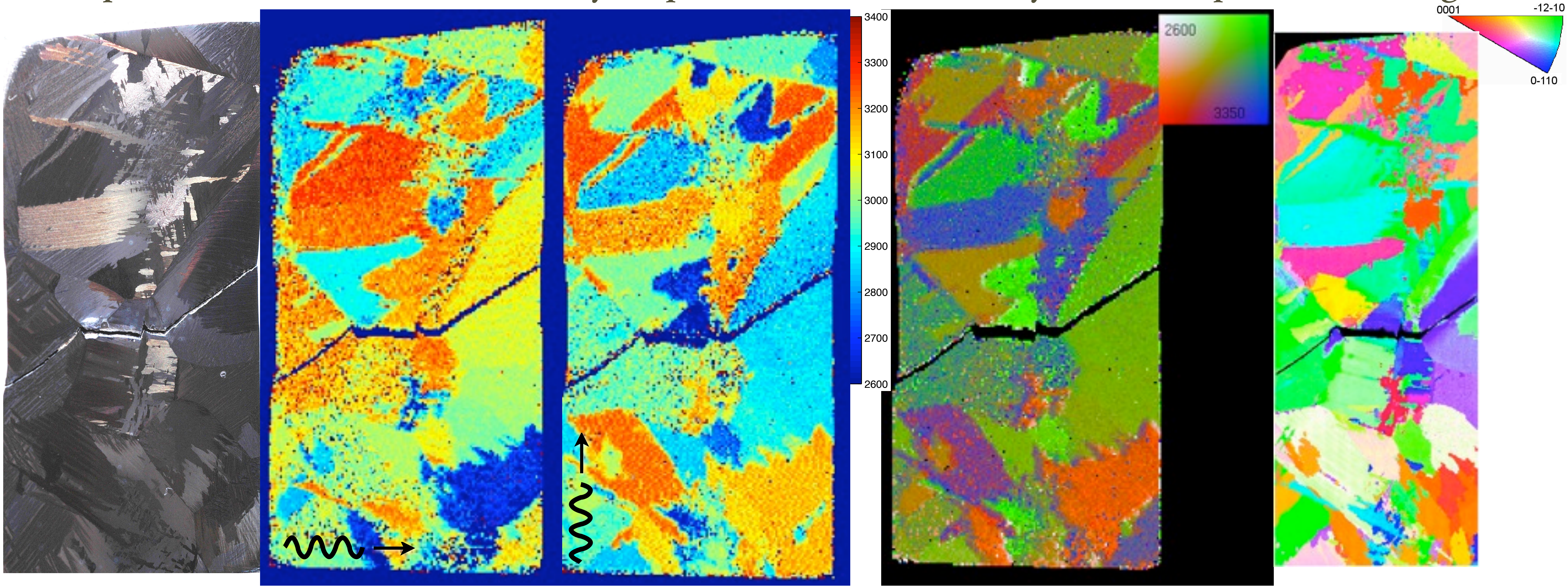






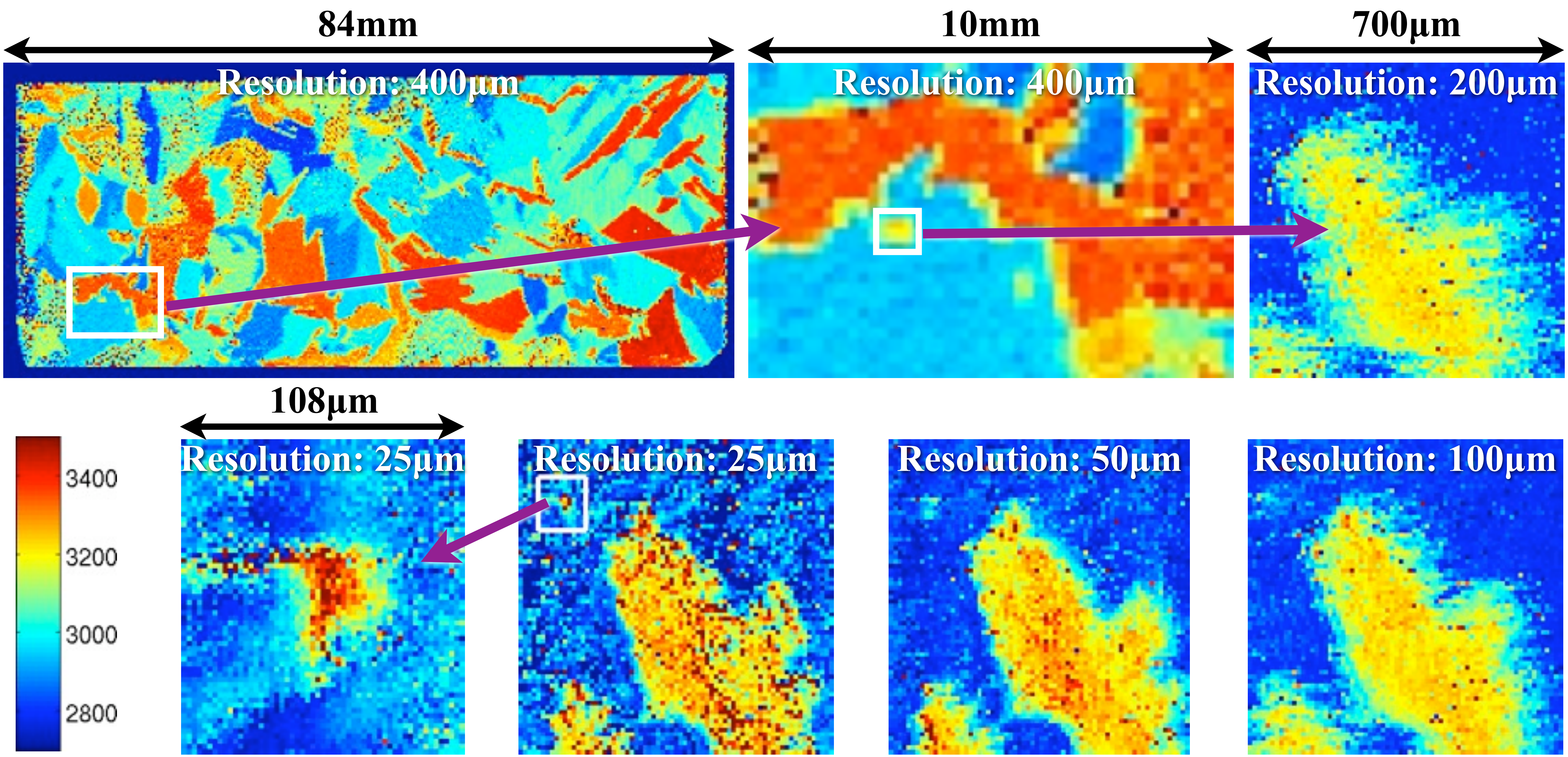
Comparison of SRAS with chemical etching and EBSD

Optical | SAW velocity maps | Velocity vector map | EBSD image



27.4x52.4mm

Illustration of the scaleability of the SRAS technique (328MHz SAWs)



