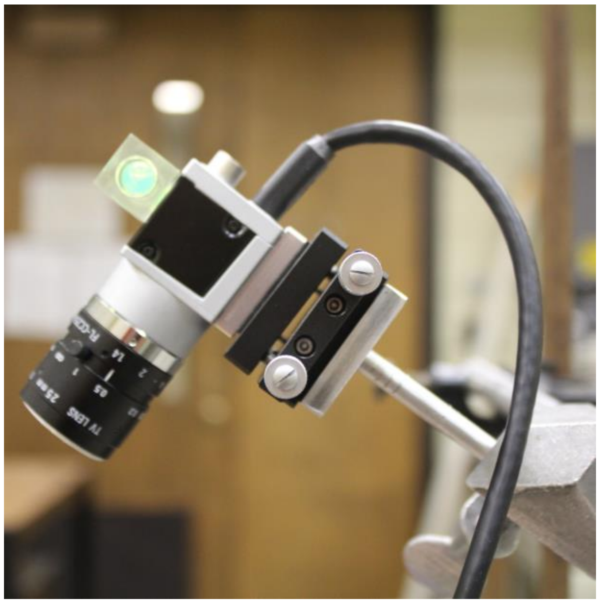
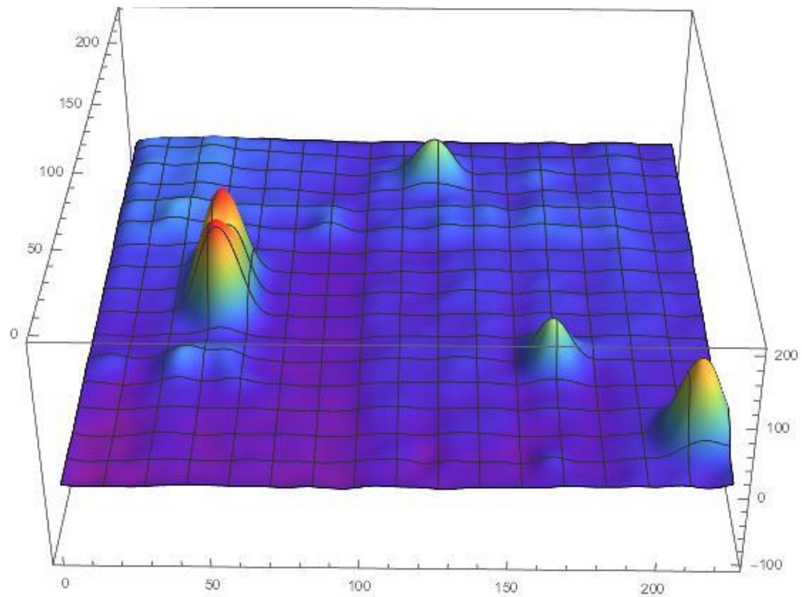
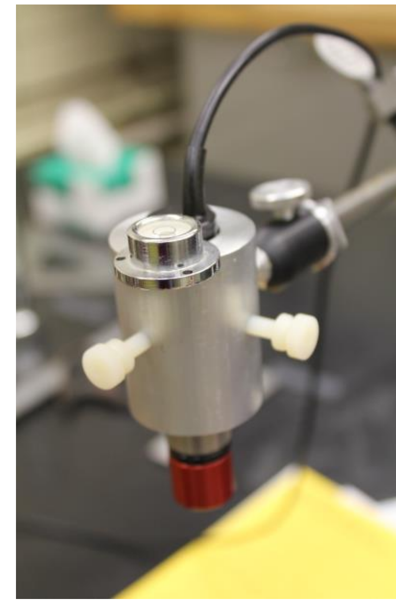
Thermal imaging and laser line imaging QA for ITk Strips Stave Cores







Soeren Prell (Iowa State University)

ATLAS Upgrade Week at CERN
November 14-18, 2016

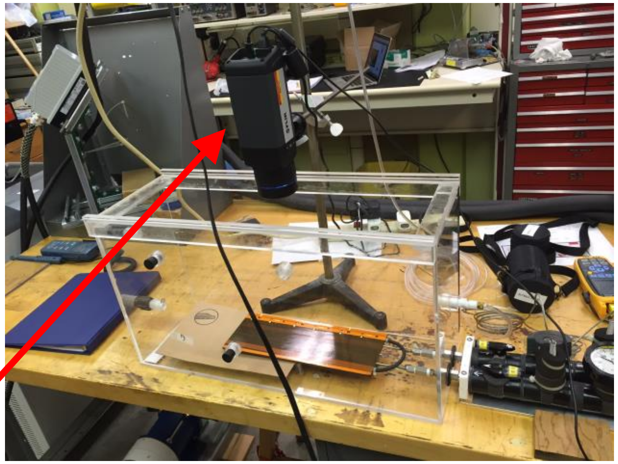
Strips Stave Core QA at Iowa State University

• Jim Cochran	professor
• Chunhui Chen	professor
• Soeren Prell	professor
• Jie Yu	postdoc
• Boping Chen	graduate student
• William Heidorn	graduate student
• Carlos Vergel-Infante	graduate student
• Roy McKay	technician

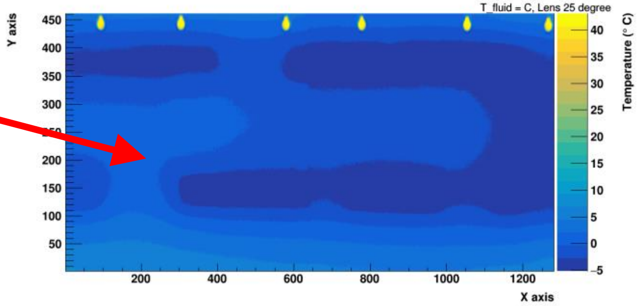
Goal: *Develop test stands for thermal imaging QA and laser line imaging QA*

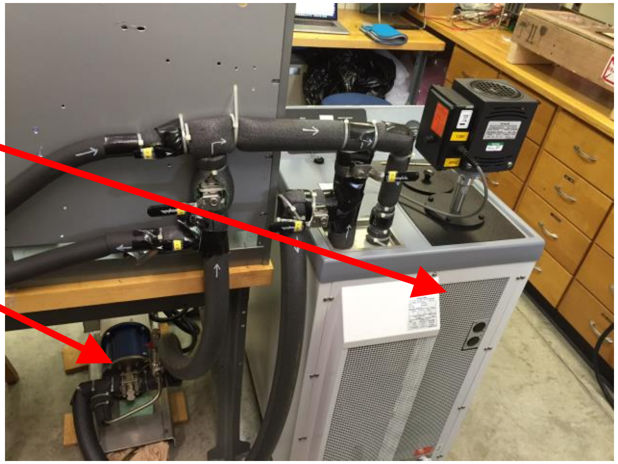
Thermal Imaging Stave QA

- Principle
  - Stave coolant circulates at low temperature (expected default – 40º C), ambient at room temperature
  - IR camera (FLIR A655sc) takes thermal image of stave to visualize cooling path
  - *Delaminations from pipe to foam to facing* show up as hot spots
  - Thermal noise ~ 0.1º C and maximum vignetting of ~ 1.0º C at −35ºC with 80° angle lens
- Cooling system
  - Recirculating chiller (SP Scientific RC211B0), T range −80 °C → + 75 °C
  - Booster pump to ensure required pressure (LiquiFlo, 180 psi @ −60 °C)
  - “Coolant” 3M Novec HFE-7100

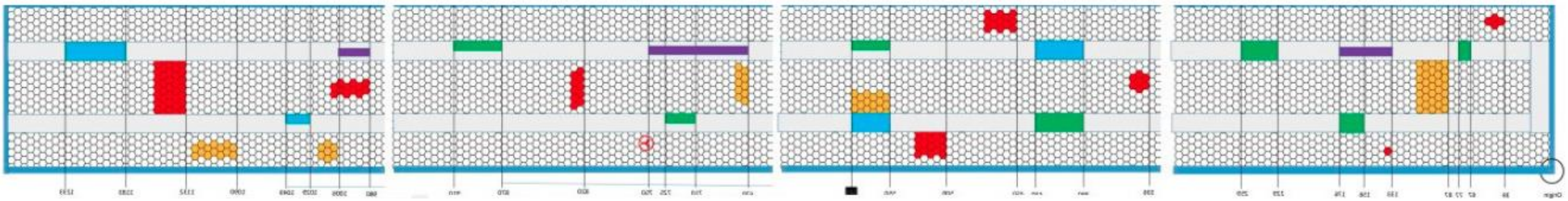


Example thermal image of mini-prototype stave





Integrated defects on long stave



Delamination Legend

- Honeycomb top
- Honeycomb bottom
- Foam top
- Foam bottom
- Pipe / foam glue

Delaminations between honeycomb and facing should not be visible with thermal imaging; will study those with laser scanning

