Laser-Driven Plate Impact Technique with Application to Al6061-T6 HEL, Spall, and EOS

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Daniel Portillo, Sidney Chocron, Michael Heim, Thomas Z. Moore, Roberto Enriquez-Vargas
Engineering Dynamics Department, Southwest Research Institute

Matt Barsotti, Eddie O'Hare, David Stevens, Alex Lakocy
Protection Engineering Consultants

Outline

- Background
- Materials
- Experimental Technique
- Main Results
- Comments and Conclusions

Background

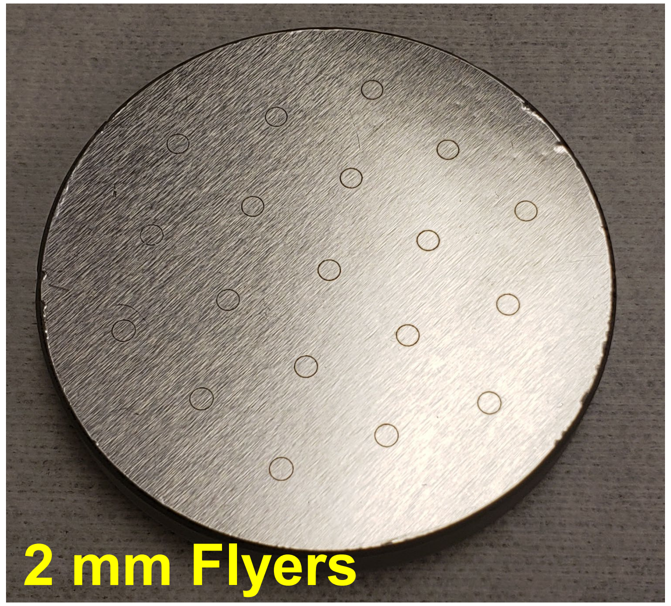
- Obtaining HEL (Hugoniot Elastic Limit), Spall, and EOS (Equation of State) data of materials is a difficult and expensive process.
- A large powder gun or, for higher pressures, two-stage light gas gun needed as well as sophisticated diagnostics.
- National laboratories, Illinois University at Urbana-Champaign, Johns Hopkins developed laser-driven flyer methods that looked very promising to obtain material properties.
- SwRI (Southwest Research Institute) and PEC (Protection Engineering Consultants) have implemented this technique and performed some improvements that allow systematic measurement of some of the properties desired.