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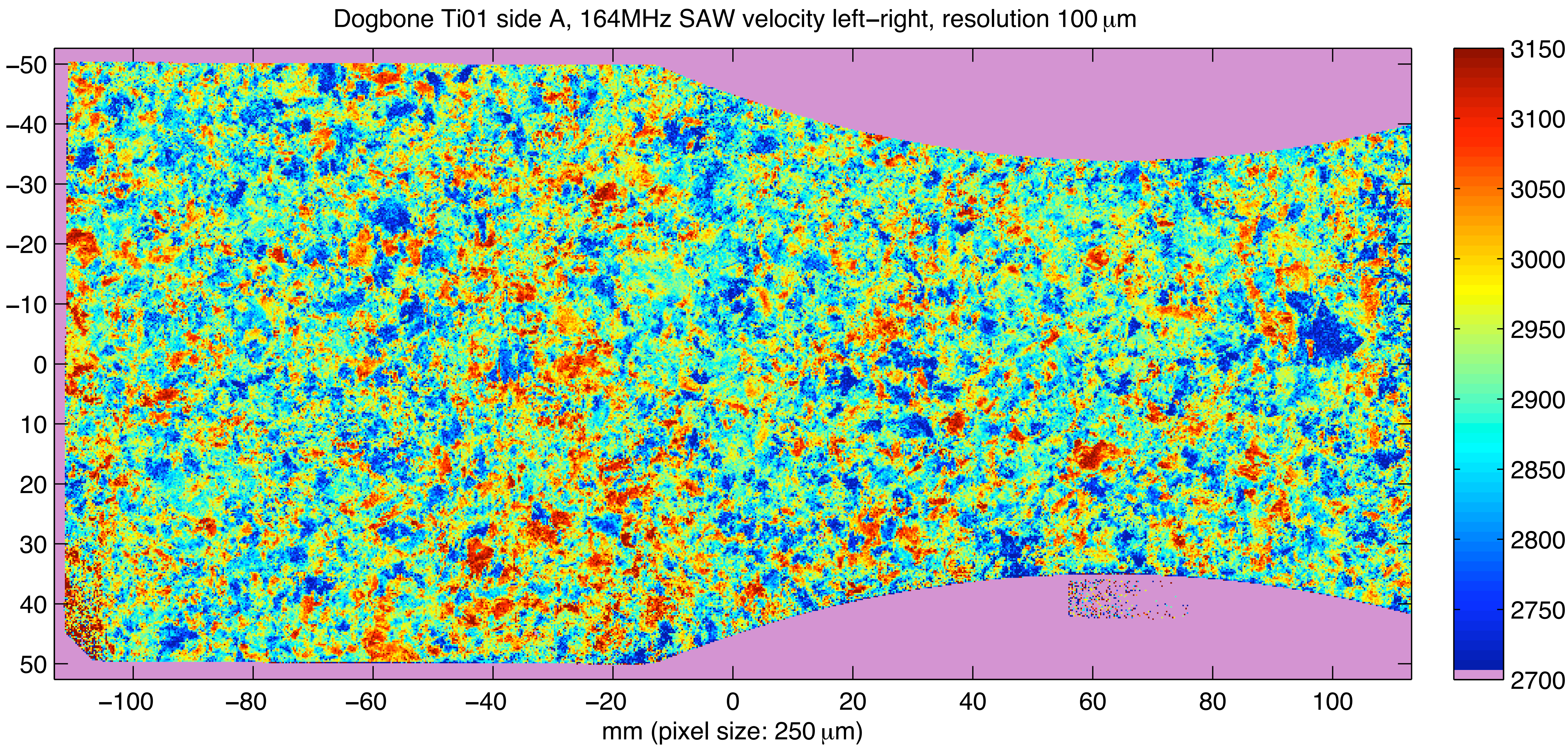
Ability to image large samples, as well as small