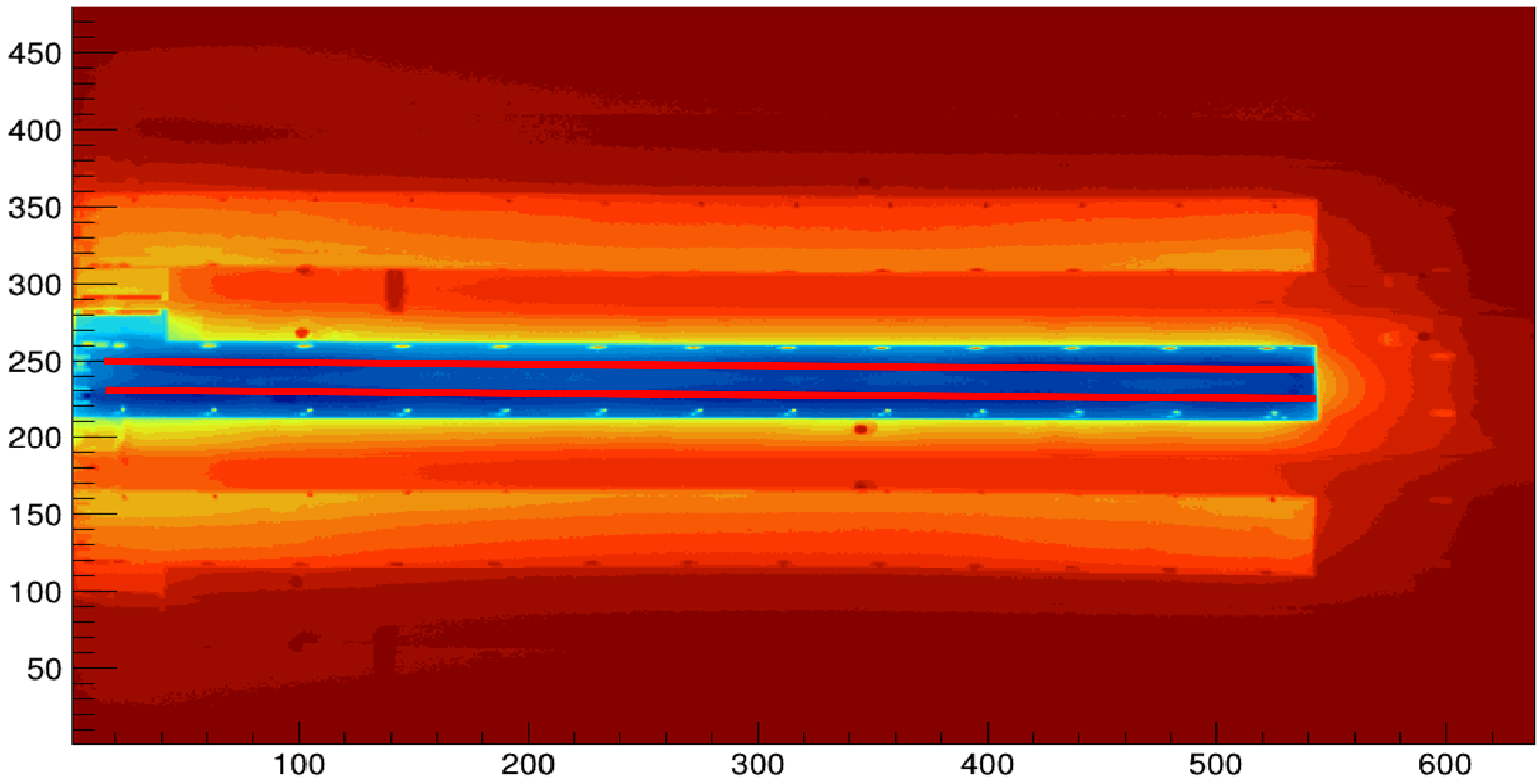
Delaminations between foam and facing should be visible as they break the cooling path; either green or blue defects should be visible depending on which side of the stave is imaged

Delaminations between foam and cooling pipe break the cooling path, but further away from imaged surface; not clear what to expect

At least one “mistery” defect at a location unbeknownst to us has been implemented.

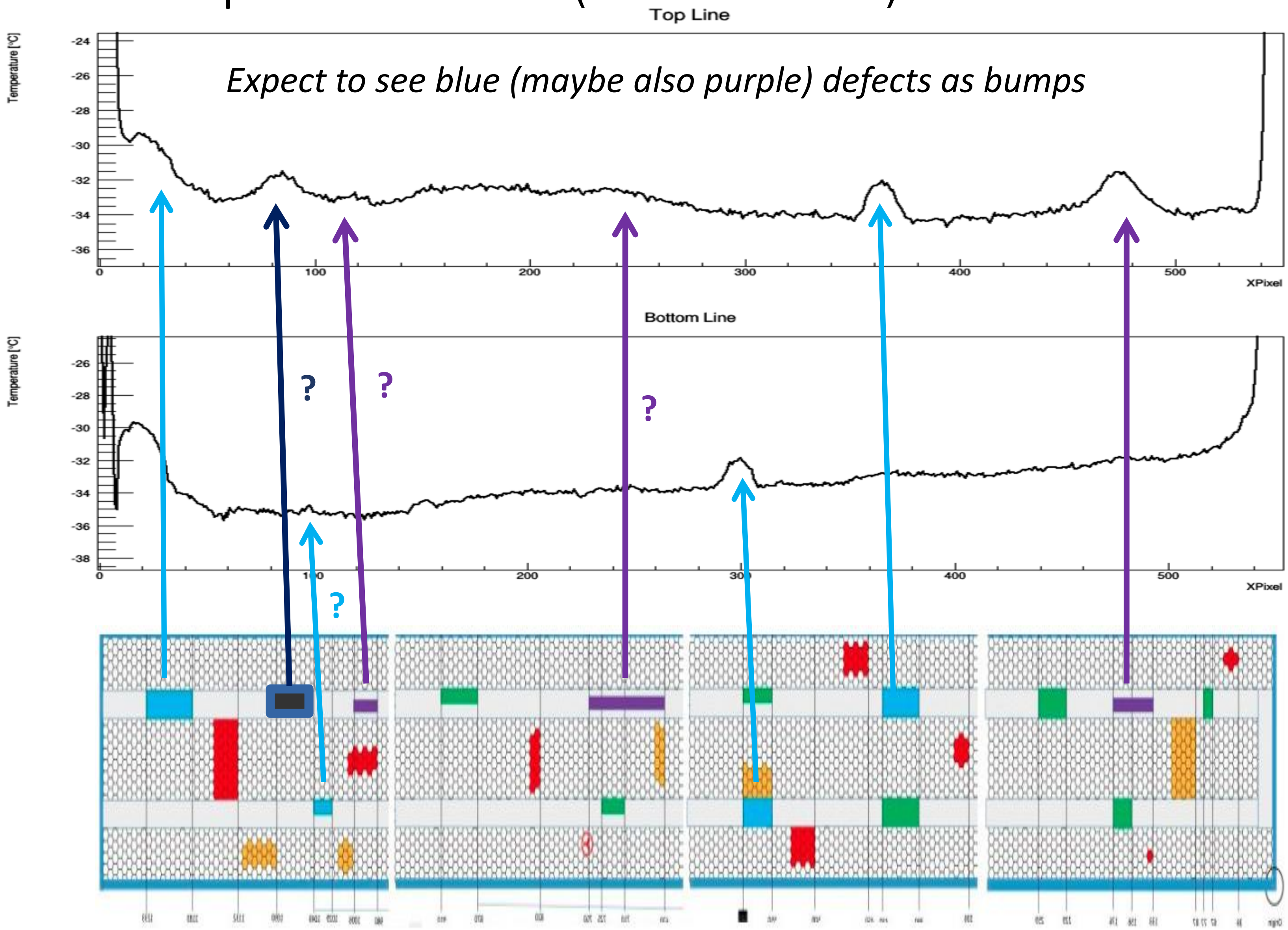
Thermal image of a full-size stave

Single image taken with an 80^o wide-angle lens at 0.9 m camera-stave distance; coolant at −55^{o}C



Delaminations are identified as bumps and dips in the temperature profile; for now we look at small regions over centers of cooling pipes

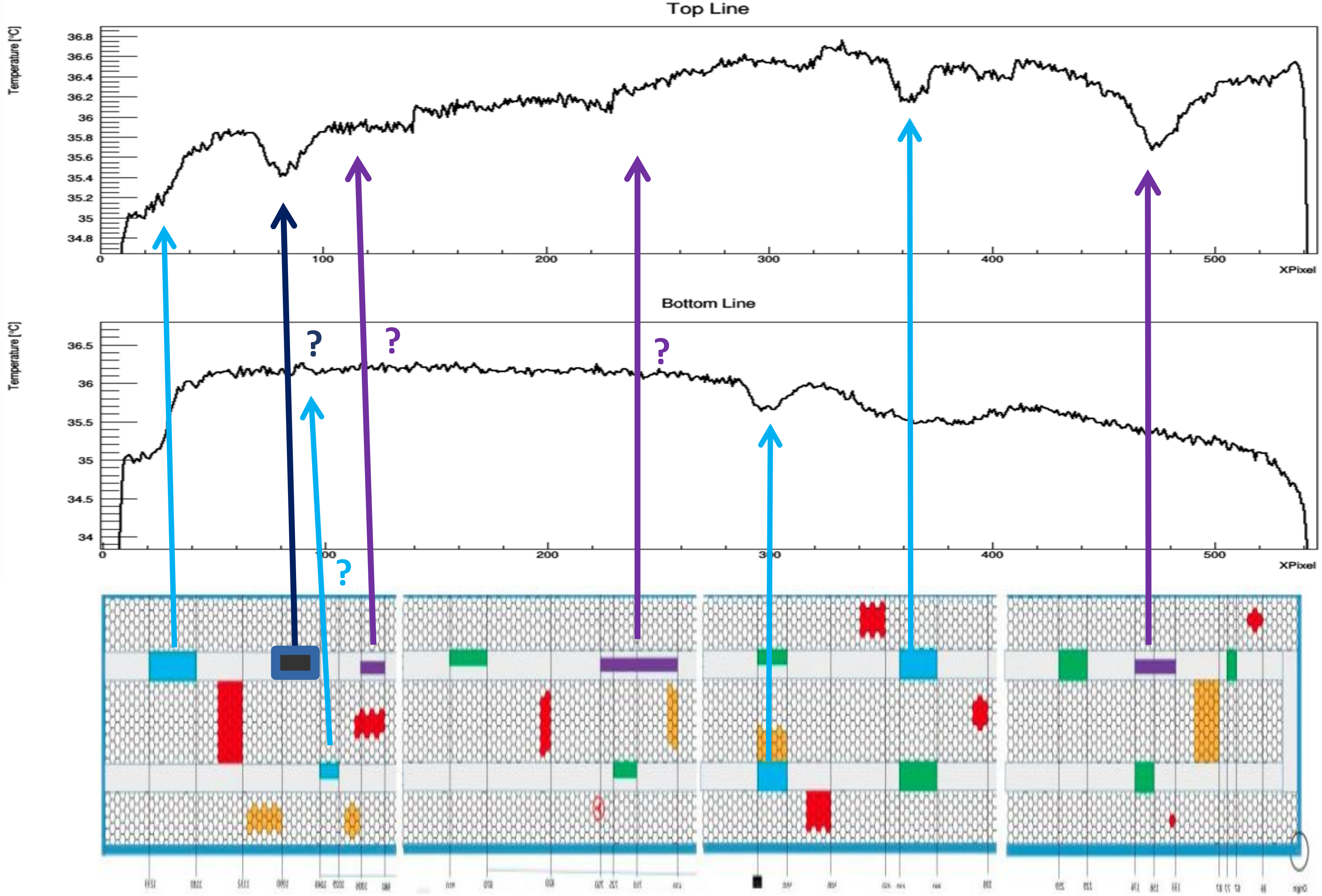
Low temperature scan (bottom side)



