Multipoint PDV Coupled with Post-Shot Recovery MicroCT for Investigating Orientation Effects on Spall Strength in High Strength Steel

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Motivation and Objective

Motivation:

- Impact-induced *spall* failure is time-dependent occurring via nucleation, growth, and coalescence of voids/cracks.

- Dynamic tensile *spall strength* is **not** a material-inherent property; it is influenced by microstructure and loading conditions.

- *Do local variations in microstructure of a material affect spall strength/failure?*

Objective: Investigate **spall failure** characteristics in **AF9628 steel** bar as a function of local microstructural variations using high-throughput multi-sample target & multi-probe PDV interferometry

AF9628 Steel* Half-round Bar

Composition (wt%): 0.24-0.32C, 2-3Cr, 0.5-1.5Mo, 0.05-.35V, <1Mn, <3Ni, <1.25Si, 0.15Cu, .02max P, S,Ca, 0.15max Ni, 0.025max Al (***W-free***)

Alloy Processing: Argon-oxygen decarburization, vacuum-arc-remelting, forging to 108 mm dia.
Heat Treatment: Normalize at 1010°C for 1 hr
Intercritical Anneal at 677°C for 4 hrs and air cool
Austenize at 1010°C for 1 hr and water quench
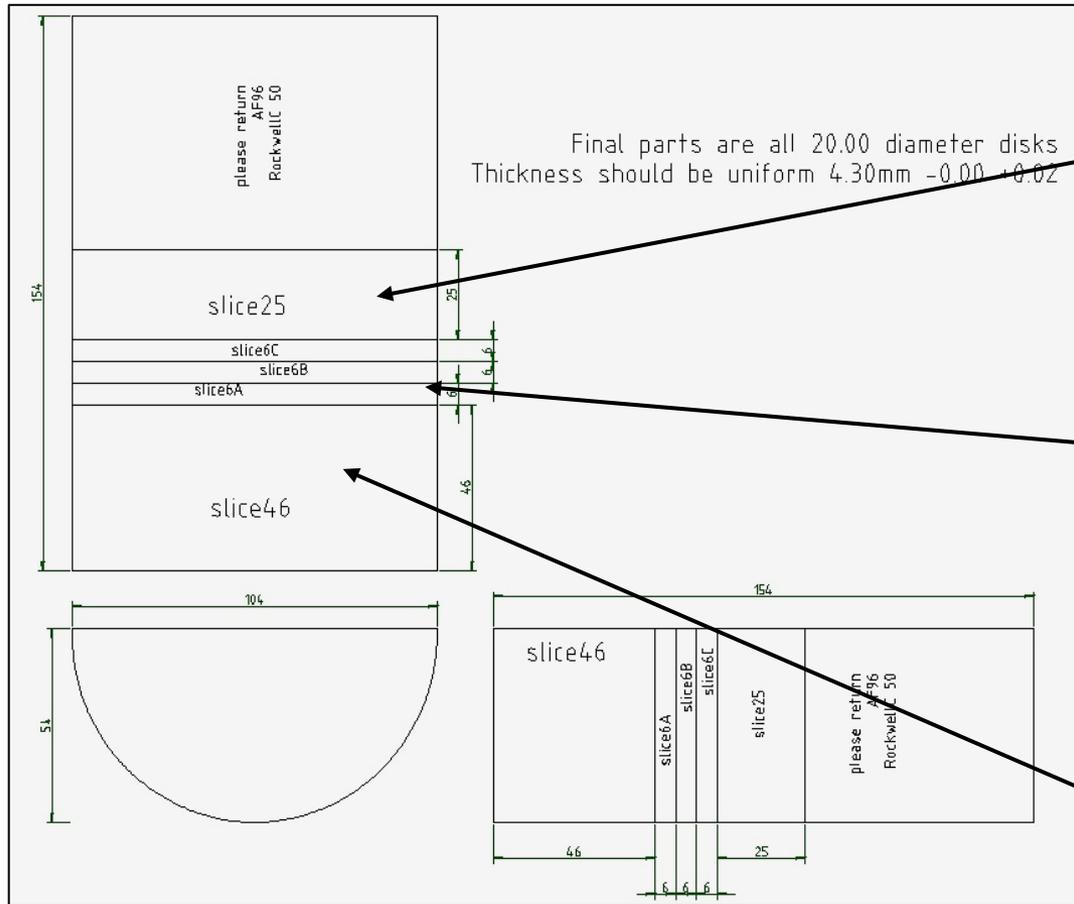Temper at 204°C for 4 hrs and air cool.

Microstructure: BCT α'-martensite with high disl density, high energy lath boundaries, Carbon interstitials, and trace retained austenite

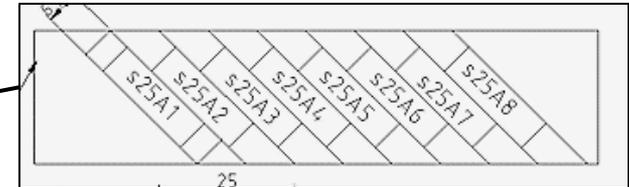**Samples**: 20-mm dia x 4.3-mm thick discs cut from radial, axial, inclined sections for spall experiments
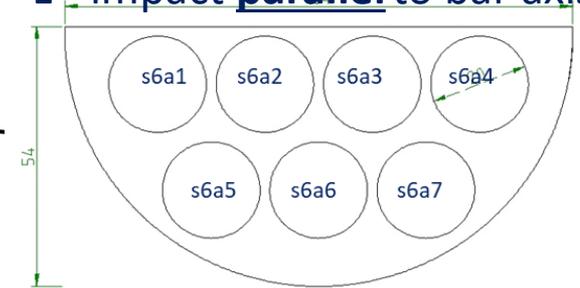
R. Abrahams, U.S. Patent No. 20160369362A1, 2016

Radius: 54 mm

Diameter: 108 mm

Length: 154 mm
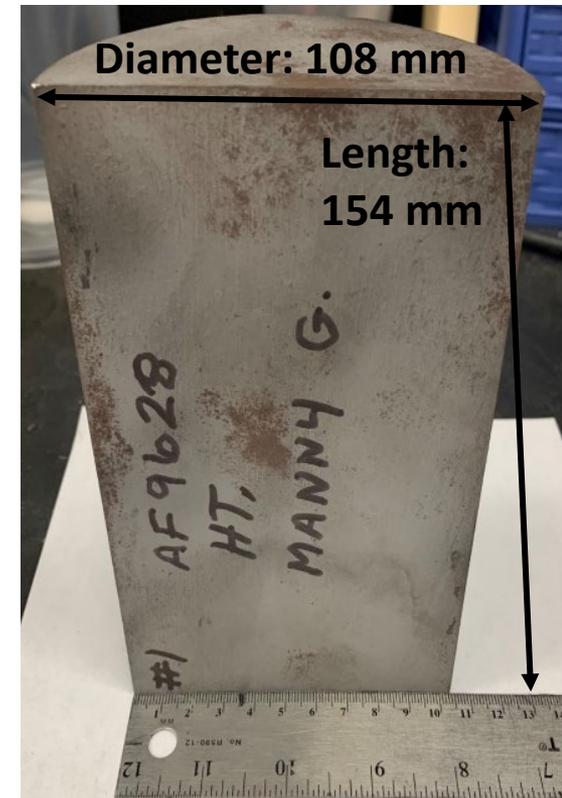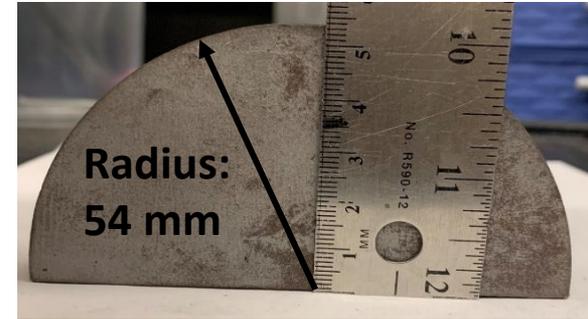
Sample Tracking from Half-round Bar with x, y, z Orientations

y - impact **45º** to bar axis

s25A1 s25A2 s25A3 s25A4 s25A5 s25A6 s25A7 s25A8

25

z - impact **parallel** to bar axis

s6a1 s6a2 s6a3 s6a4
s6a5 s6a6 s6a7

54

x – impact **normal** to bar axis

s46a1 s46a2 s46a3 s46a4
s46a5 s46a6 s46a7 s46a8

please return AF96 Rockwell C 50

Final parts are all 20.00 diameter disks
Thickness should be uniform 4.30mm –0.00 +0.02

slice25

slice6C
slice6B
slice6A

slice46

154

104

51

slice46 slice6A slice6B slice6C slice25 please return AF96 Rockwell C 50
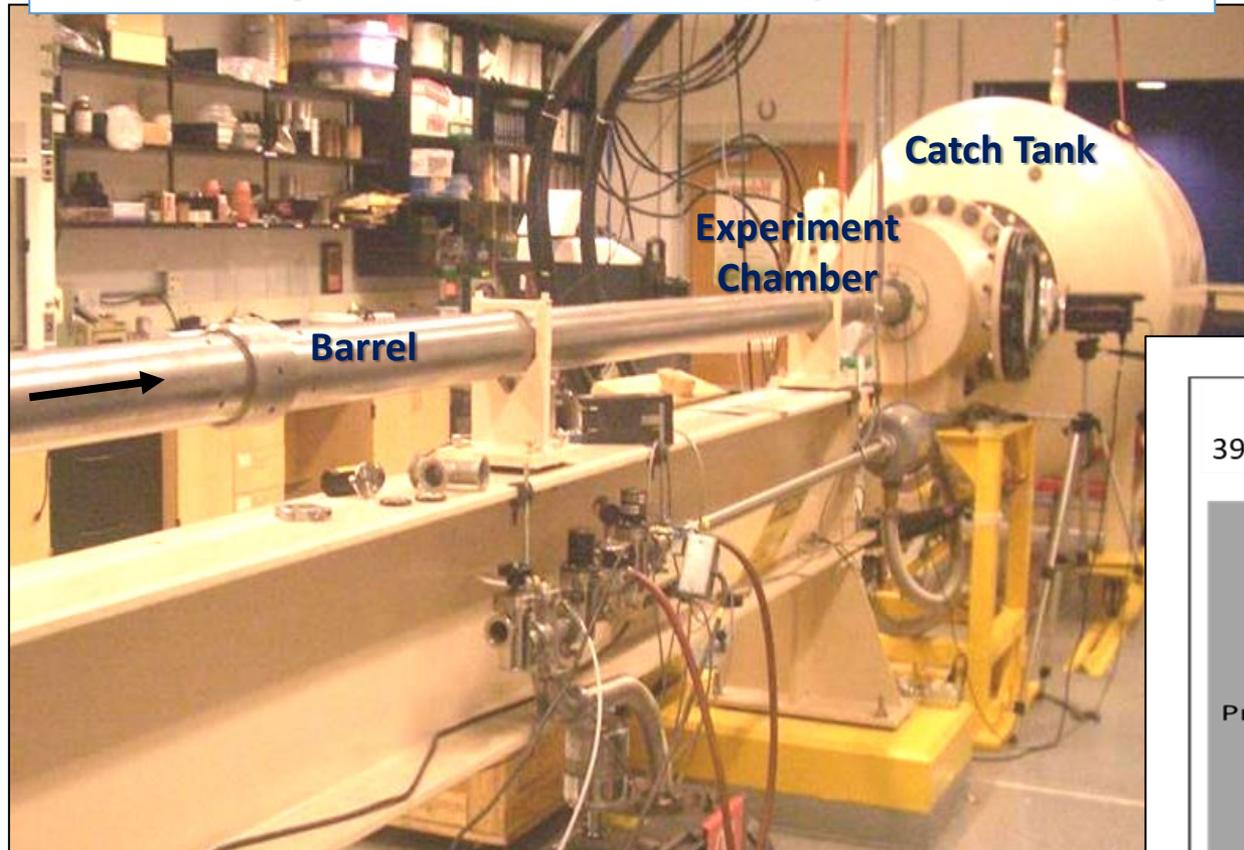
154