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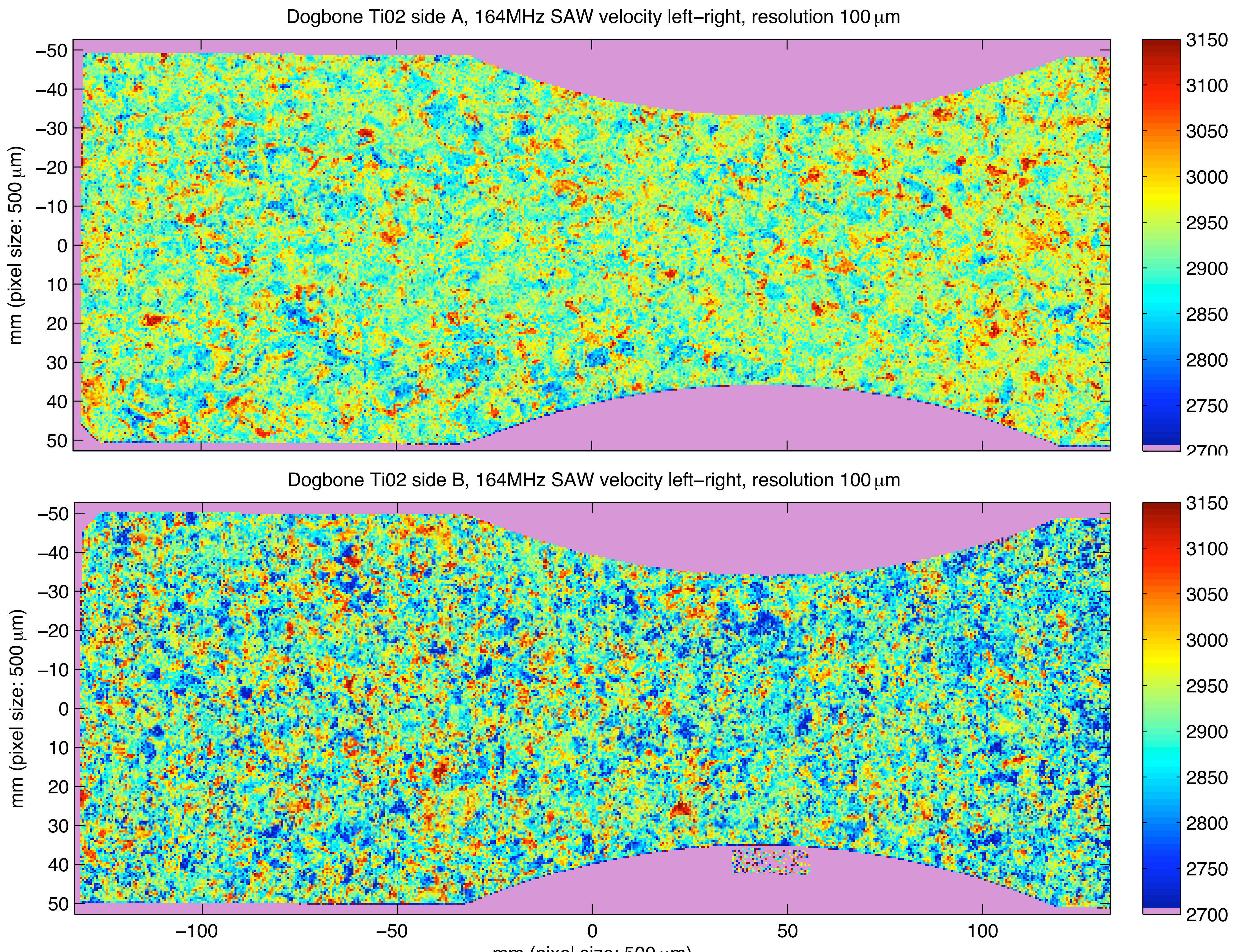
Important microstruture differences



Velocity change as a function of coating thickness

- Large block of silicon nitride is coated with ~30nm of high purity gold, through a mask consisting of three capital letters*

- Mask is removed, then entire area is coated with ~500nm of aluminium
- Gold letters are completely obscured