Solid blue defects are clearly visible, however small, partial defect is not...
Purple defects are inconclusive, more work is needed

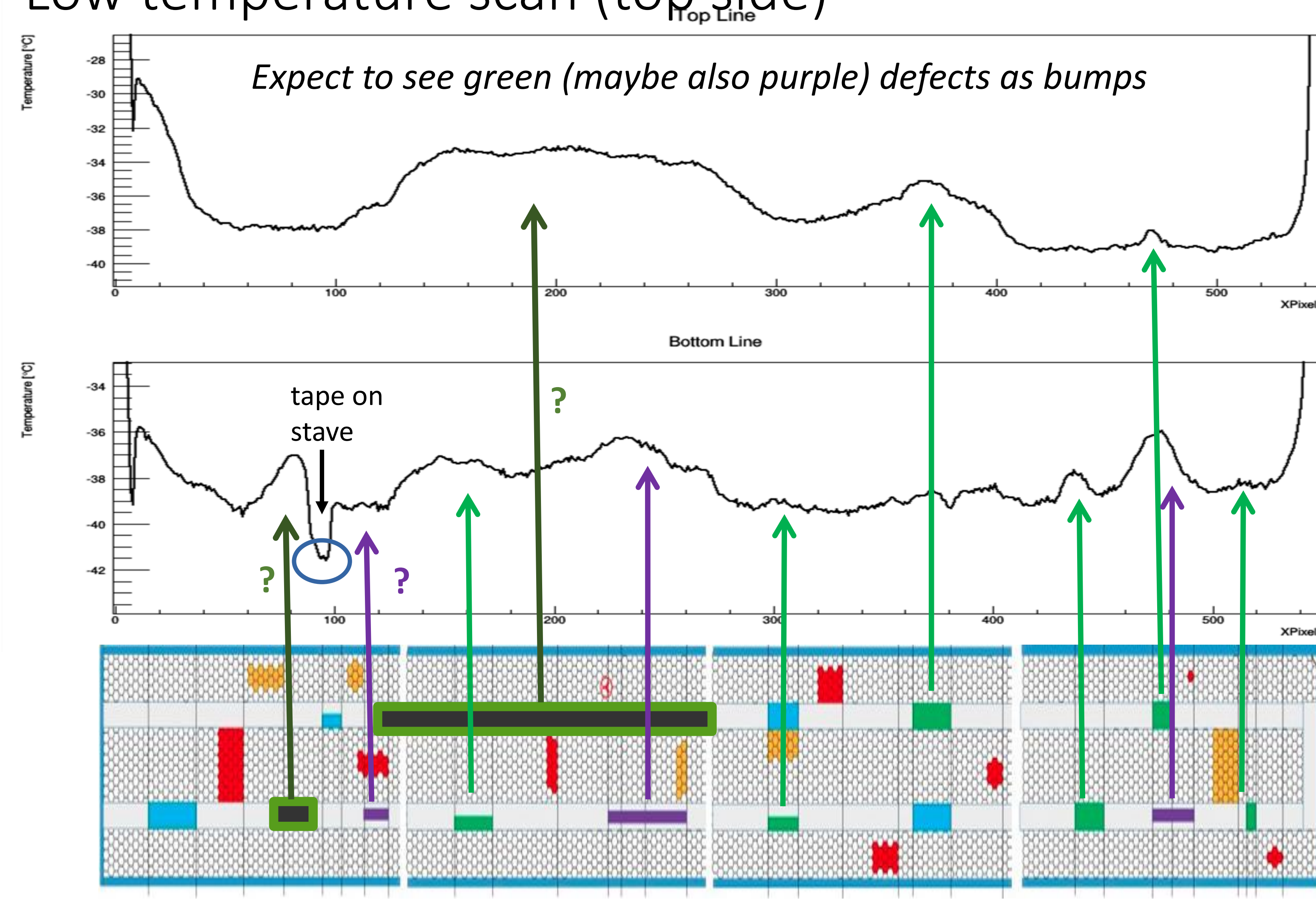
High temperature scan (bottom side)

Expect to see blue (maybe also purple) defects as dips



Solid blue defects are clearly visible, however small, partial defect is not...
Purple defects are inconclusive, one unexpected defect found (dark blue)

Low temperature scan (top side)



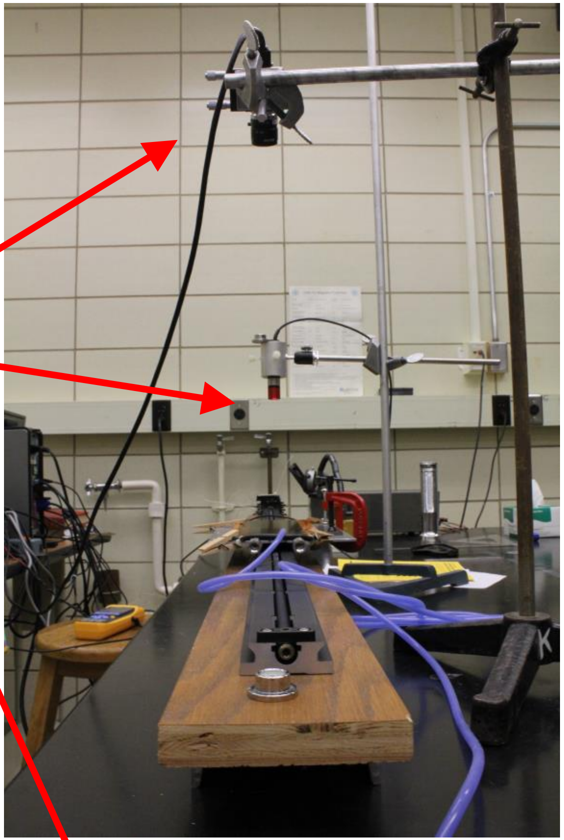
Larger solid green defects are clearly visible, 1cm defects and partials not so obvious. Purple defects are inconclusive. Unexpected defect found in same place as on bottom side (dark green). Large defect (dark green) on top line, intended? Unexplained features on bottom line.

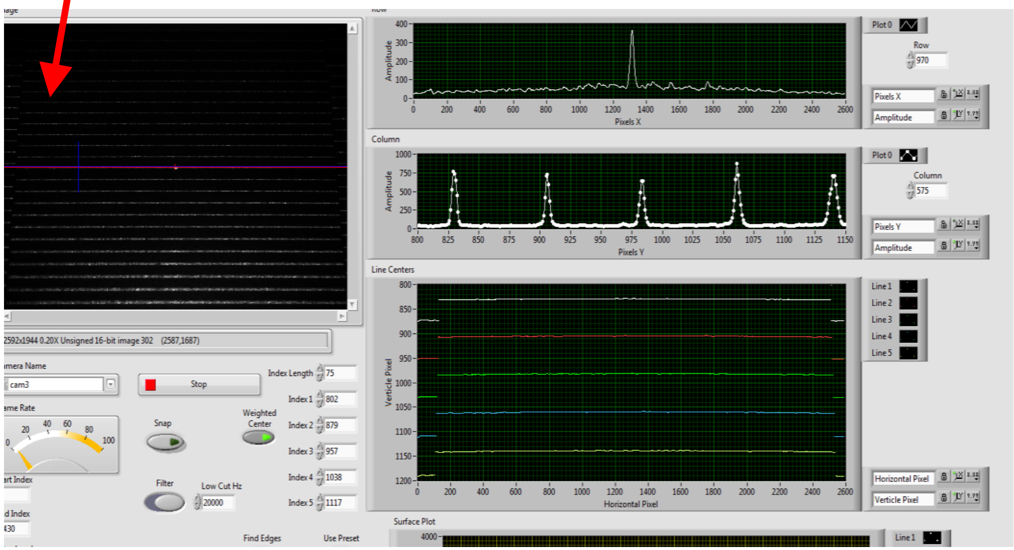
Thermal Imaging Stave QA
(cont'd)

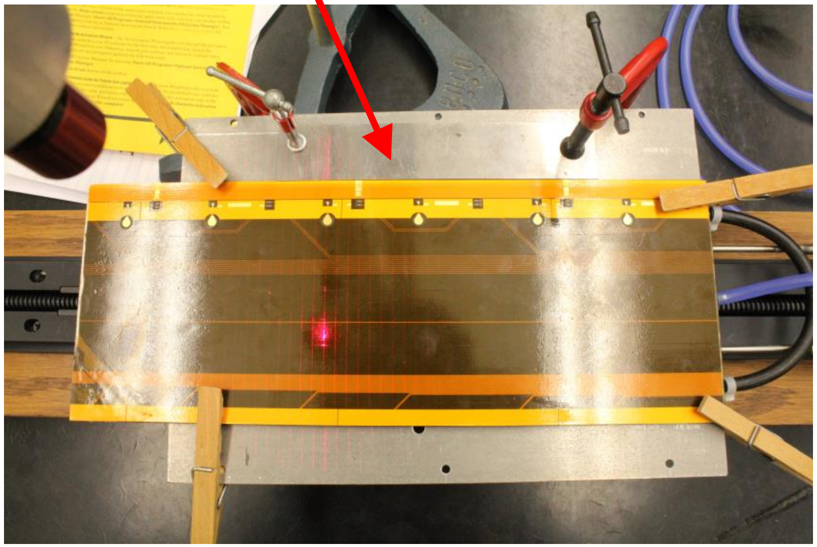
- "To-do"
  - Defect characterization and identification
    - Characterize defect shapes in terms of known defect properties (type, width, length, temperature, etc.)
    - Create temperature templates for a flawless stave
    - Develop defect-finding algorithms
  - Set-up improvements and cross-checks
    - Look into two-side thermal imaging with aluminum mirrors (the QMUL set-up)
    - Thermally image the same stave core at both QA sites (ISU and QMUL) and compare the results

Laser Scanning Stave QA

- Principle
  - Scan stave surface with laser array and CCD camera triangulation
  - Labview software reads out camera, performs center-of-line finding and in-situ height calibration
  - Subtract image of non-pressurized stave from image of pressurized stave (at 3-5 psi) to make *delaminations between honeycomb and facing* visible