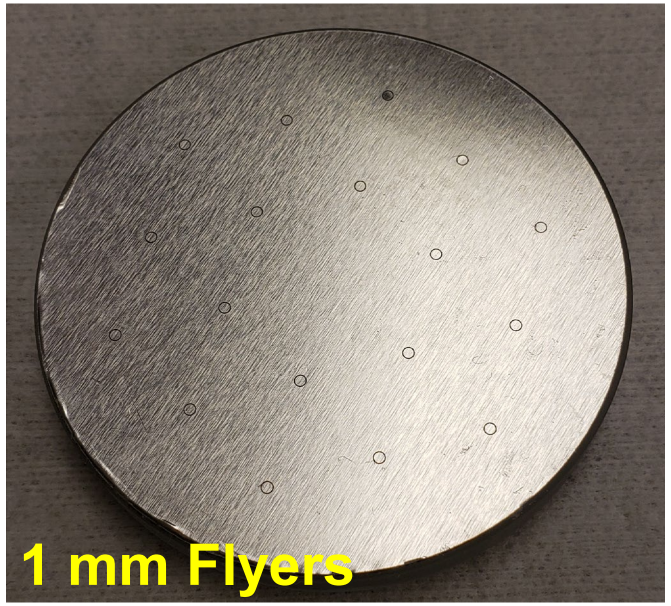
Materials

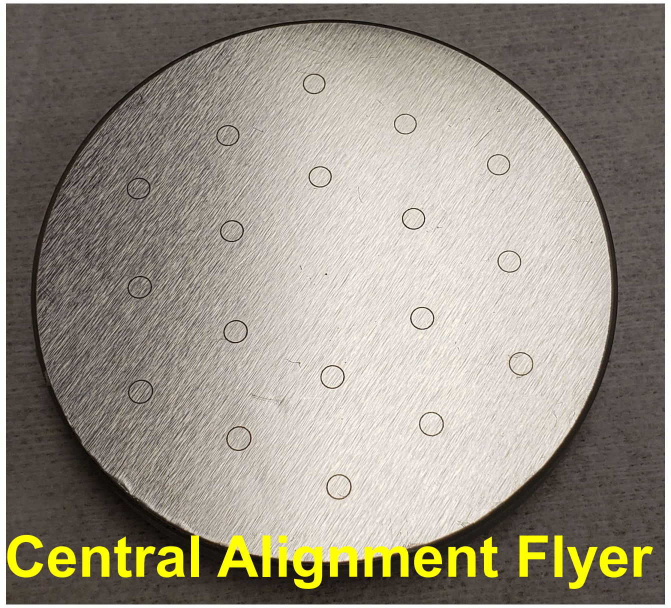
- Etched flyers were typically 50 µm-thick, Al 1235 (Al 1100), 2 mm diameter. For EOS other materials and flyer diameters were used.
- Targets
  - Borosilicate glass, 3.175 mm
  - Al 1235, 50 µm
  - Al 6061, 150 µm
  - IN718, 127 µm
  - SS 304, 100 µm
  - SS 316L, 100 µm

Al 1100-O Flyer Plates

- Laser etch parameters for 2 mm flyers at 25, 50, 100 μm foil thicknesses have been found.
- Thicknesses are found off the shelf.
- Sample plates of 1 mm flyers have been made.

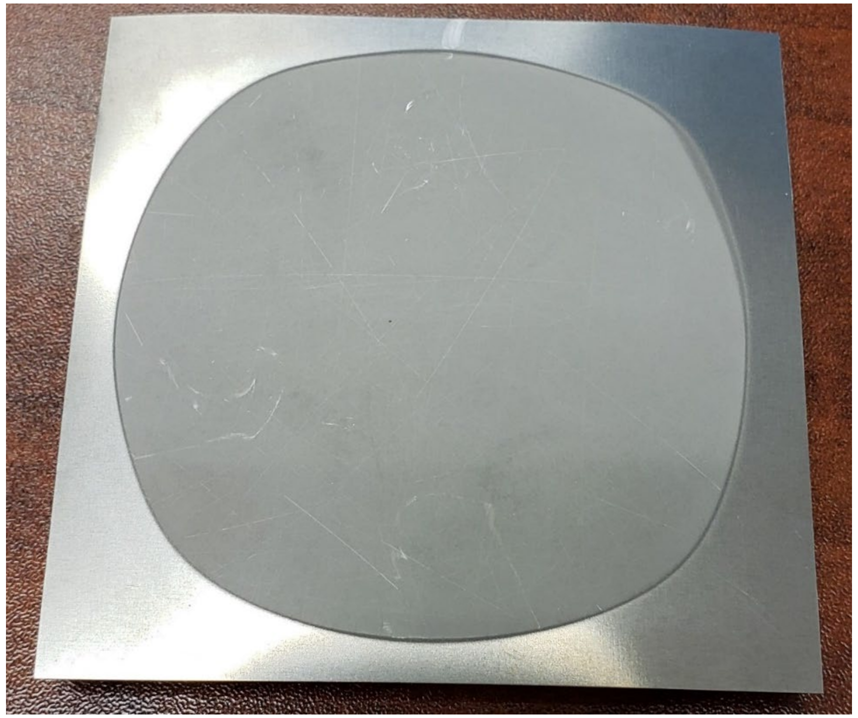






Lapping In718 EOS Flyers

- Over 9 thickness measurements the average thickness was 53 microns with bounds of 51 and 54 microns