46   25
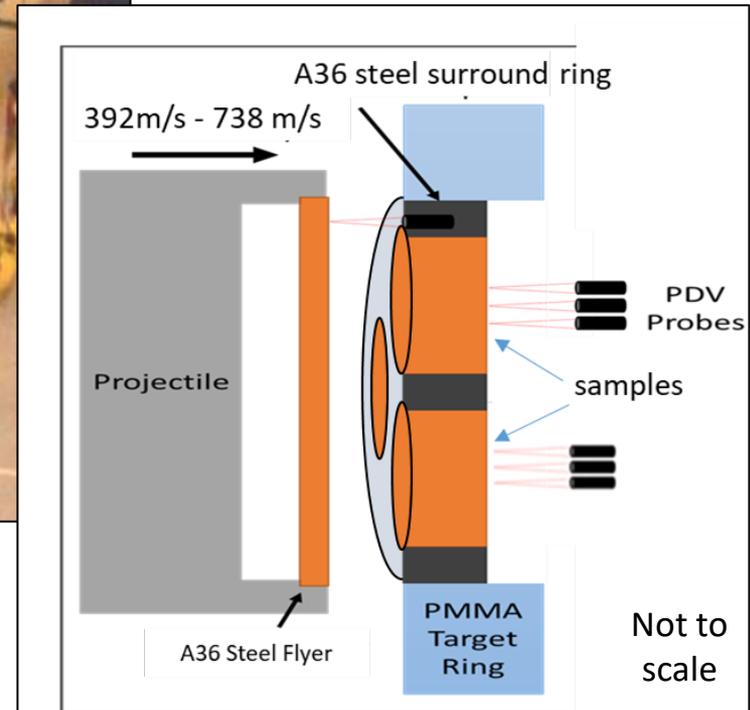
6 6 6

154

25

46
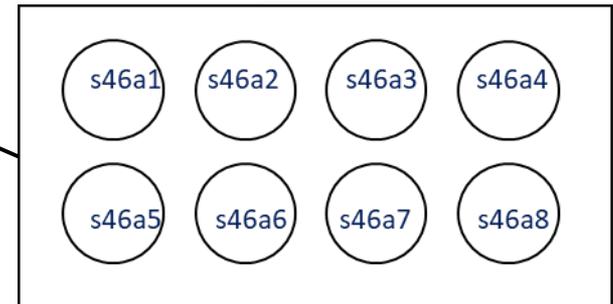
Sample and Impact Orientation:
y – Inclined (45º) sections cut from Slice 25 block – impact **45º** to bar axis
z – Radial flat-surface half-section slices – impact **parallel** to half-bar axis
x – Vertical Slice 46 cut parallel to bar axis – impact **normal** to bar axis

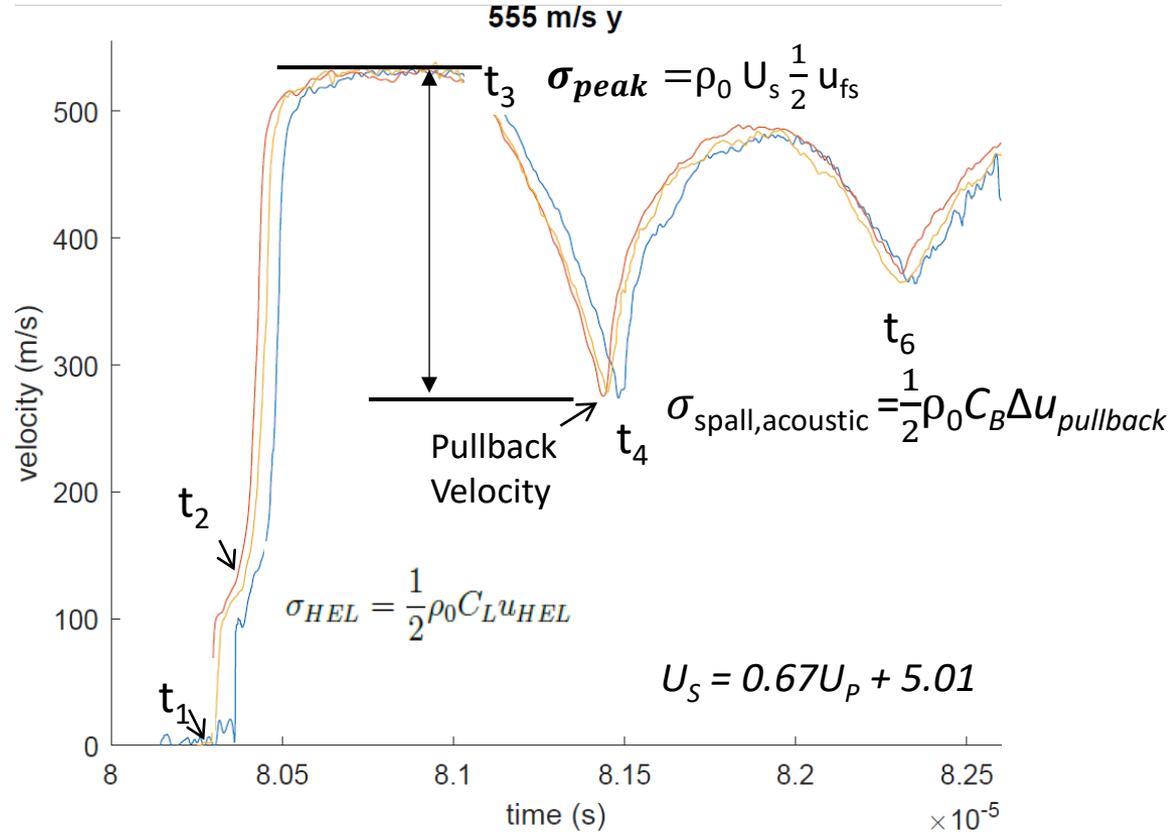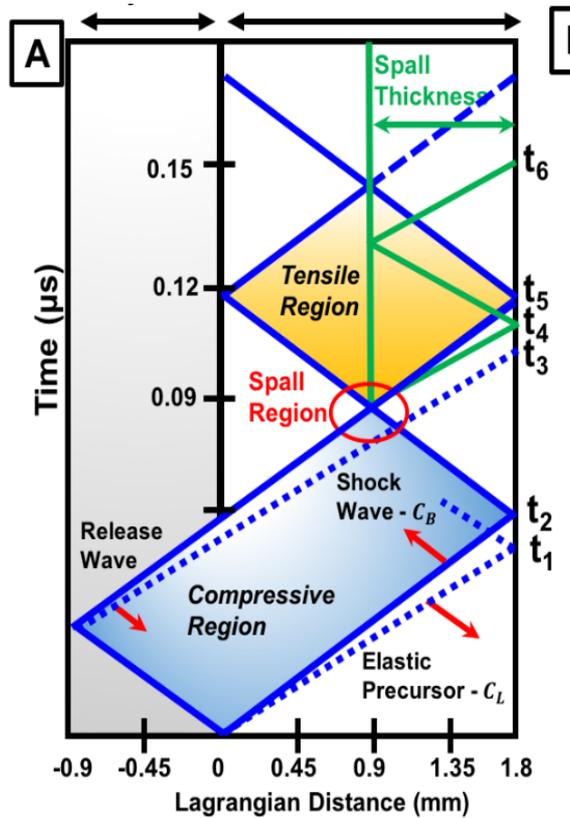# Gas-Gun Plate-on-Plate Impact Spall Experiments

80-mm keyed-barrel He-Gas Gun (70 to 1200 m/s)

High-throughput three-sample target fixture with each sample backed by 1 conventional PDV and 2 heterodyne frequency upshifted PDV probes