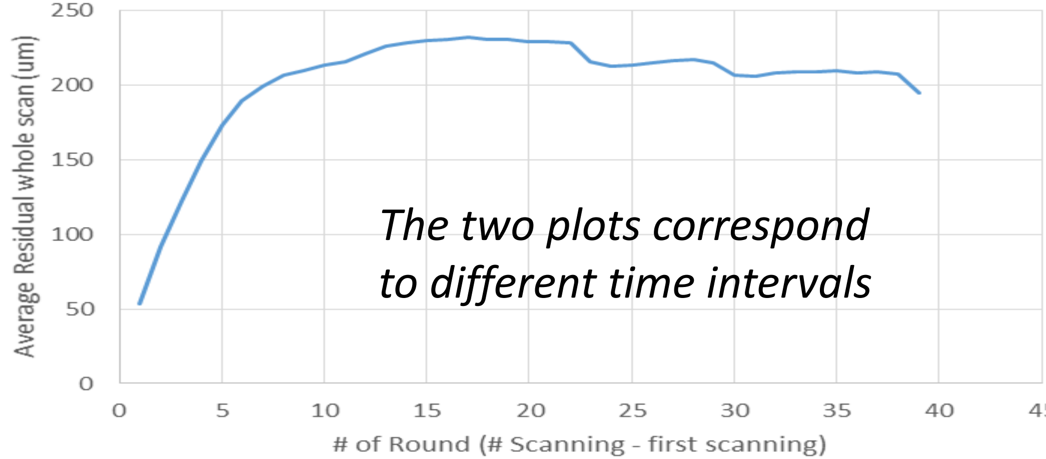




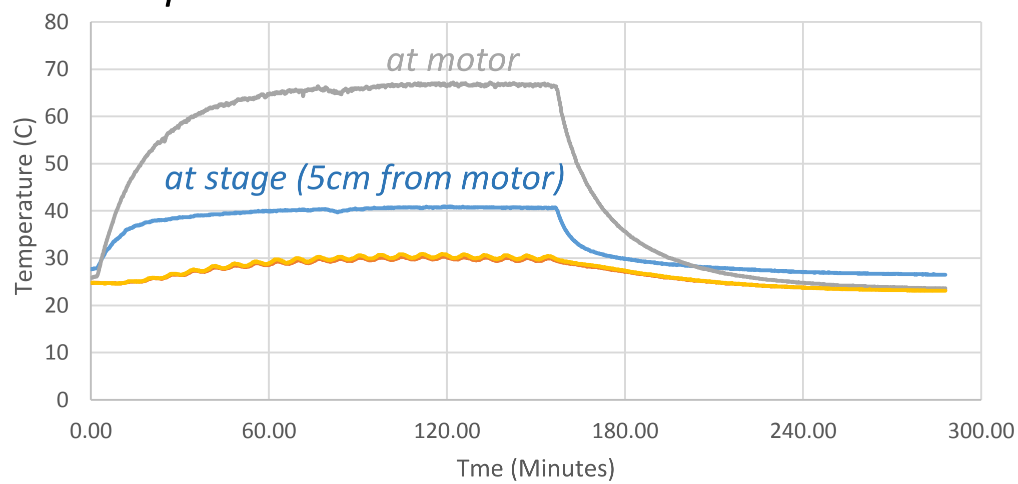
Laser Scanning Stave QA (cont'd)

- Average height of stave surface increases for first ~15 scans by up to several hundred micron
- With default software settings the stage motor's temperature increases from 23°C to ~70°C
  - This causes (vertical) thermal expansion of linear stage
- Cooling the motor with a fan reduces the effect to a max temperature of 35°C
  - This results in a max height change of ~50µm

Stave surface height average residual with respect to 0^{th} scan in microns

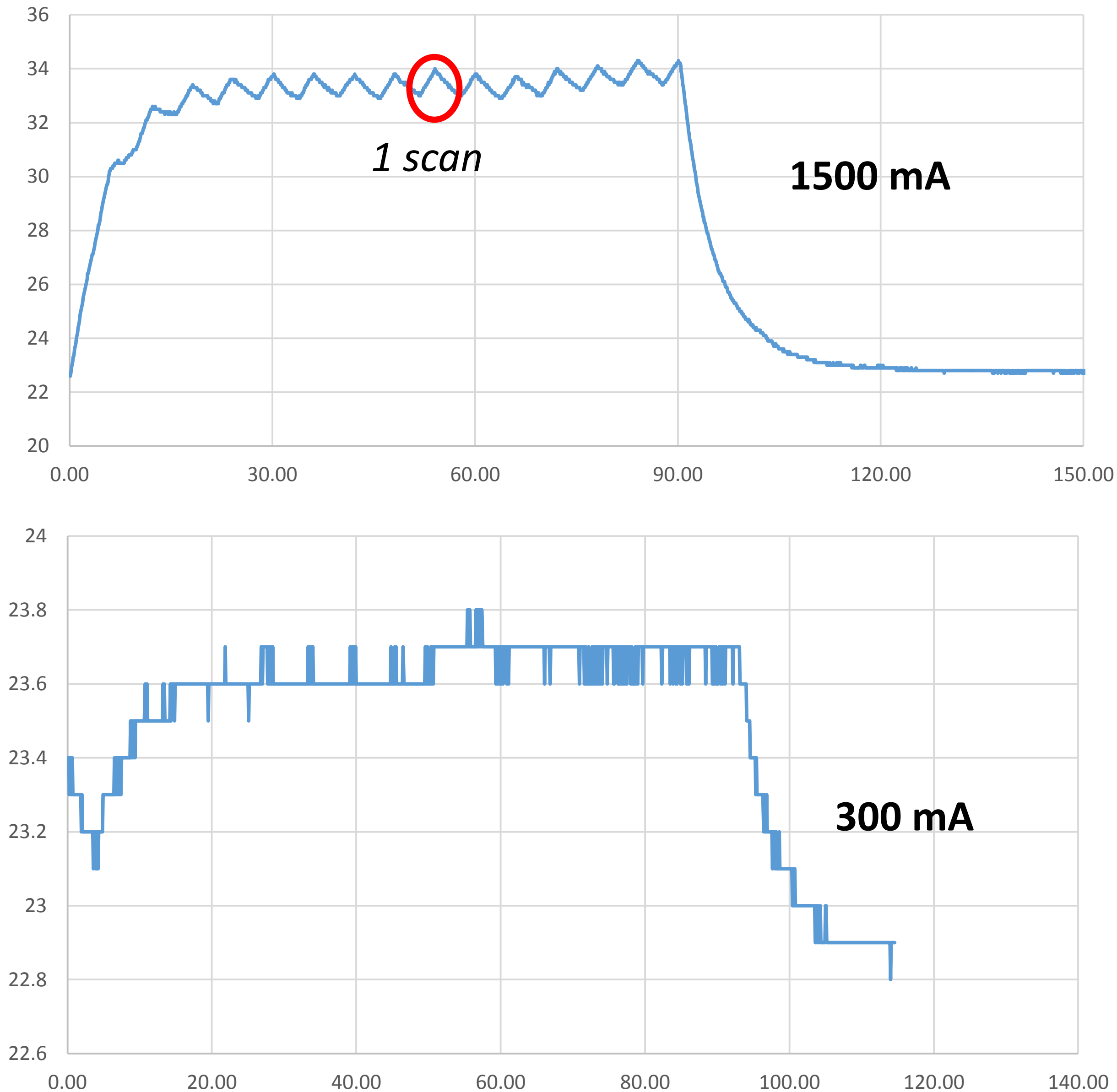


Temperatures versus time



Laser Scanning Stave QA (cont'd)

Stage motor temperature versus time during stage operation (w/ fan)



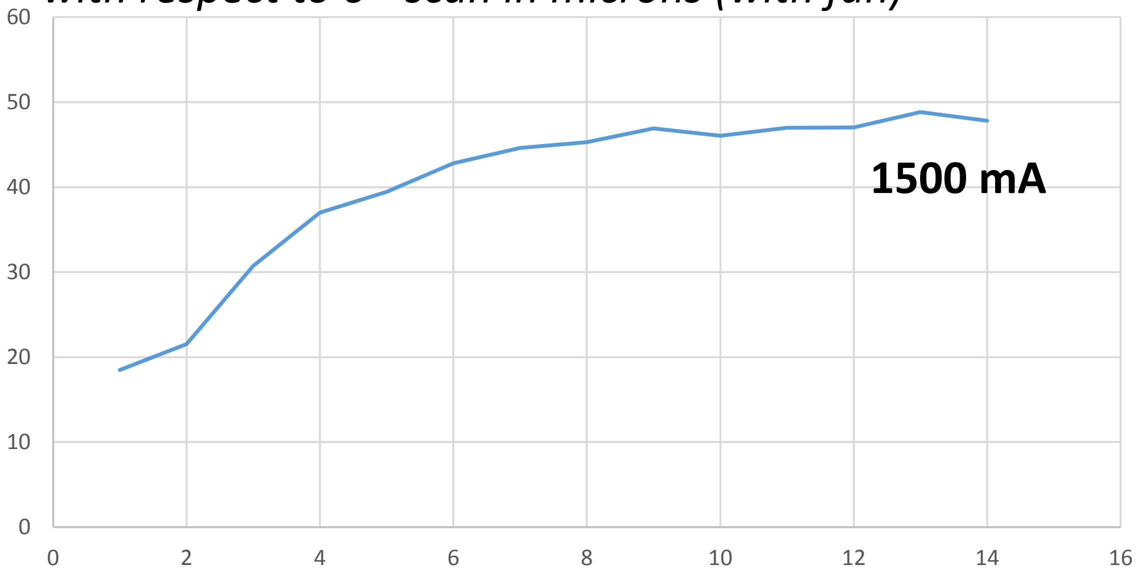
Limiting the current to the stage motor also helps.