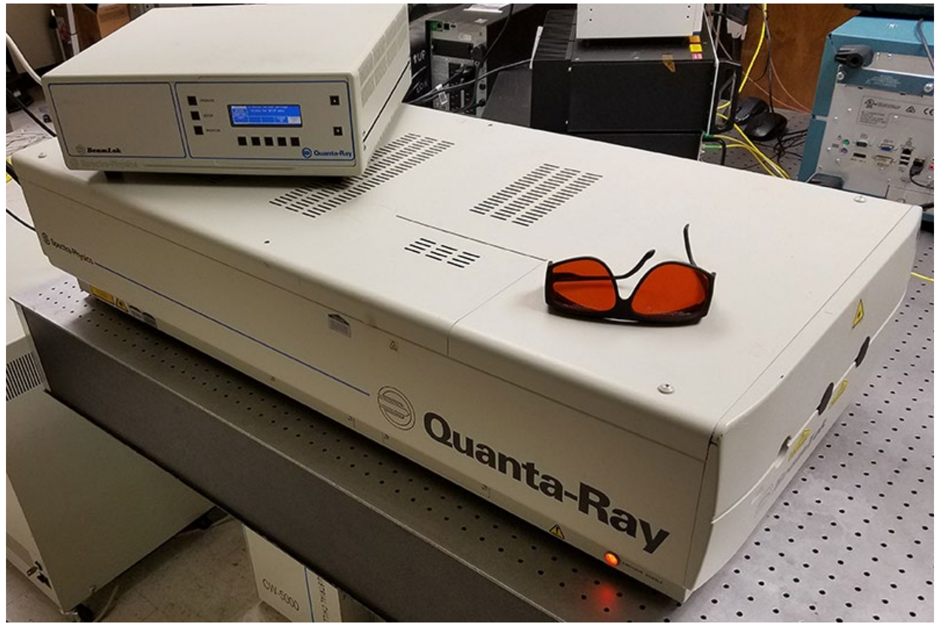
Test Configurations

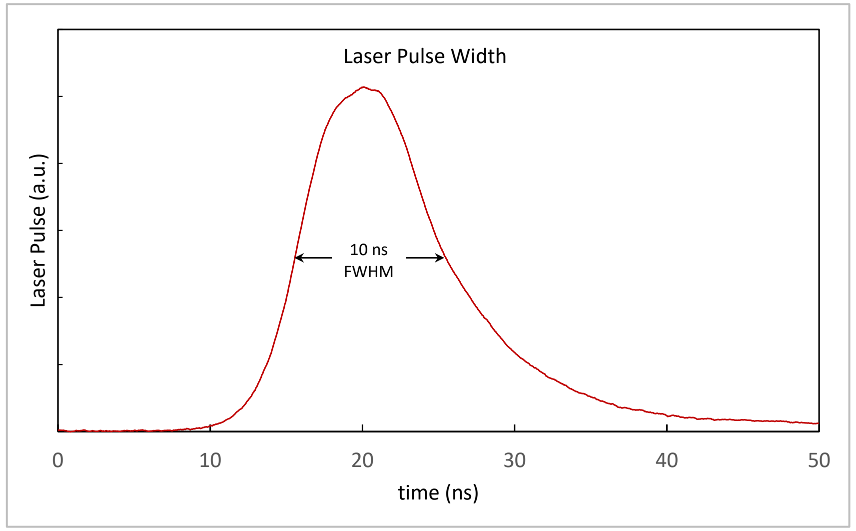
- Two overall configurations
  1. Flyer Impacting Glass
  2. Flyer Impacting Foil

- Employed special test fixturing to enable multiple shots under vacuum

Drive Laser

- Quanta-Ray Pro 350 Nd:YAG Laser
  - 2.2 J/pulse total, 678 mJ Oscillator only at 1064 nm (NIR)
  - 10 ns pulse width at 10 Hz rep rate
- System tuning/modifications:
  - Producing 3.3 J/pulse