Catch Tank

Experiment Chamber

Barrel

A36 steel surround ring

392m/s - 738 m/s

Projectile

PDV Probes

samples

A36 Steel Flyer

PMMA Target Ring

Not to scale

Measurements of Sample Back (Free) Surface Velocity

$$\sigma_{peak} = \rho_0 \, U_s \, \frac{1}{2} \, u_{fs}$$

$$\sigma_{spall,acoustic} = \frac{1}{2}\rho_0 C_B \Delta u_{pullback}$$

$$\sigma_{HEL} = \frac{1}{2}\rho_0 C_L u_{HEL}$$

$$U_S = 0.67 U_P + 5.01$$

555 m/s y

Pullback Velocity

Cross section showing incipient spall failure

MicroCT of midlayer showing spall zone in soft-recovered impacted sample
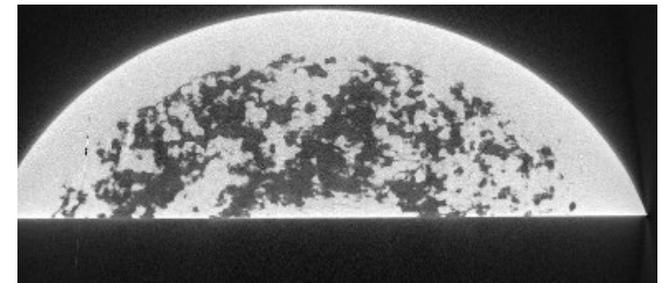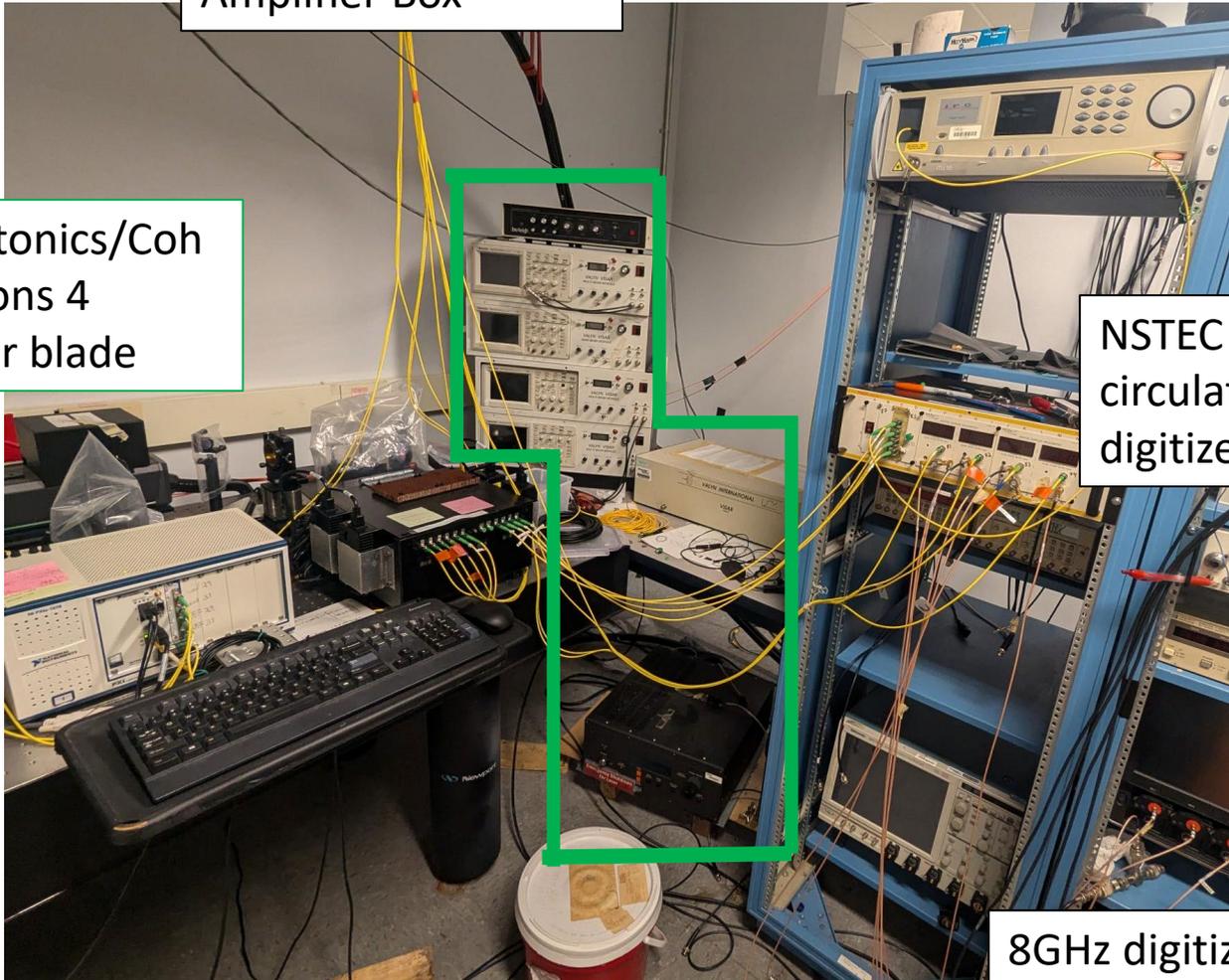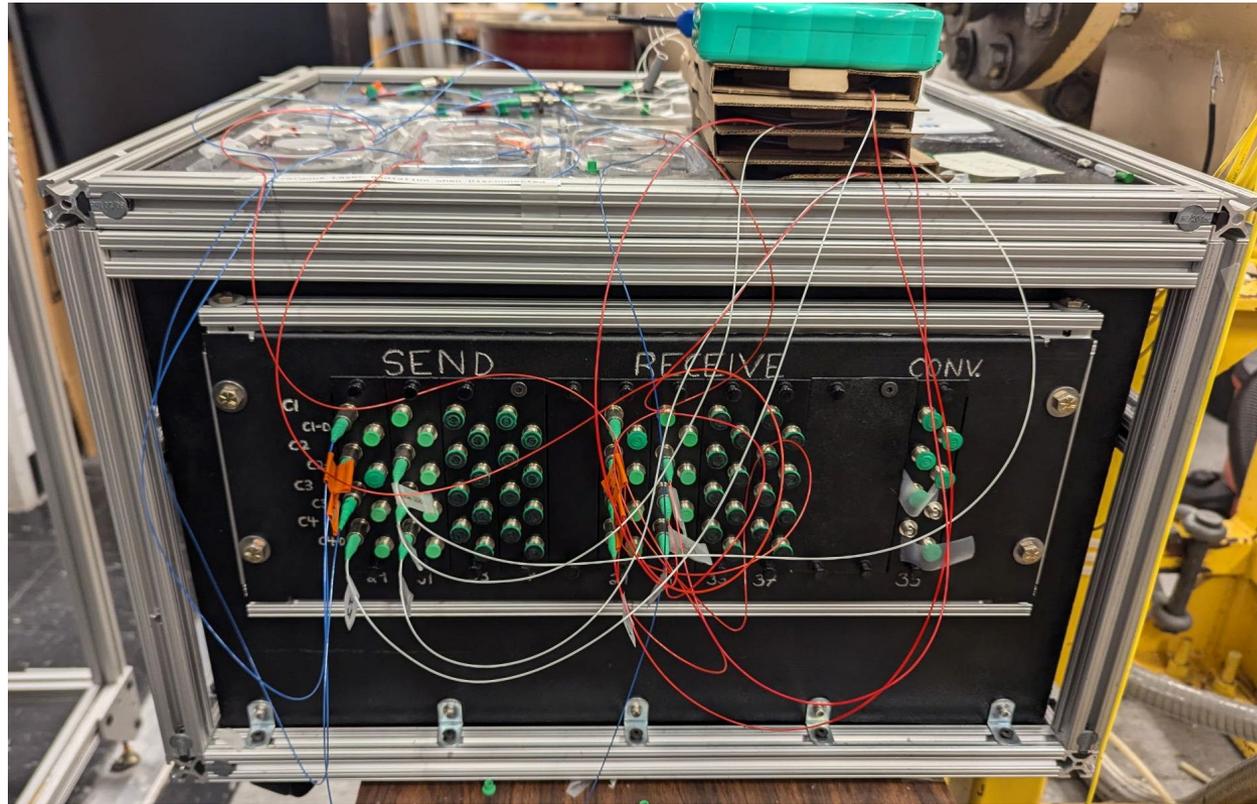
Custom Demux and Amplifier Box

2W IPG laser

QuantifiPhotonics/Coherent Solutions 4 channel laser blade

NSTEC box with circulators and optical digitizers

8GHz digitizer

VALYN VISAR and 1 W 532CW Laser

- Custom box built with Travis Voorhees containing connections for using ITU29 and ITU 31 in addition to the conventional ITU33 band simultaneously
- Conventional, and two different upshifted frequencies on each of the 4 Channels to digitizer through the original NSTEC box
- Each channel has a option for adding in a ~5Km delay leg for time multiplexing
- A 2 to 1 coupler was used to combine the send and receive path into the single collimated PDV probe

Multipoint PDV on Multi-Sample with recovery

Three probes on 3 samples at exact same impact velocity allowing observation of the heterogeneous response of the material
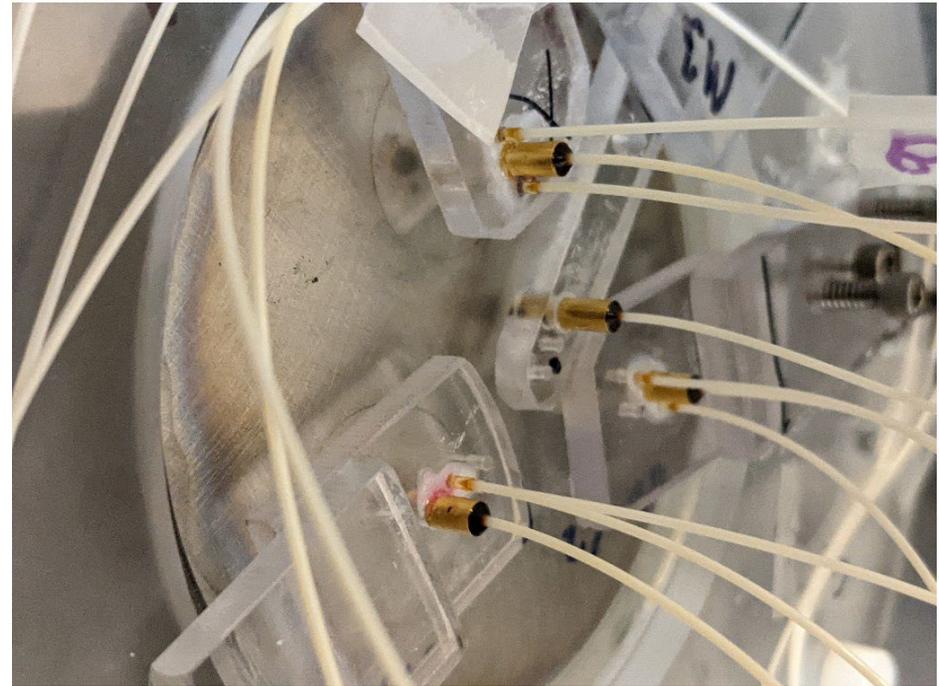
1.2mm collimated probes from AC Photonics 1CL15P020LCH01
3.2mm collimated probes from AC photonics 1CL15P020LCB01