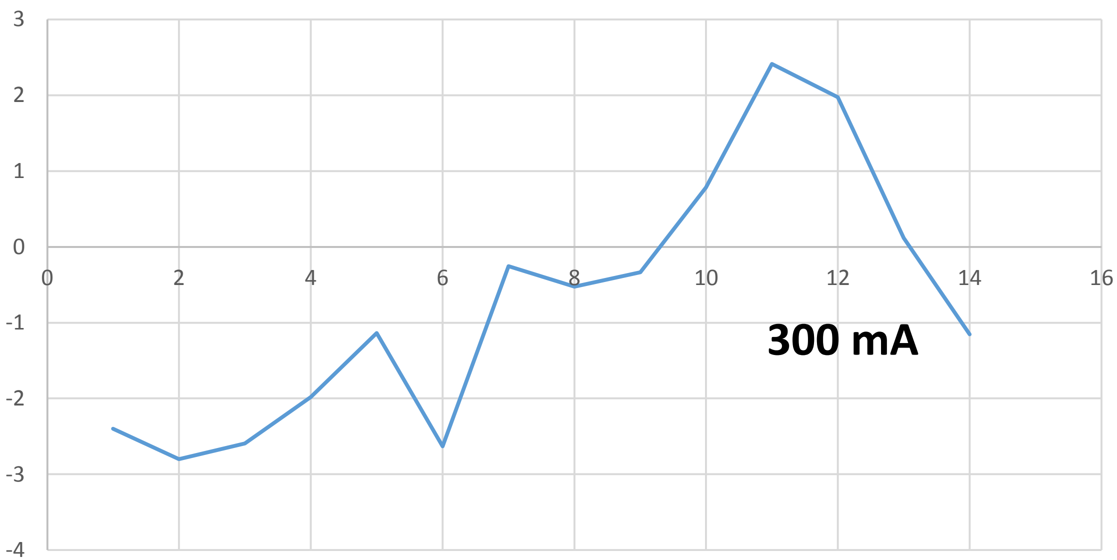
At 1500 mA (default) the max temperature change is +10˚C, at 300 mA it is +1˚C

In both cases, the scan speed of the stave was 1 mm/s.

Laser Scanning Stave QA (cont'd)

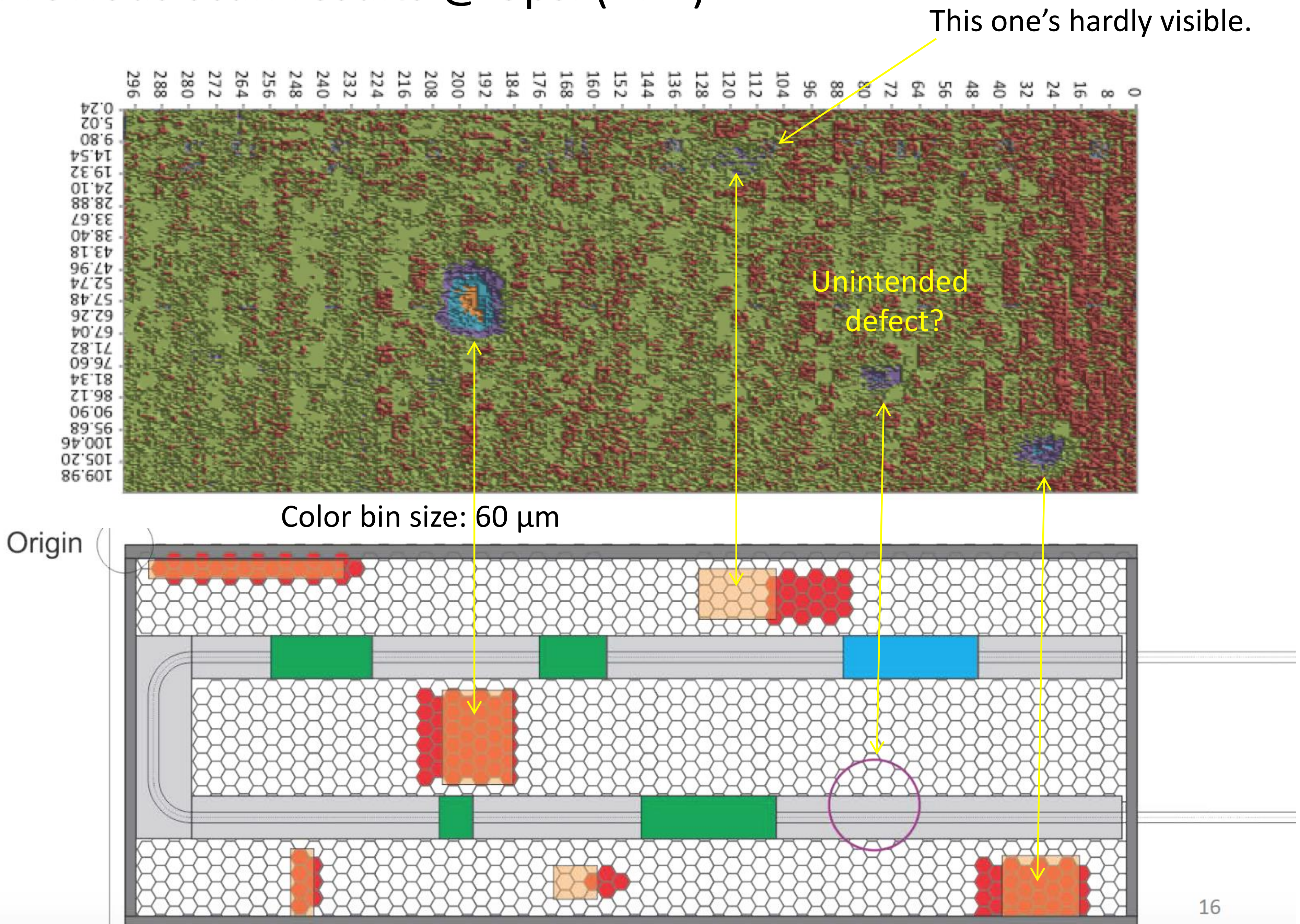
Stave surface height average residual with respect to 0^th^ scan in microns (with fan)





- At 1500 mA, the average height of the stave surface increased up to ~50μm
- At 300 mA, it's not clear if there's still a significant increase in height
- Any small remaining height difference (few microns) can be subtracted in software

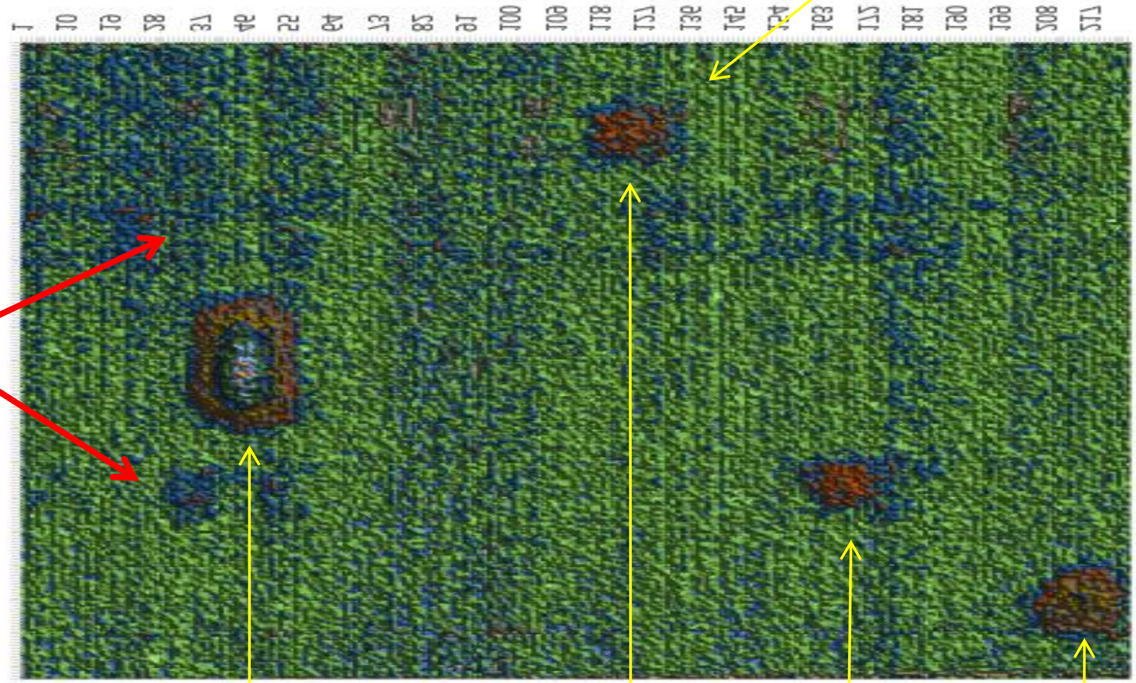
Previous scan results @ 3psi (BNL)



New scan results @ 3 psi

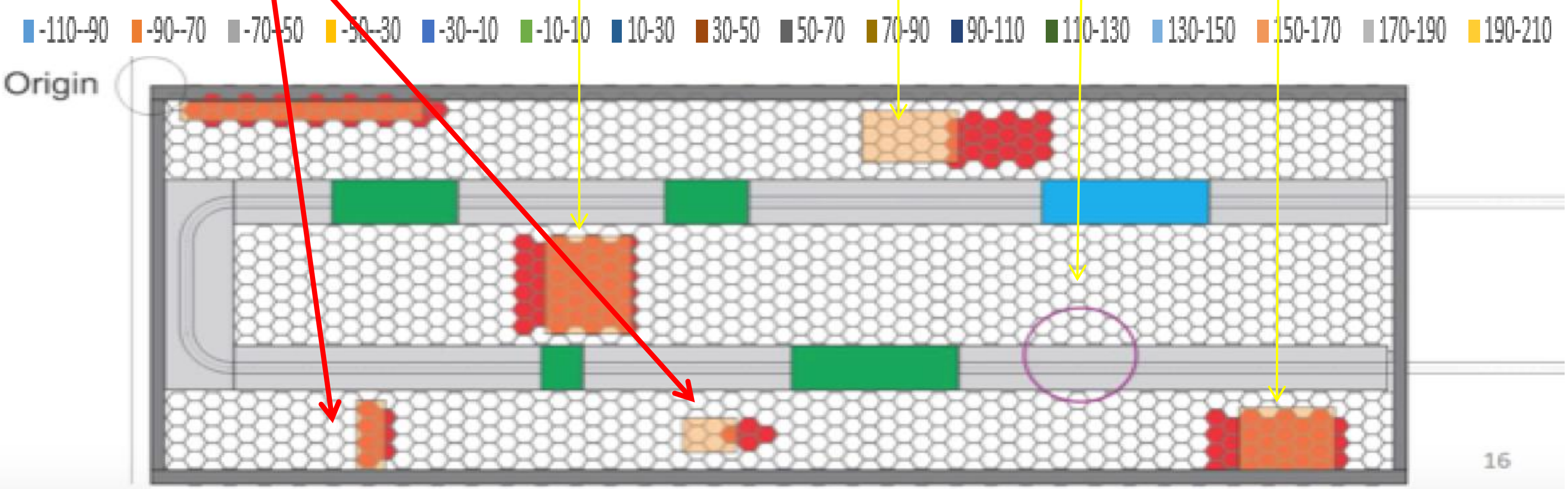
Now clearly visible.