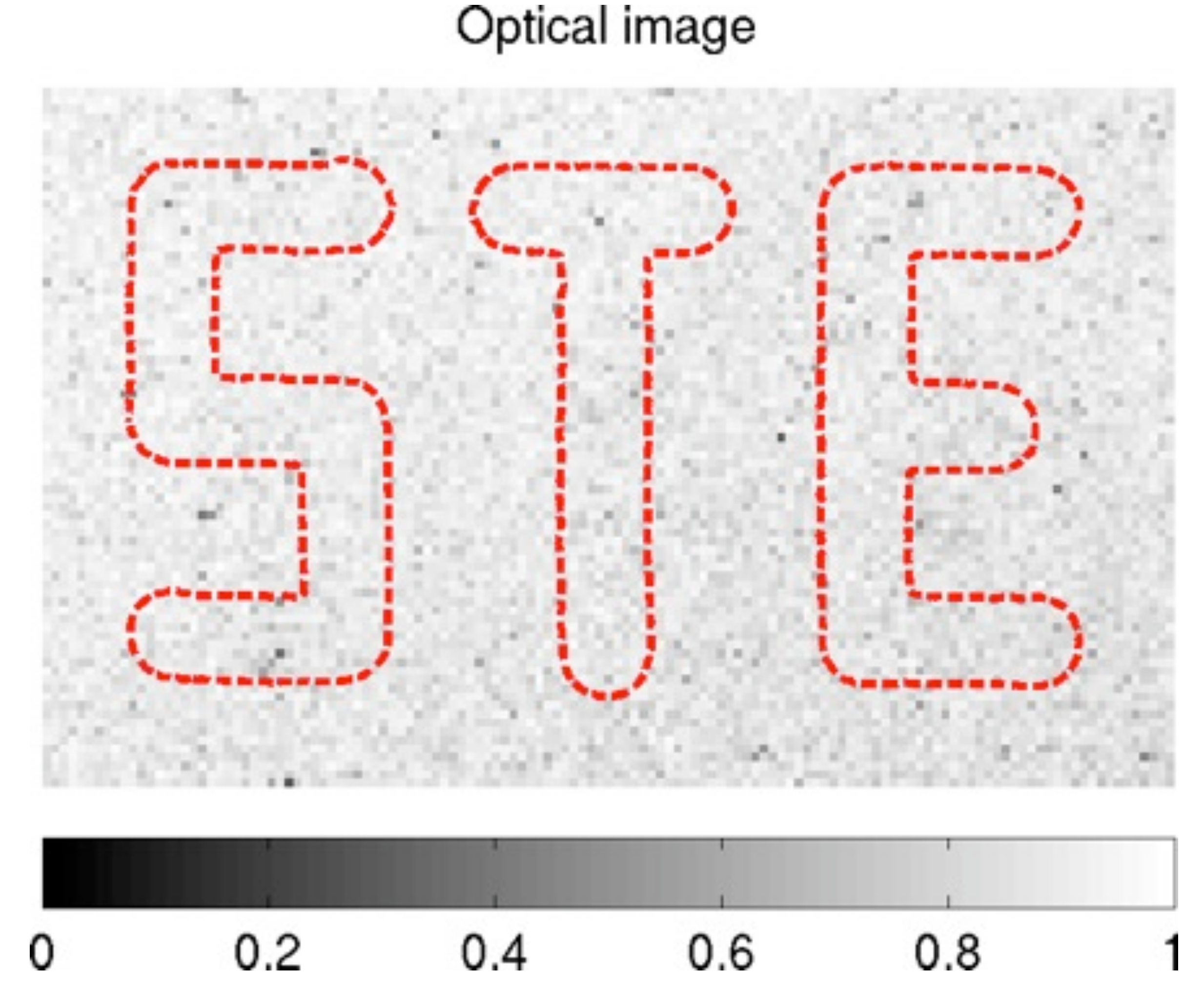