Softer recovery with architectural foam as probe holder

# Measurements using High-Fidelity PDV Analysis

For robust analysis of M-PDV signals, created a semi-automated brute-force code* to calculate **all** reasonable velocity histories using *HiFiPDV,* followed by SIRHEN-2 for precision analysis of spall pullback signal
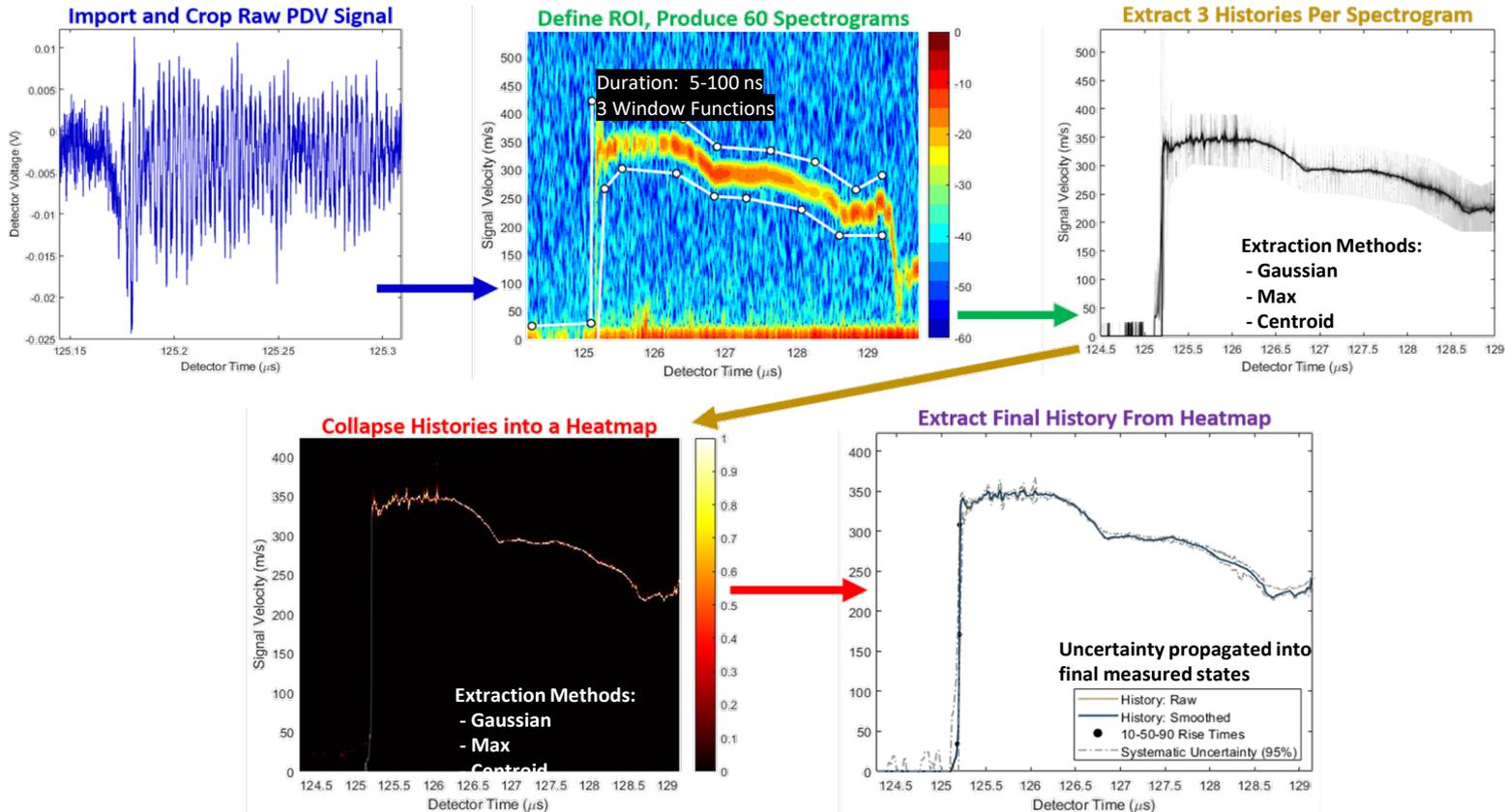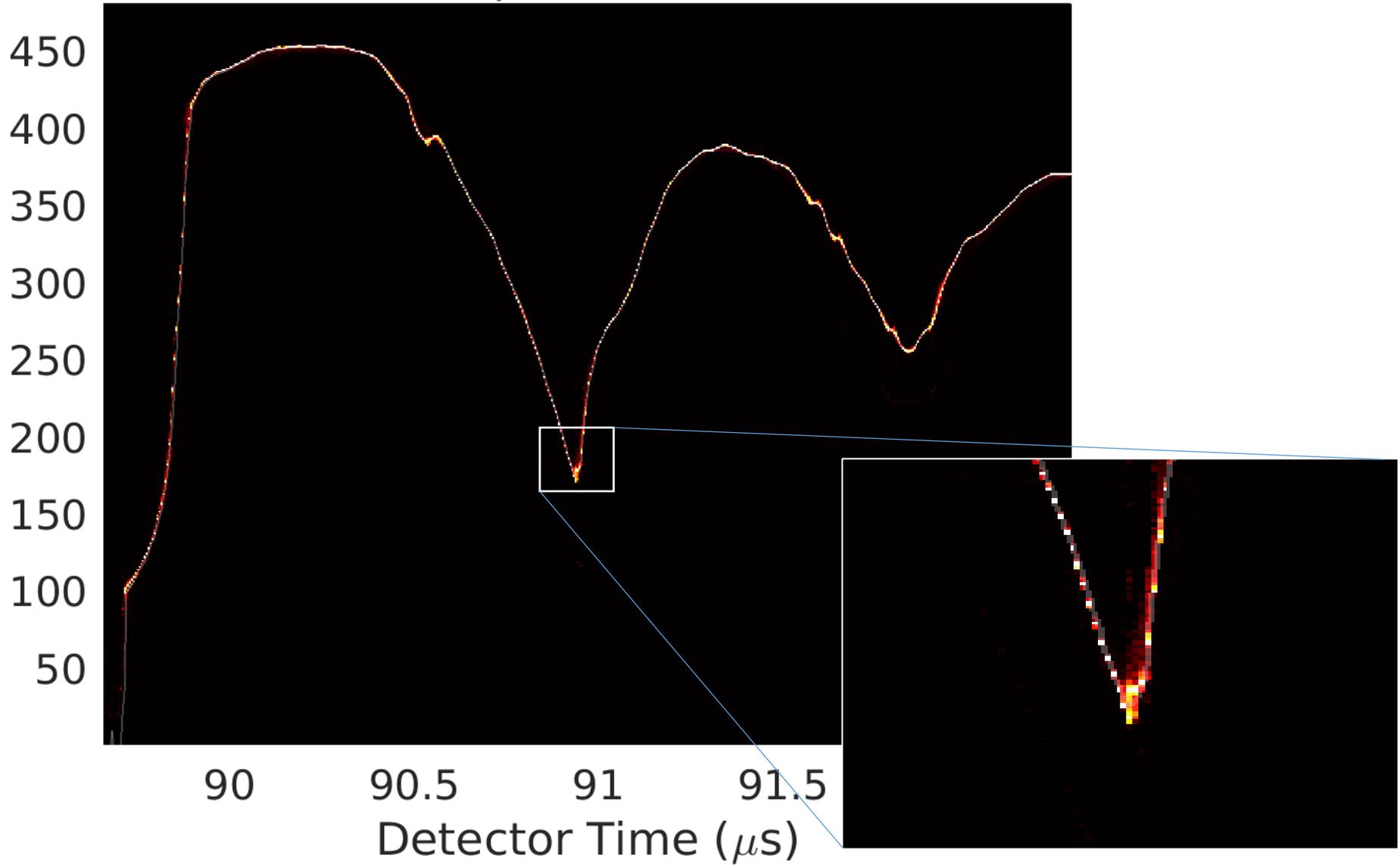

*Travis Voorhees, Ph.D. Dissertation, Georgia Tech, 2020

Cautions for using Application of HiFiPDV for Spall Signature
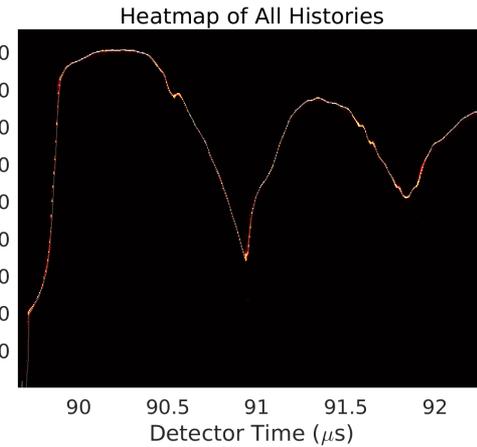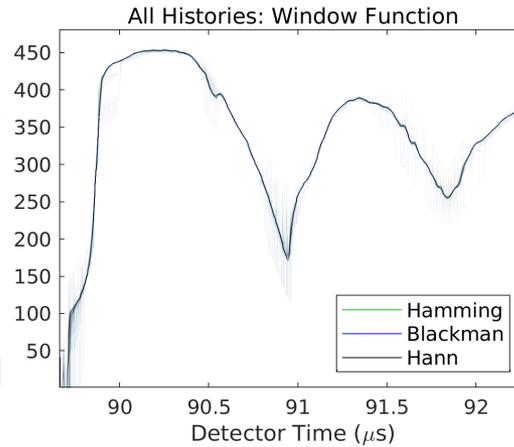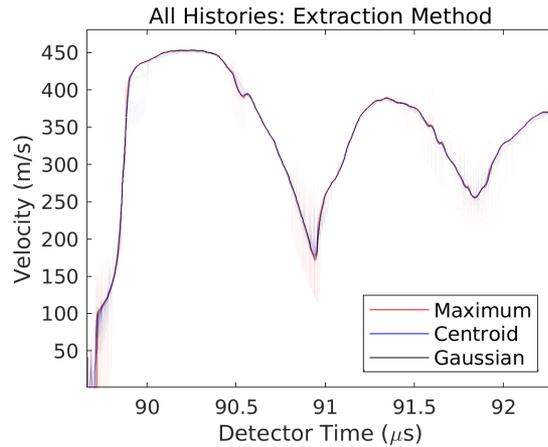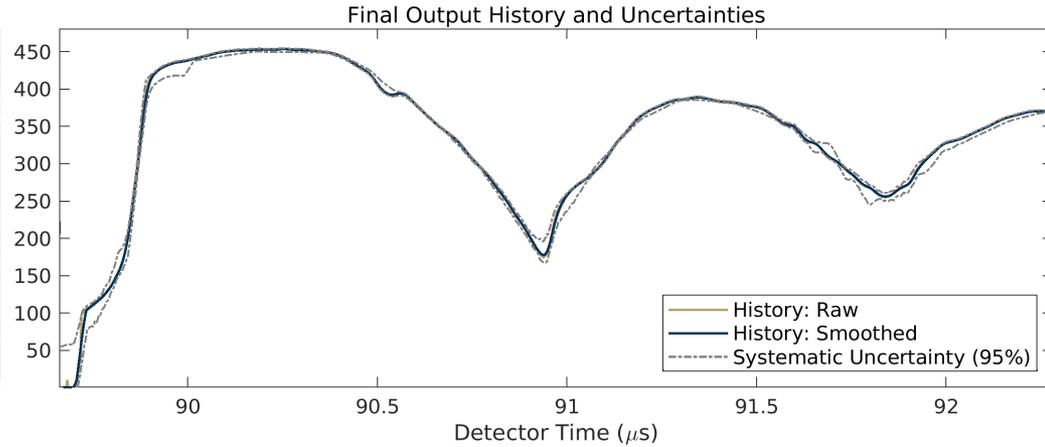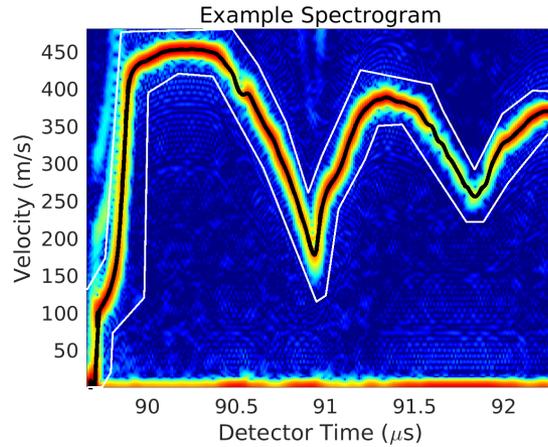
Heatmap of All Histories

Multi-PDV velocity profiles Calculated with Sirhen2

a.