Color bin size: 20µm

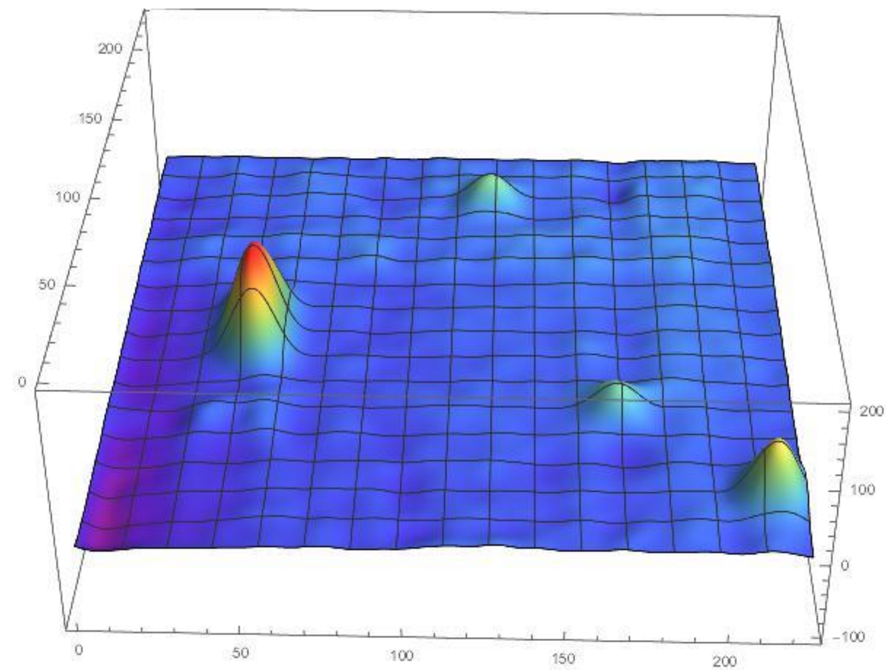


Some additional structures are visible.

Small defects not visible, yet.



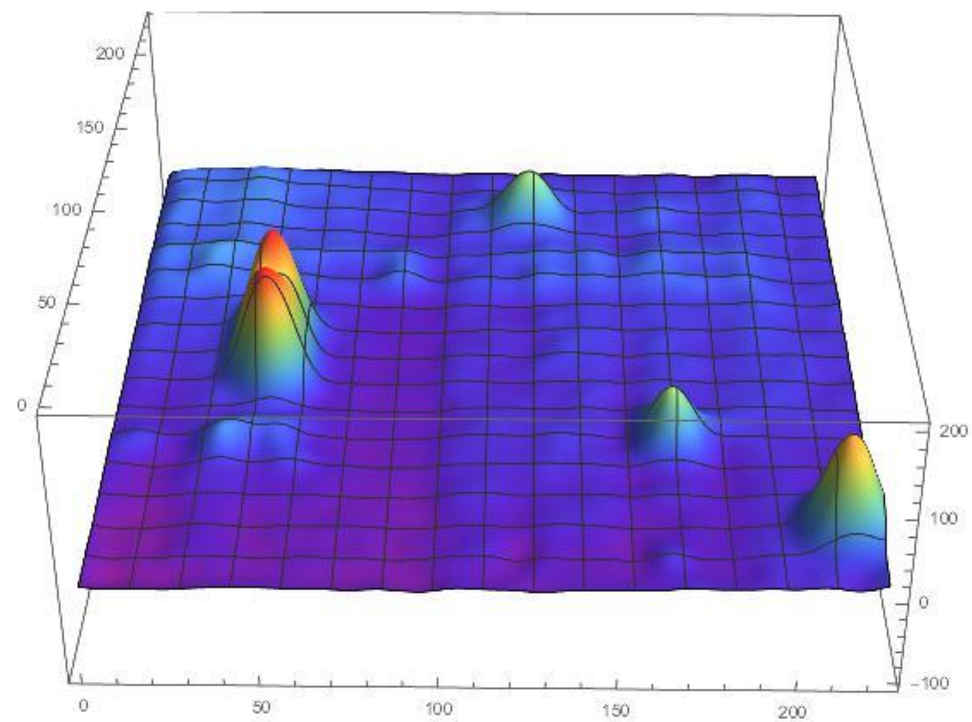
New scan results @ 3 psi



Smoothed 3-dimensional plot with low-pass filter (hides isolated pixels with large amplitude)

Defect better visible at higher pressure, need to quantify sensitivity vs pressure

New scan results @ 5 psi

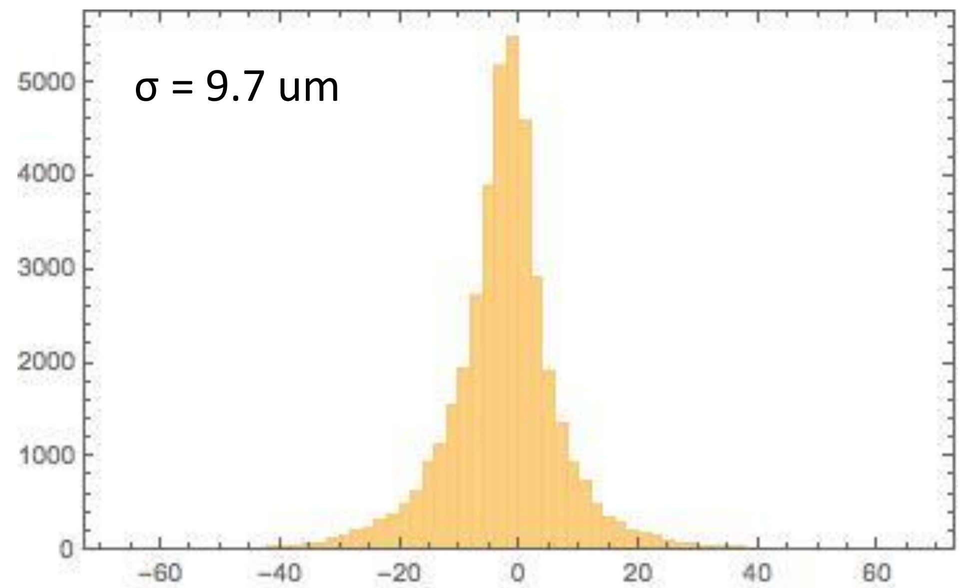


Laser Scanning Stave QA
(cont'd)

- Resolution measurements
  - Pixel RMS of stave height difference between two scans with no pressure is < 10 µm for short stave (~25cm)
    - This excludes the highly reflective part of bus tape where camera intensity amplitude becomes saturated
  - Note, defects of a ~2 cm diameter area have a height of ~200 µm and are clearly visible at 3 psi

- Potential improvements
  - Remove fan and power supply from table to reduce vibrations
  - Correct for small number of isolated pixels with large residuals

Height difference per pixel between two scans with no pressure applied



Laser Scanning Stave QA

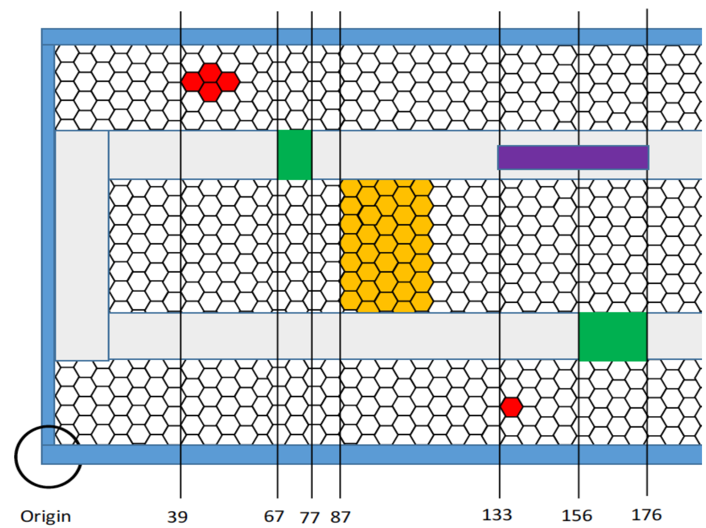
(cont'd)

- Improved set-up
  - Move laser-camera system instead of stave with linear stage
    - Heavier aluminum support structure may require increase in max. stage current and dissipated power
  - Move set-up from 'regular table' to optical table
    - Less vibrations, easier alignment, and larger heat sink for stage motor
- Nest step: full-size stave scan
  - Seal close-out of full-size stave with defects from Yale (1.3m)
  - Determine sensitivity of method with full-size stave

camera holder

laser holder

stage mount

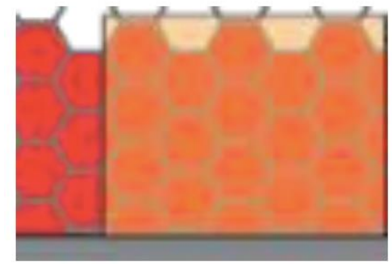


Laser Scanning Stave QA
(cont'd)

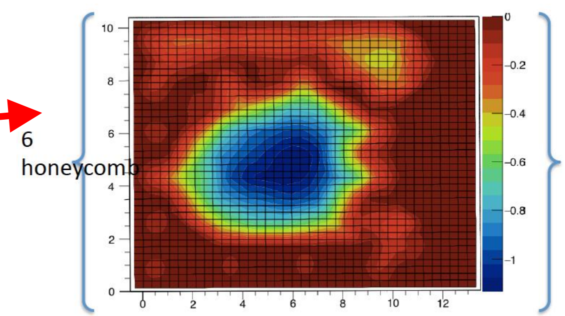
- More "To do"
  - Software improvements
    - Develop separate improved center-of-line finding algorithms (saturated amplitude or not)
    - Develop automated defect recognition
  - Defect characterization
    - Depending on the resolution it might be possible to identify defect types based on defect shape