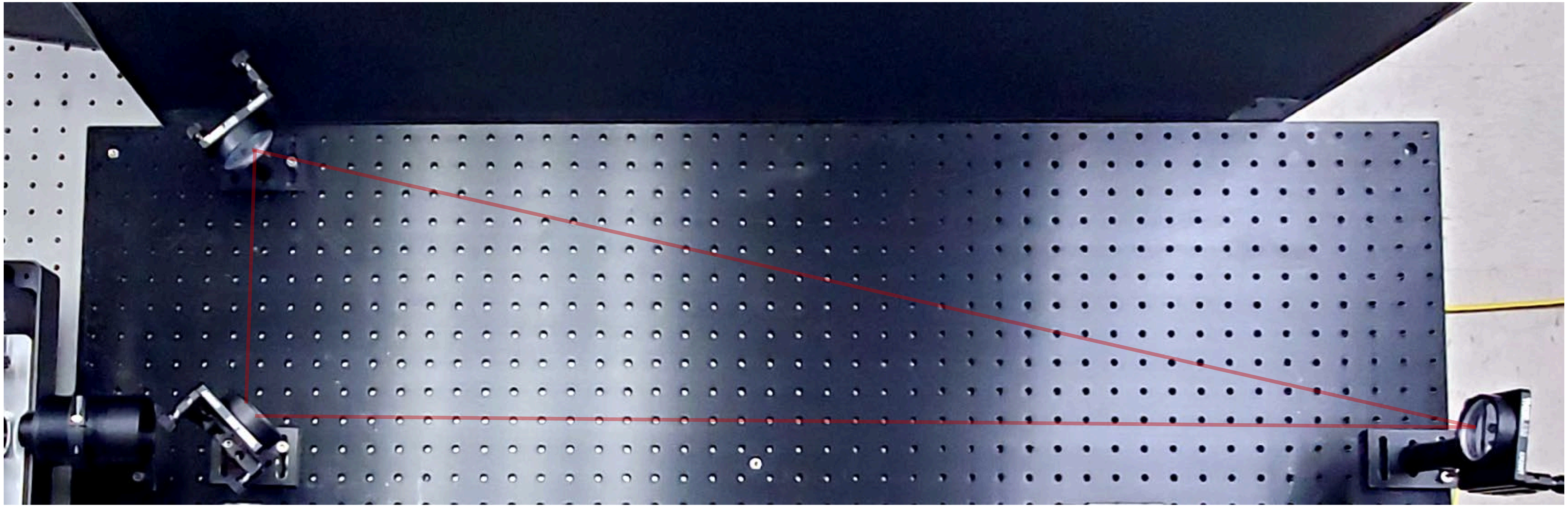


PDV (Photon Doppler Velocimetry) System

- Heterodyne PDV system employs reference & probe beam
- Offset frequency offset set at 9.94 GHz
- Oscilloscope sampling at 100 GS/s