Using the quick output from the earlier HiFiPDV, the window parameters were optimized for sharpest signal in SIRHEN2
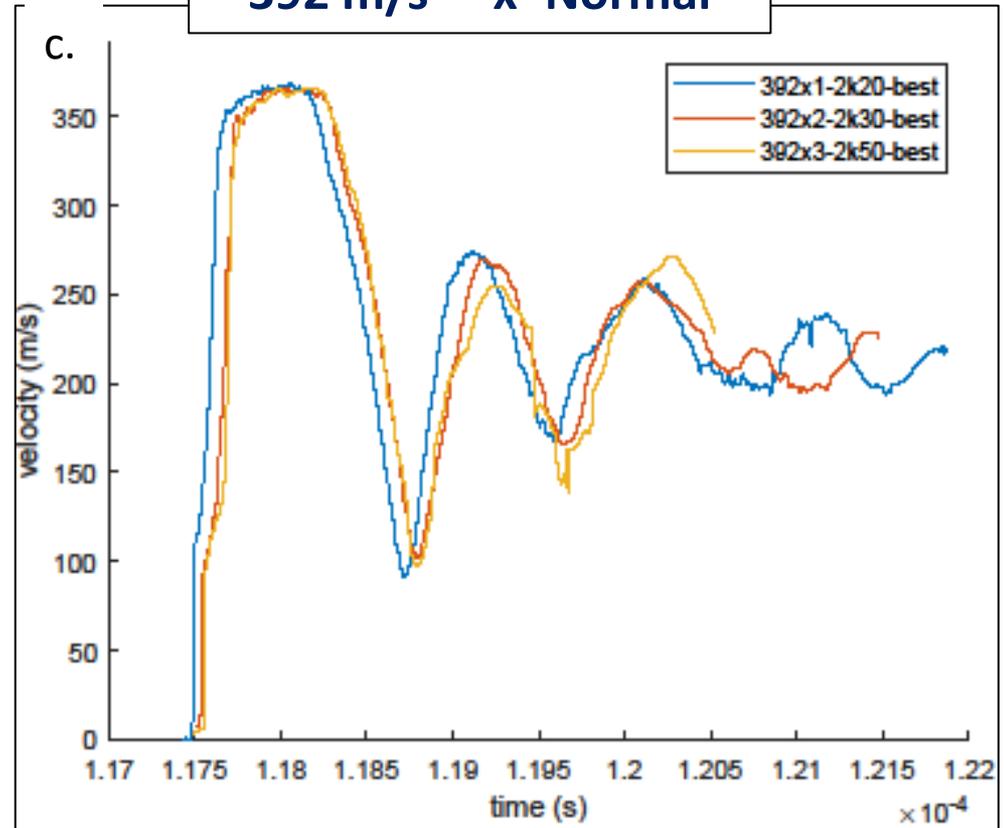
392 m/s – 'x' Normal

c.

Table of Experiments

| Shot No.	Material x-normal y – 45º z – parallel	Sample Thickness (mm)	Velocity (m/s)	Average Peak Velocity (m/s)	Average Spall Strength** (GPa)	Impact Stress (Gpa)
2208	x-s46b3	4.55	392	364.7	4.79±.12	7.27
2302	x-s46b6	4.54	415	385.0	4.78±.06	7.69
2306	x-s46b7	4.56	500	474.5	4.80±.17	9.53
2205	x-s46b2	4.55	555	530.8	4.76±.10	10.70
2208	y-s25a3	4.55	392	365.0	5.18±.03	7.28
2302	y-s25a6	4.54	415	387.0	5.43±.03	7.73
2306	y-s25a5	4.56	500	474.5	4.92±.05	9.53
2205	y-s25a4	4.55	555	531.5	4.57±.04	10.71
2208	z-s6b4	4.55	392	366.0	5.26±.06	7.30
2302	z-s6b6	4.54	415	386.0	5.09±.07	7.71
2201	z-s6a4gt*	5.09	480	455.5	5.22±.12	9.14
2306	z-s6b7	4.56	500	473.0	5.06±.02	9.50
2205	z-s6b1	4.55	555	530.0	4.77	10.68
2107**	z-s6a1gt*	5.09	738	674.0	4.30±.013	13.71

*Slightly thicker targets (early experiments); **Uncertainty in spall strength values is less than variations between measurements; ***Shot 2107 at impact stress above phase transition threshold for A36 Steel flyer*
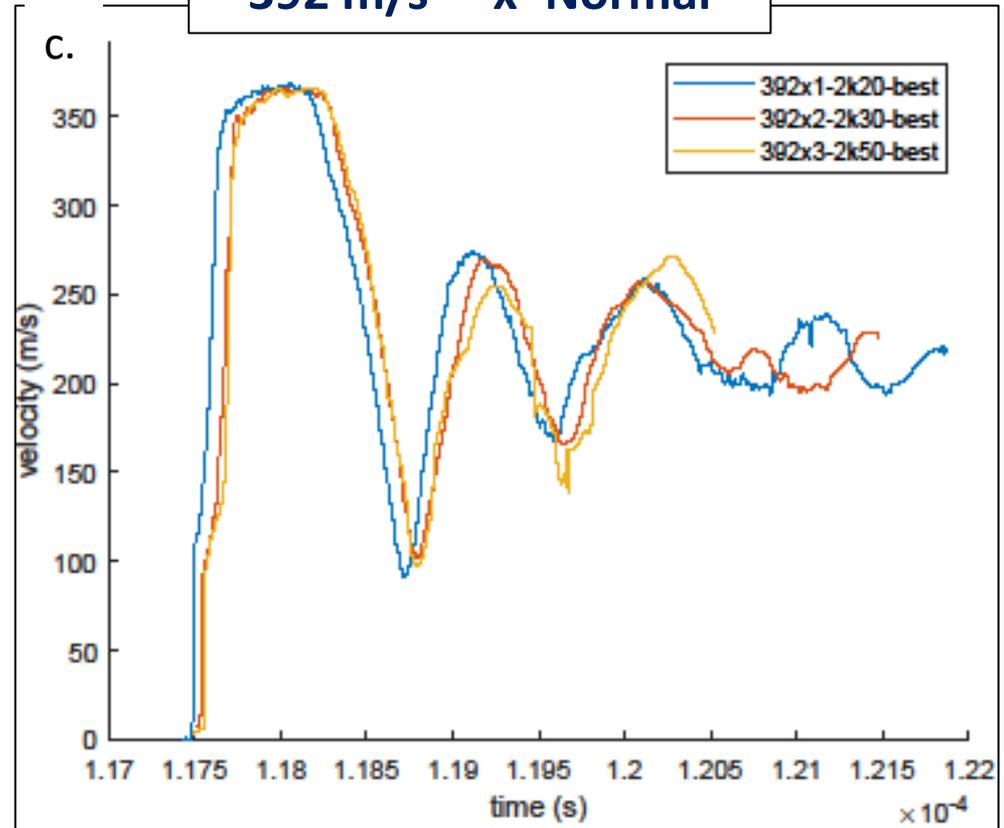
CT-scans of Sample Cross-sections and multi-PDV velocity profiles
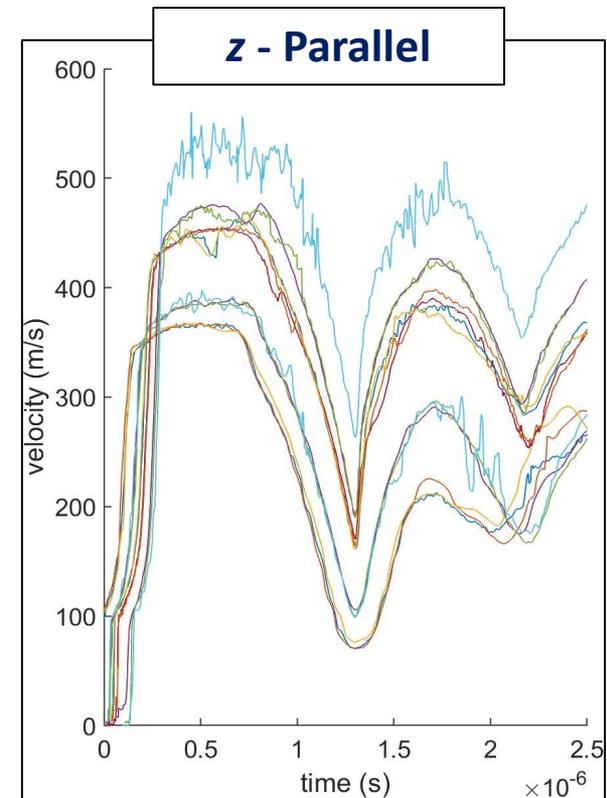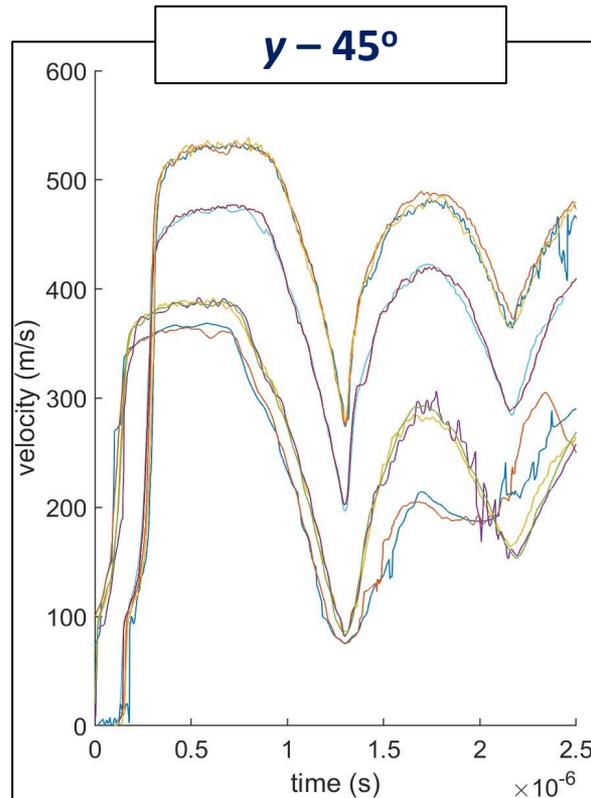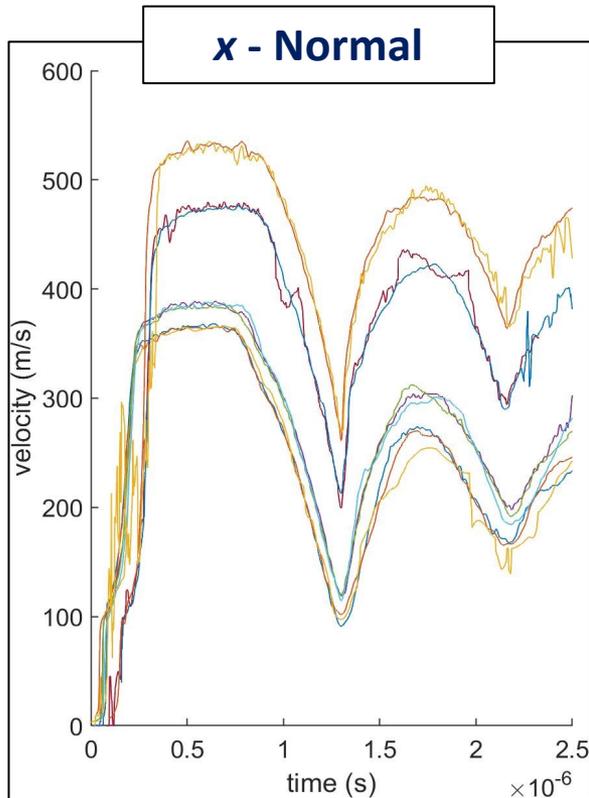
a.