Early defect scan from BNL (resolution is about 2x better now)

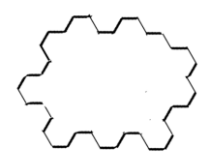
Integrated defect



Best simulated defect



Best simulated defect shape



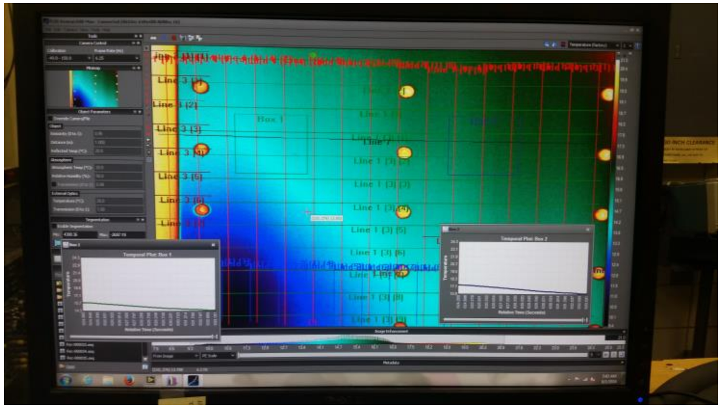
From here to production…

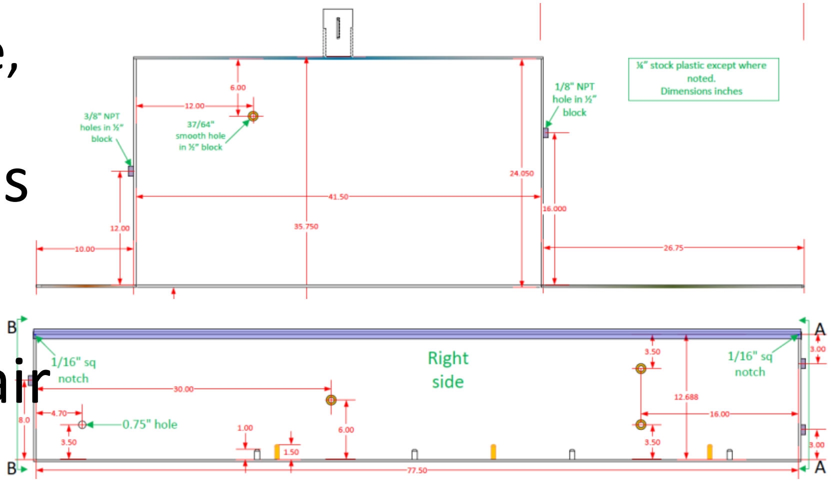
- until Sep ‘17
  - Test and characterize several full-size stave cores, document results
  - Converge on final test set-up
- Oct ‘17 – Mar 18
  - Design, build and commission final full-size testing station at ISU
- Apr ‘18 – Sep ’18
  - Pre-production testing at ISU, document results
- Oct ‘18 – Jul ‘19
  - Design, build and commission final full-size testing station at Yale
  - Continue pre-production testing

Back-up slides

Thermal Imaging Stave QA

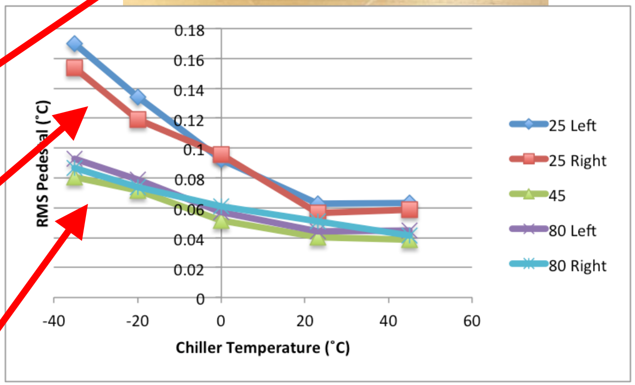
- FLIR A655sc thermal camera chosen as optimal match to QA
- Original idea: camera with a default 25° angle lens scans along full stave length
  - At the minimum distance from the stave (30 cm), the short side of the field-of-view (FOV) matches the stave width)
- However: with an 80° angle lens we can image a full-size stave from a single camera position (at 90 cm distance from stave)
  - Allows for much simpler QA procedure, important for stave mass production
- Tested 80° and 45° wide-angle lenses that we borrowed from FLIR for a week
- We have built an enclosure for dry-air environment for the full-size stave





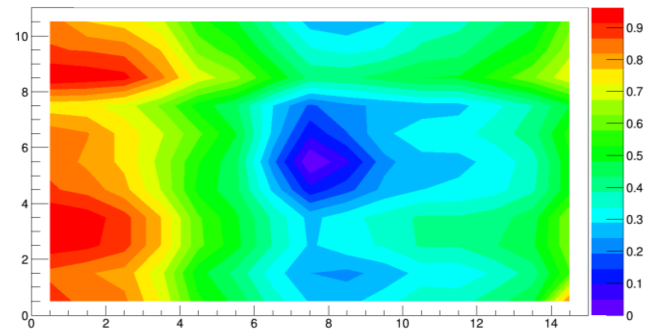
Thermal Imaging Stave QA (cont'd)

- Made thermal noise measurements at several temperatures with all 3 lenses (all at 30 cm camera distance from object)
  - Measured by scanning FOV over a uniform-T surface (cooled Al plate made by Duke U)



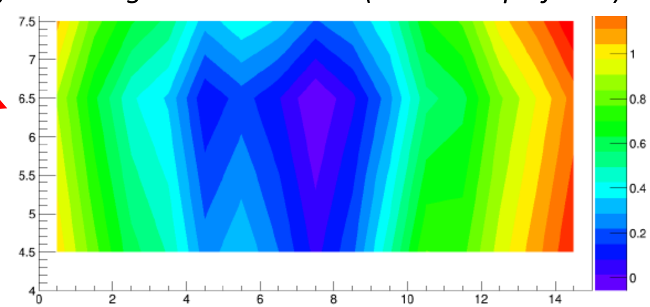
- Total thermal noise of ~ 0.15° C at −35°C object temperature with 25° angle lens
  - Dominated by pixel-to-pixel variations, probably due non-uniformities of the plate surface; explains why the wide-angles lenses have a smaller noise of about 0.08° C

ΔT for 25° angle lens at − 35° C (full FOV)



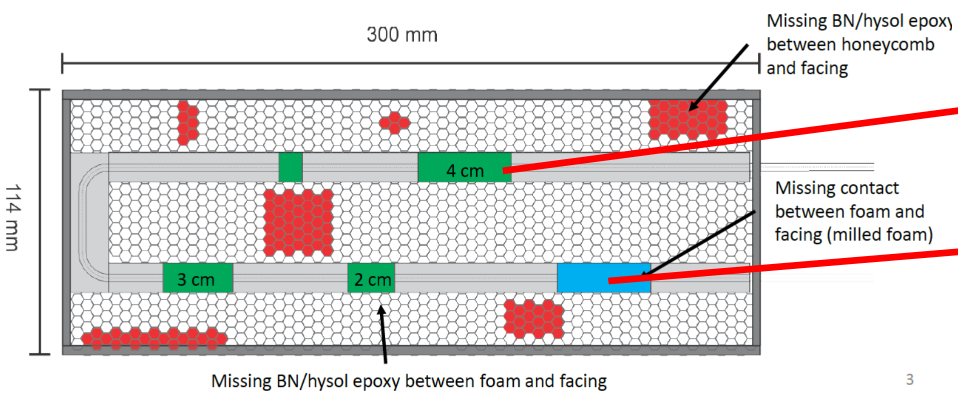
- Maximum vignetting* of only ~ 1.0° C even for the 80° lens (could be reduced by calibration)

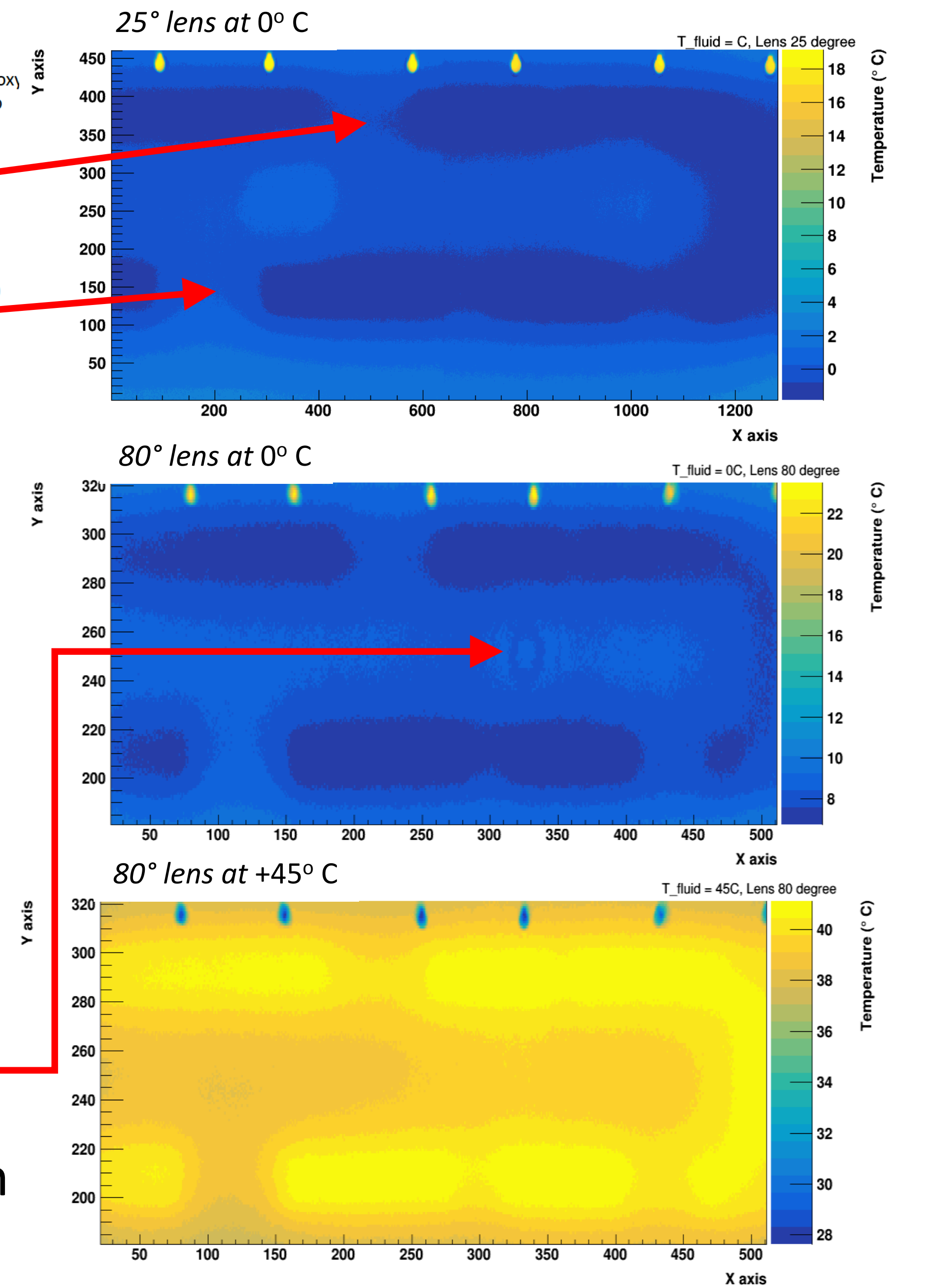
ΔT for 80° angle lens at − 35° C (center strip of FOV)