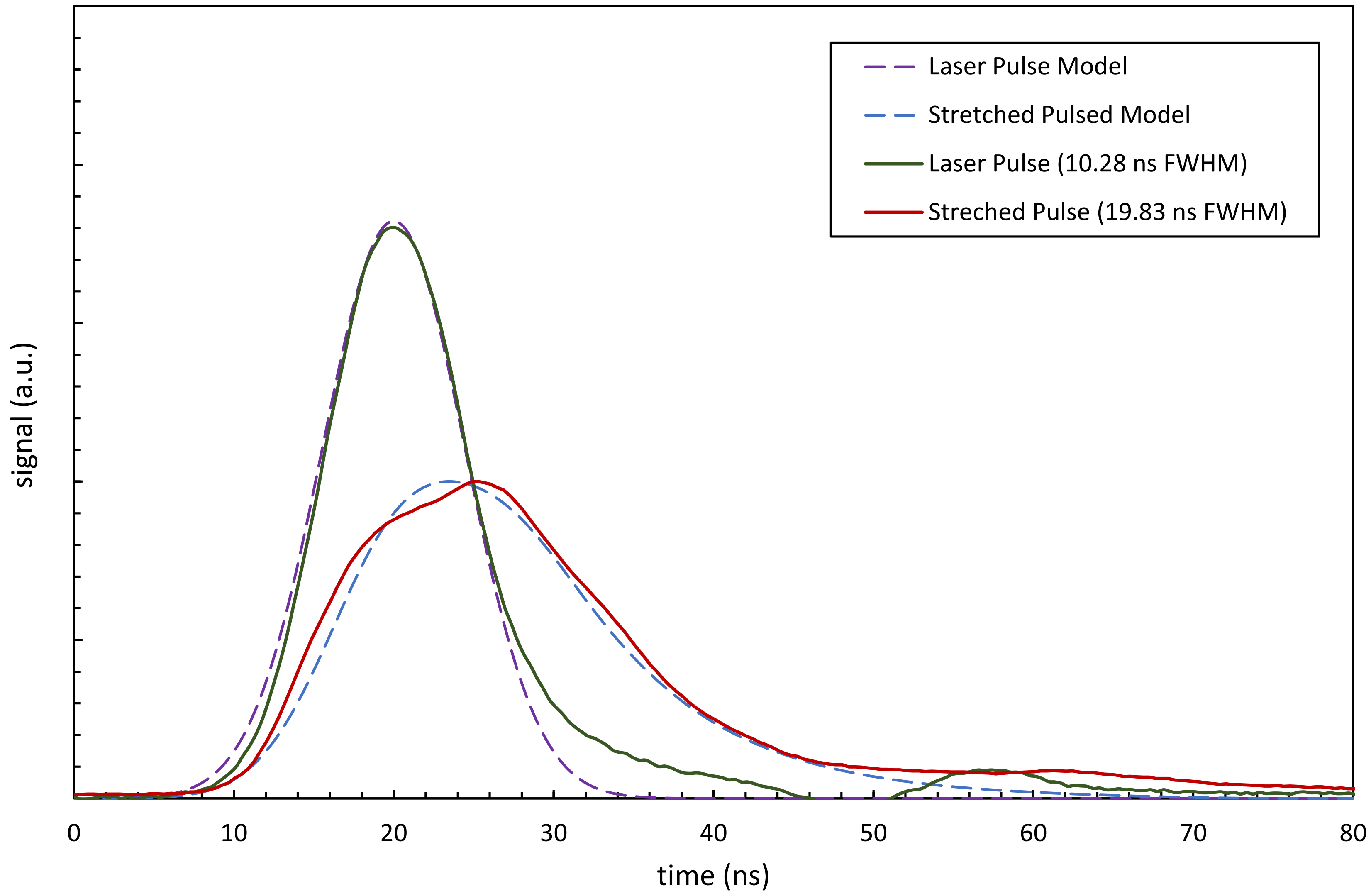
Pulse Stretcher Assembly

- Pulse stretcher opto-mechanics & optics is assembled

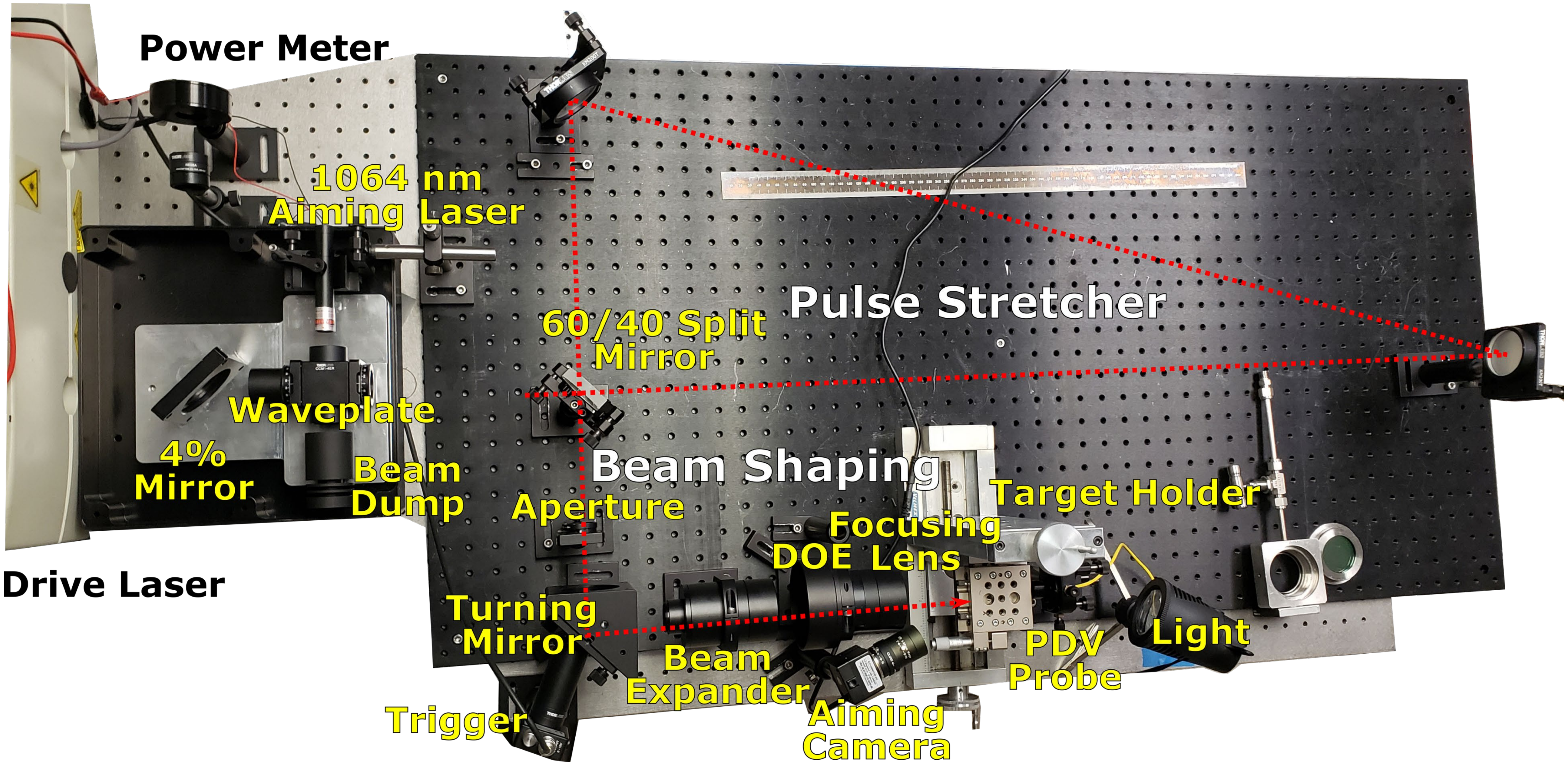


Pulse Stretcher Performance

- Pulse stretcher is aligned and optimized to generate 18 ns – 20 ns pulses
- Measured values compare favorably to the numerical model with nearly identical amplitude values
- Pulse is stretched from 10.28 ns to 19.83 ns FWHM (full width at half maximum)