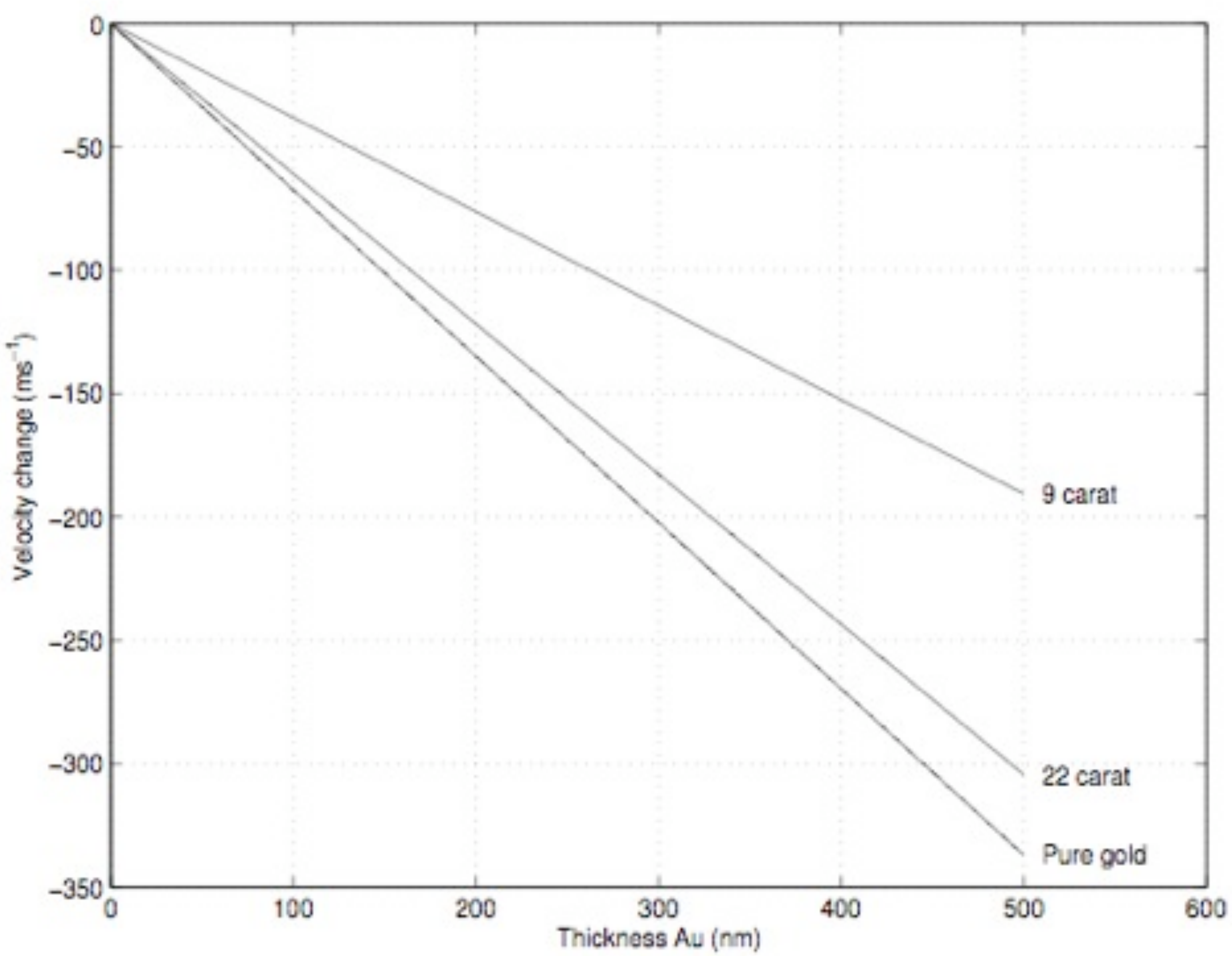