** Vignetting: Bias ΔT in the measured T depending on the location in the FOV. Typically concentric around the center of the FOV.*

Thermal Imaging Stave QA (cont'd)

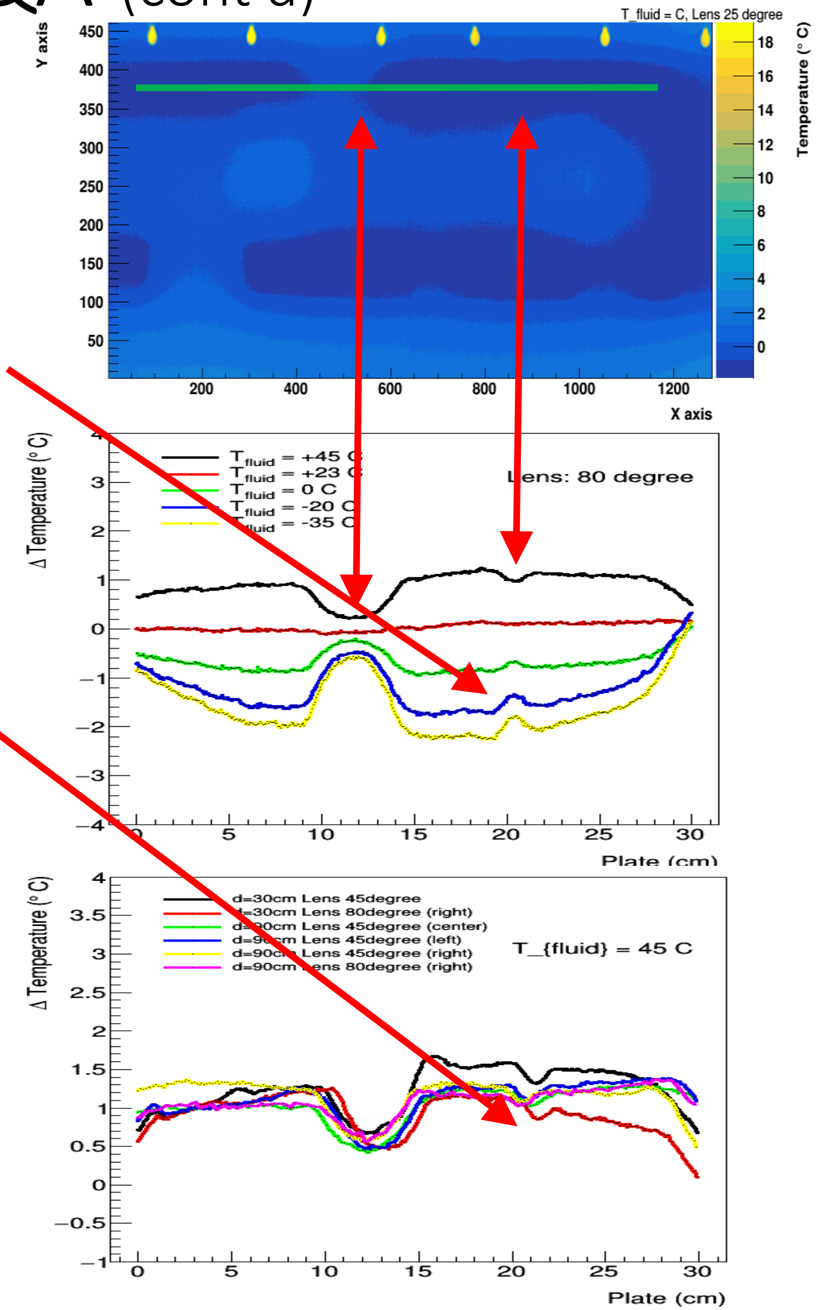




- Studies with mini-stave with implemented defects
  - Image delaminations between foam and facing (green & blue areas) (Note: horizontal axis flipped in thermal images wrt to stave pic)
  - Delamination defects are clearly visible already at 0 °C (also at + 45 °C) with all lenses
  - Reflection of camera on stave surface ("Narcissus effect") seen at 0.3 m; not noticeable at 90 cm

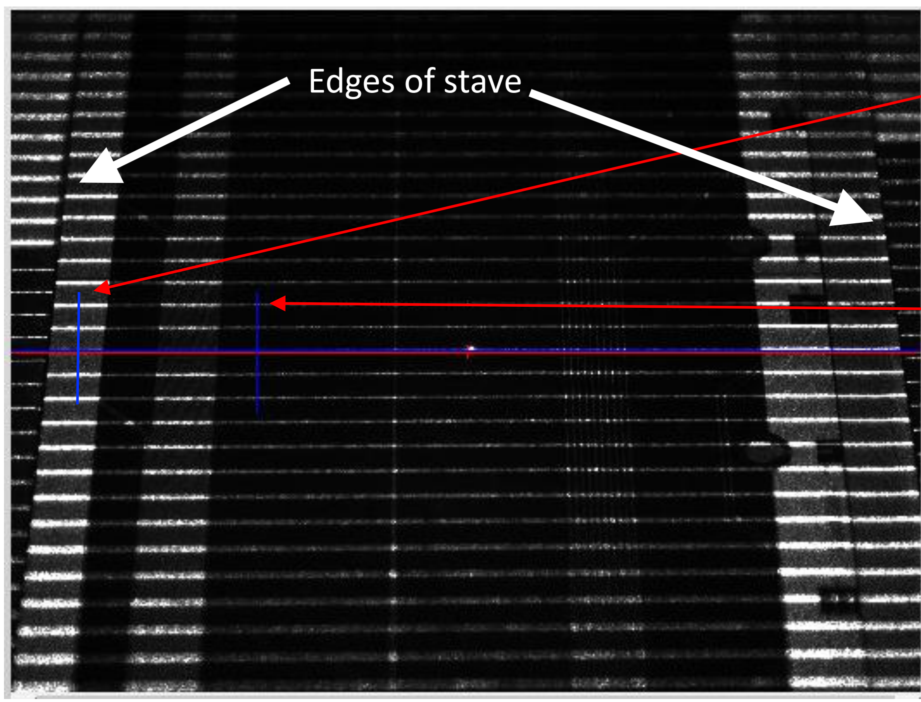
Thermal Imaging Stave QA (cont'd)

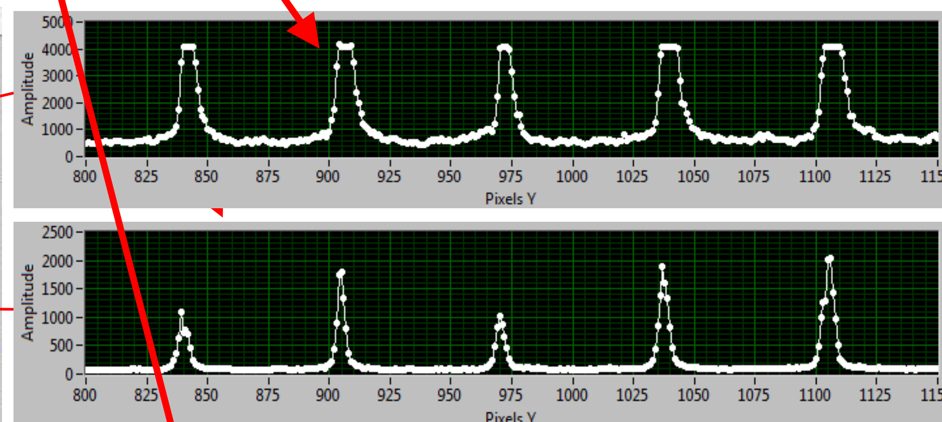
- Sensitivity tests: look at T along center of foam area (green line)
  - Smallest defect (1 cm) is clearly visible at -35 °C and + 45 °C with 80° lens (also with other lenses)
  - No significant degradation between 0.3 m and 0.9 m camera-object distance (black line, center fig vs red and pink lines, bottom fig)
- Next steps
  - Finish enclosure to thermally image full-size stave at −35 °C and below (compatible with 25° and 80° lenses)
  - Measure first full-size stave (with defects) from Yale
  - Converge on optimal set-up
  - Develop automated defect finding software



Laser Scanning Stave QA (cont'd)

- Laser array
  - Currently we use only the five center lines of the laser array
  - Amplitude for laser lines can reach maximum value (varying reflectivity); current code to determine line center is not optimized for different amplitude shapes
- Height-to-pixel scale factor calculation
  - Determined one scale factor per line from displacement at edge of stave
  - Measured scale factors (μm/pixel) agree well with geometric calculation for all five lines





	further	further-center	center	closer-center	closer
average	74.1430	72.3061	69.3639	67.7210	65.3019
calculate	73.5986	71.5211	69.5216	67.5964	65.7420