b.
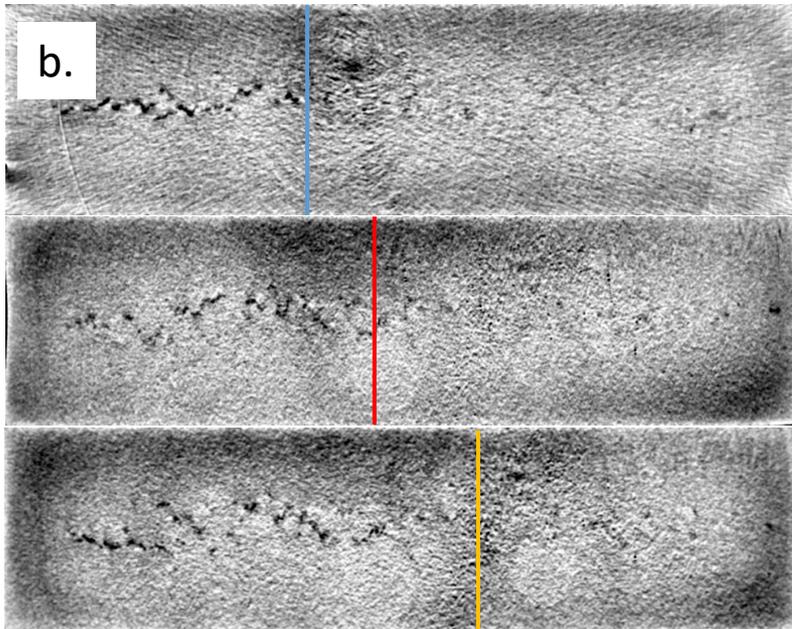
Virtual MicroCT cross sections

392 m/s – 'x' Normal

c.

Obvious evidence of spall failure seen in CT images and PDV profiles showing pullback signal
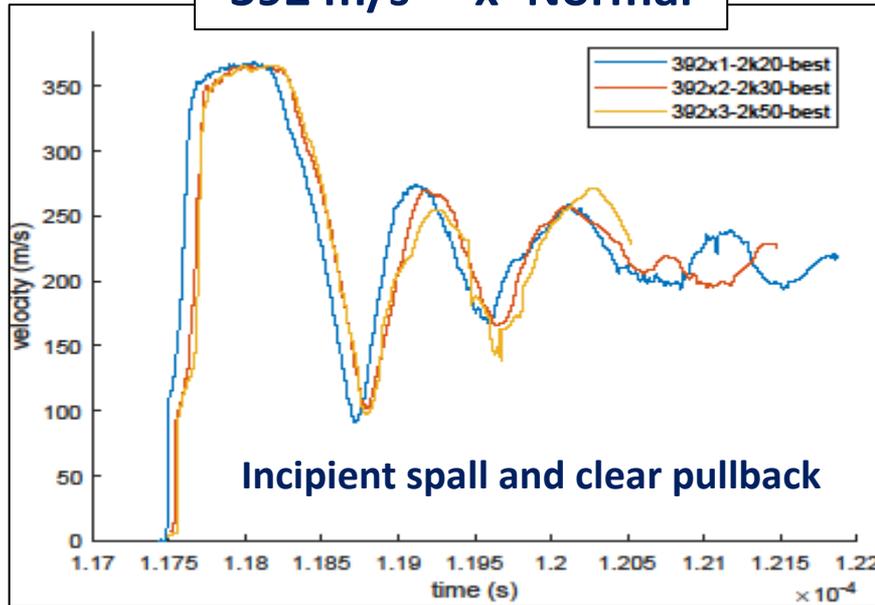
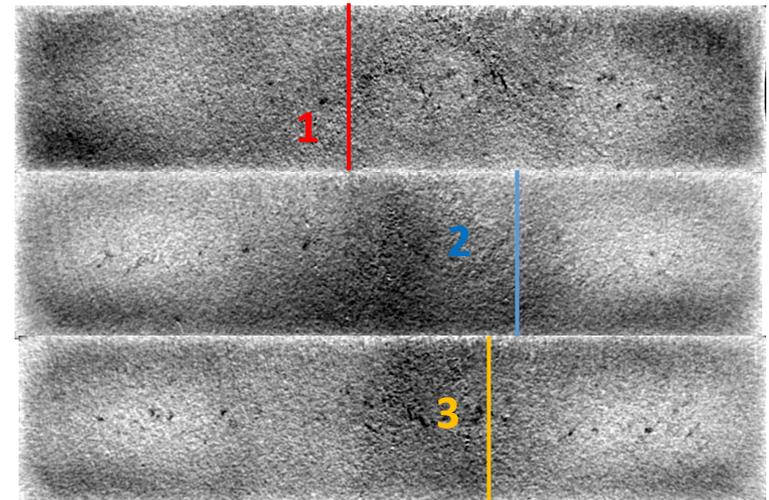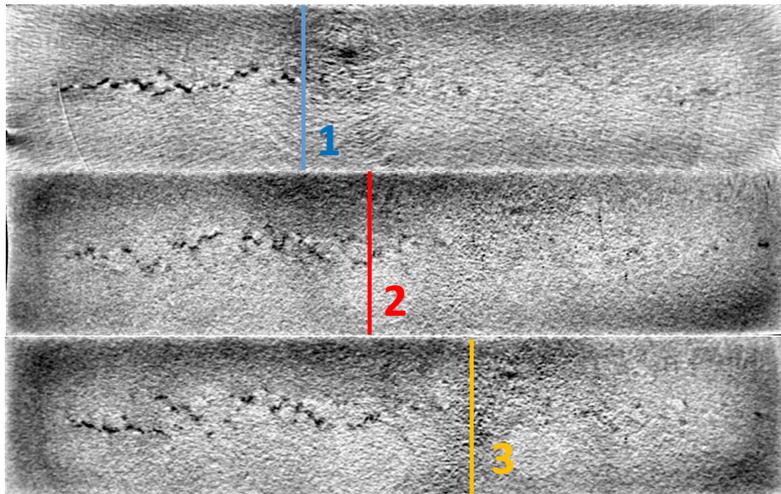# Velocity Profiles at Different Impact velocities for all Orientations
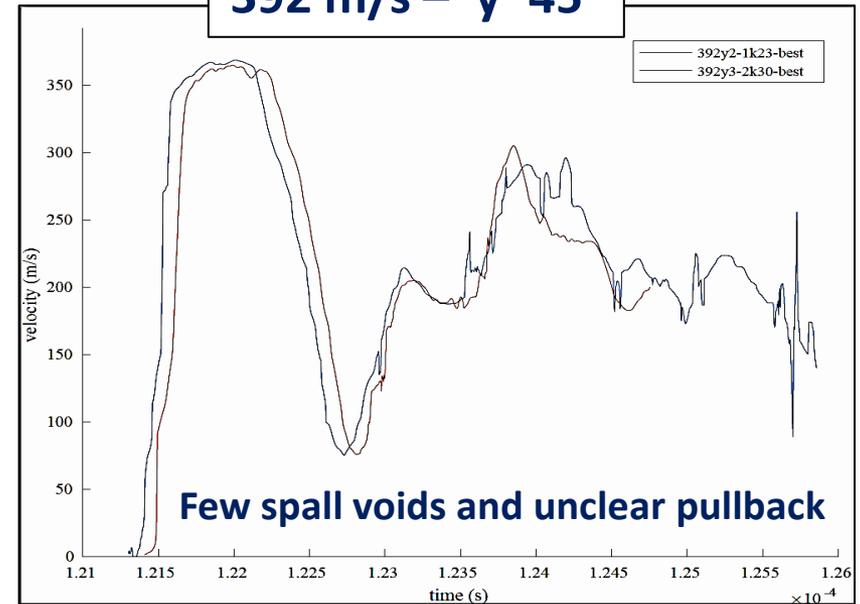

At lowest impact velocity (392m/s) - *x (Normal)* orientation shows clear spall pullback signal. Orientations *y (45º)* and *z (Parallel)* show spall uncertainty as their pull-back signal drops down below HEL