Image size 13x8mm

*chosen completely at random

Velocity change as a function of coating thickness

- Velocity map is acquired, and hidden gold layer is revealed due to change in velocity
- Image has been spatially filtered to reduce noise



Velocity image, indicating coating thickness

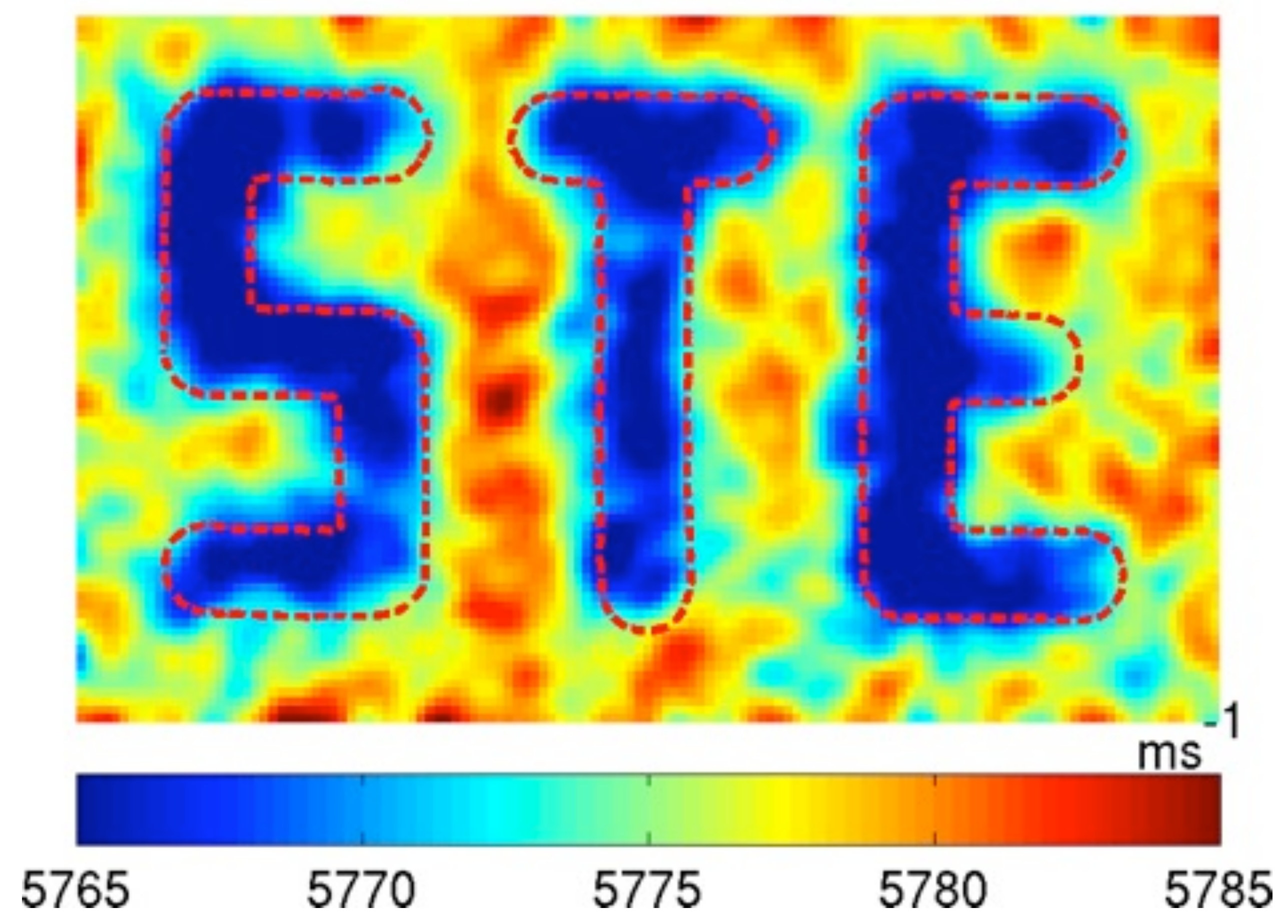


Image size 13x8mm

SRAS: Conclusions

- Spatially Resolved Acoustic Spectroscopy is a **robust** and **rapid** technique for **quantitatively** measuring the SAW phase velocity
- It is non-contact and is completely non-destructive
  - Excitation powers <15mW have been used
- Lateral resolution is currently approximately 25μm
- Sample size limited only by scanning stages
- Trade-offs between lateral resolution and velocity resolution: the higher the frequency the better
- More work needs to be done to relate SAW velocity in multiple directions with crystallographic orientation

Thanks for your attention

Thanks to E.E. Sackett, L. Germain and M.A. Bache of The University of Wales Swansea for the EBSD images

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