Comparing 'x' and 'y' Orientation Effects at Lowest Impact Velocity
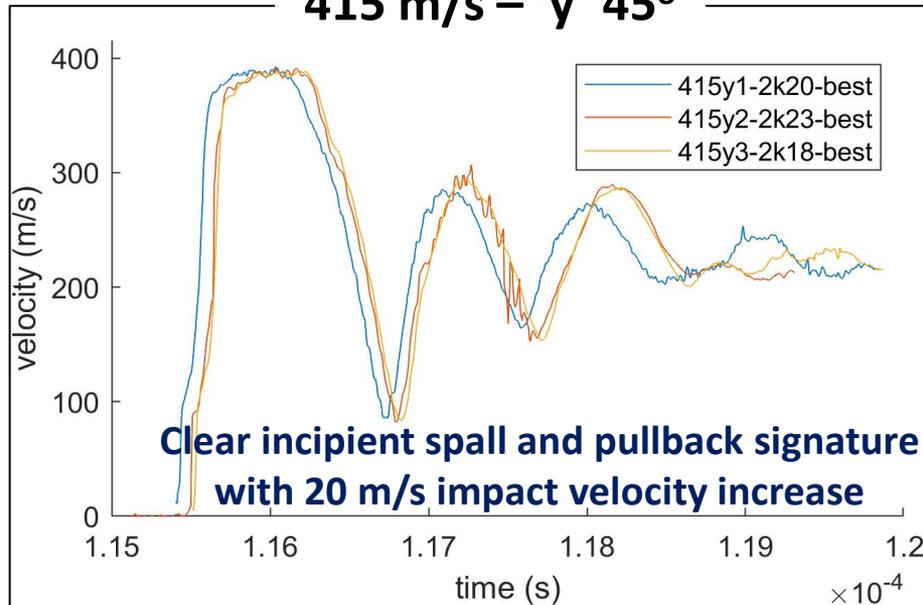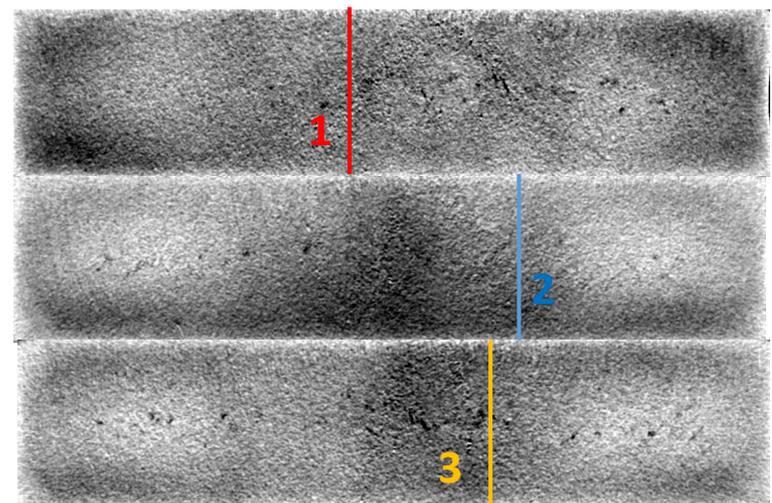

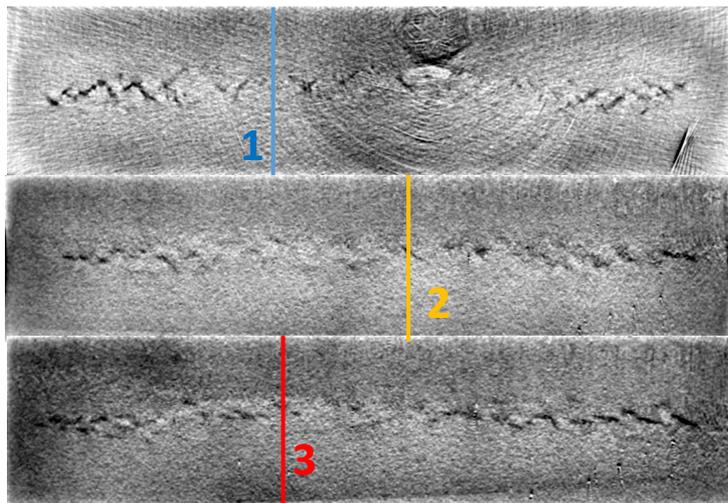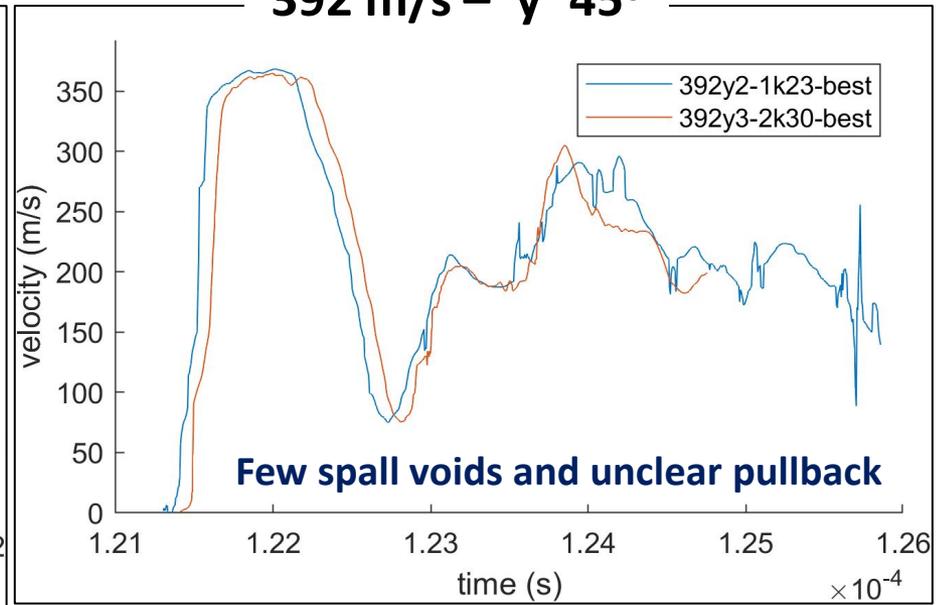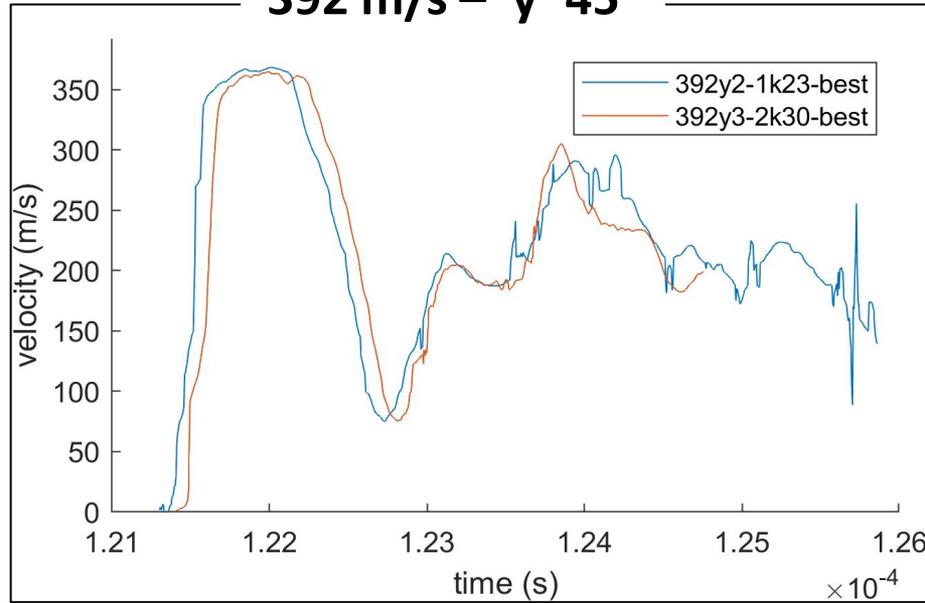392 m/s – 'x' Normal

392 m/s – 'y' 45°

Comparing Effects at Slightly Different Impact Velocities

415 m/s – 'y' 45°

Clear incipient spall and pullback signature with 20 m/s impact velocity increase

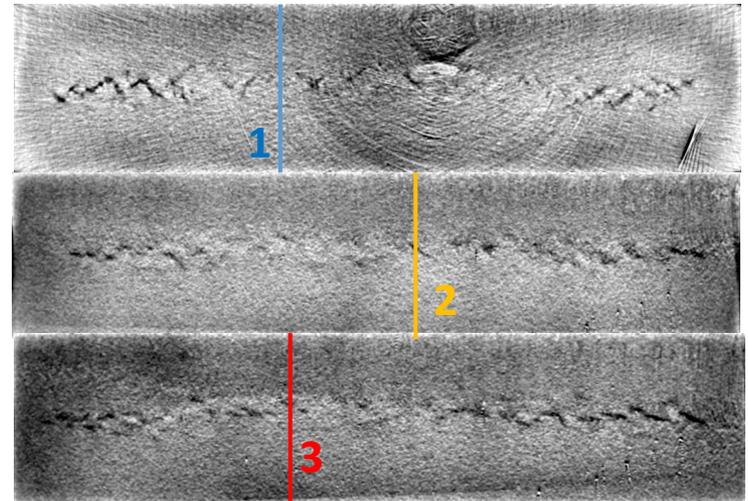**392 m/s – 'y' 45°**

Few spall voids and unclear pullback

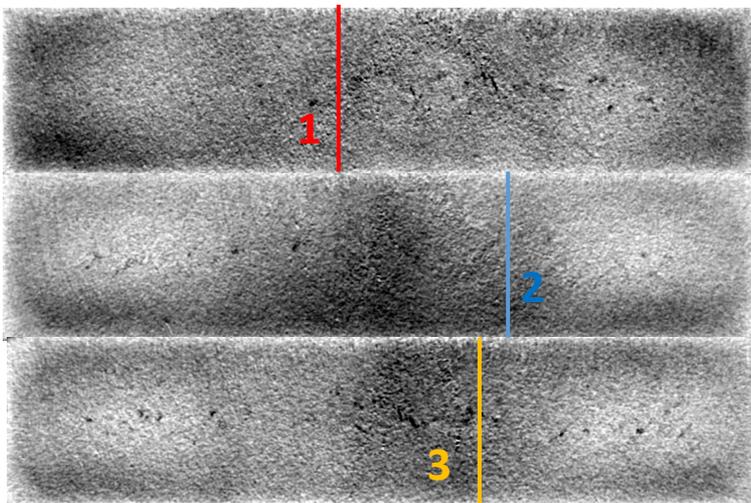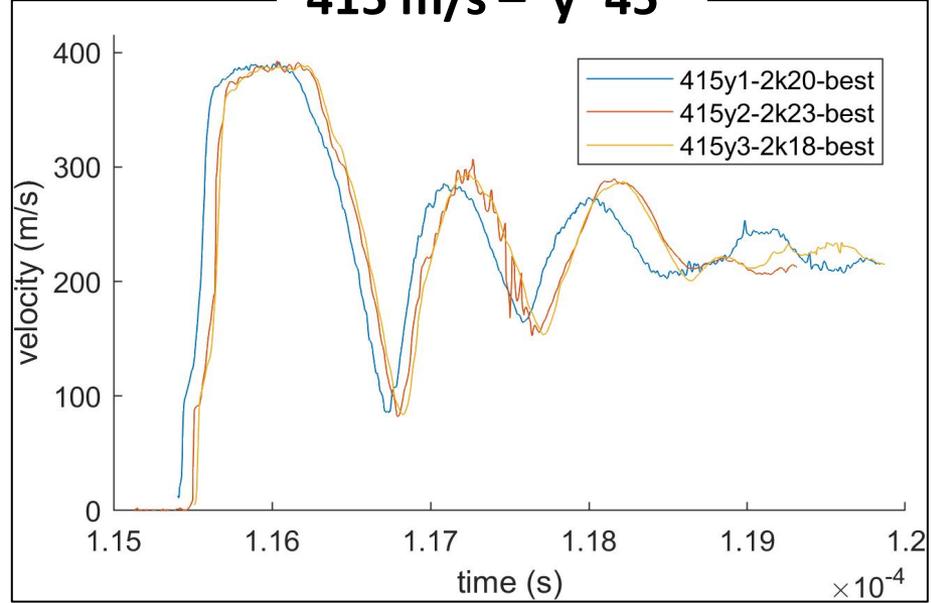# Comparing Effects at Slightly Different Impact Velocities
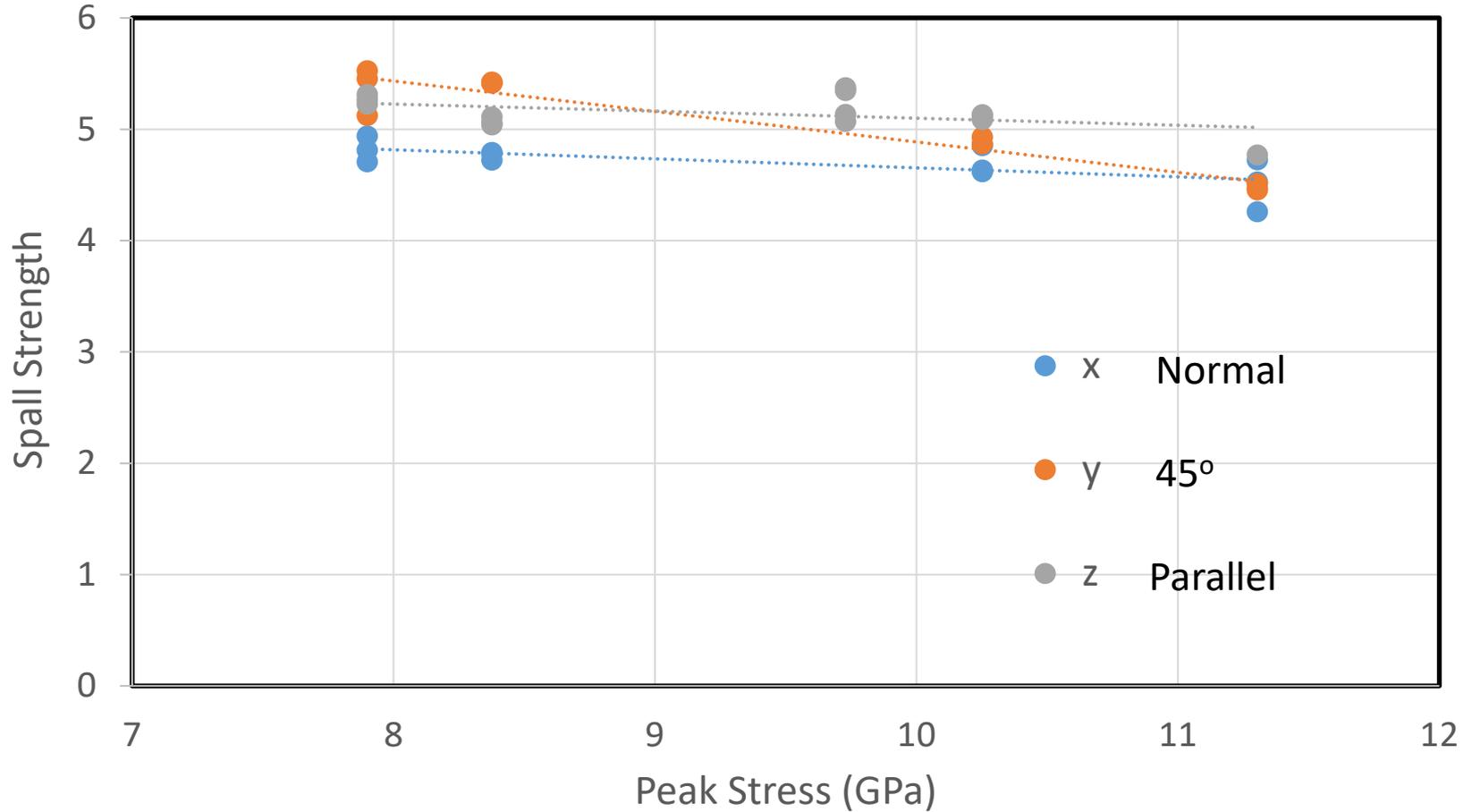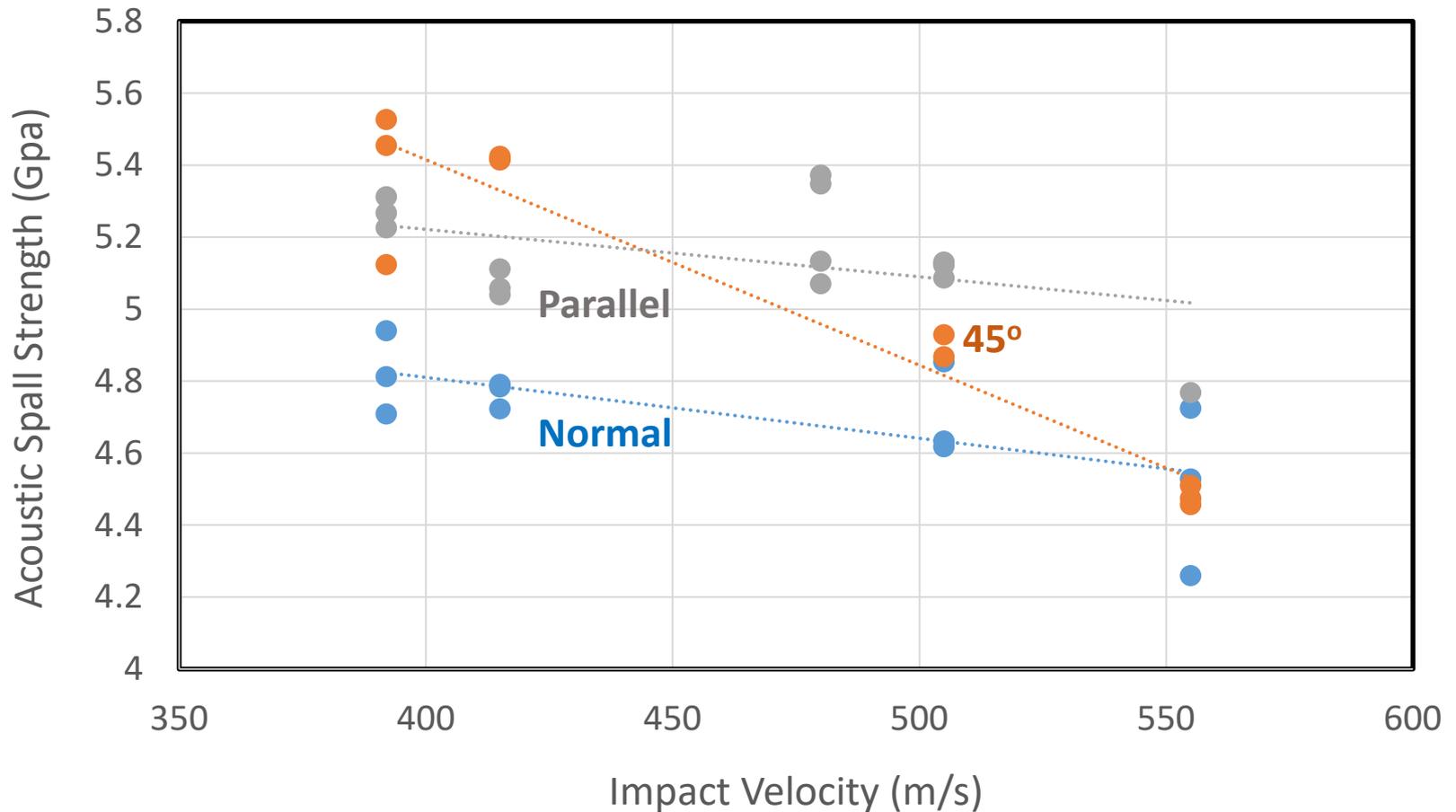
Spall Strength as a function of Peak Stress

Spall Strength as a function of Peak Stress

Eglin spall strength values constant with peak stress and slightly higher current data

Summary & Concluding Remarks

- **Motivation:** *Do local variations in microstructure across fabricated AF 9628 bar affect spall strength and failure?*

- **Current Results**:

  - Spall strength in *'x' direction* – impact **normal** to bar axis is less than along *'z' - parallel* and *'y' - oblique* orientations

  - Spall strength decreases with increasing peak stress, with *'y' – oblique* impact orientation showing greatest decrease

  - Current spall strength measurements in AF9628 bar exhibit clear differences likely due to local variations (anisotropy) in microstructure or texture in forged and heat treated bar.

Multipoint PDV Coupled with Post-Shot Recovery MicroCT for Investigating Orientation Effects on Spall Strength in High Strength Steel

Gregory Kennedy and Naresh Thadhani Georgia Institute of Technology

Multipoint PDV was used to investigate dynamic tensile (spall) failure, of High Strength Steel in plate-impact experiments with a multi-sample target configuration. The multiple sample geometry allowed for direct comparison of three different orientations along the as-received bar at the same impact conditions. The samples were prepared to have the spall plane oriented normal to the bar axis, parallel to the bar axis, and 45o to the bar axis to investigate the heterogeneity of the response across the different orientations, while using multiple PDV probes per sample to examine heterogeneity within each sample. The details of the free surface velocity traces captured by PDV were examined in relationship with the damage as determined from microCT scan of the recovered impacted samples, including mapping the probe locations with the microCT images.