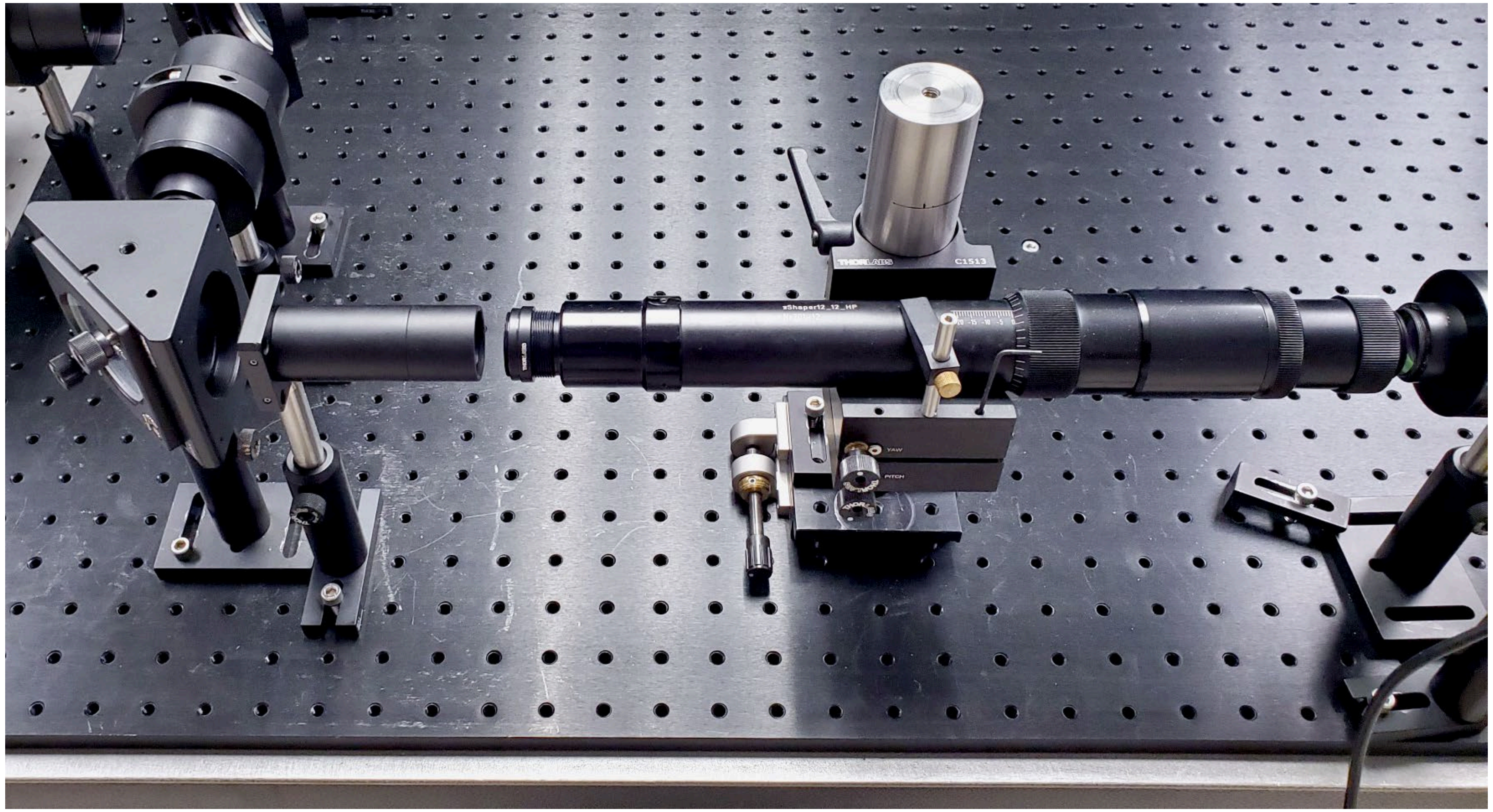


Overview of Current Laser System



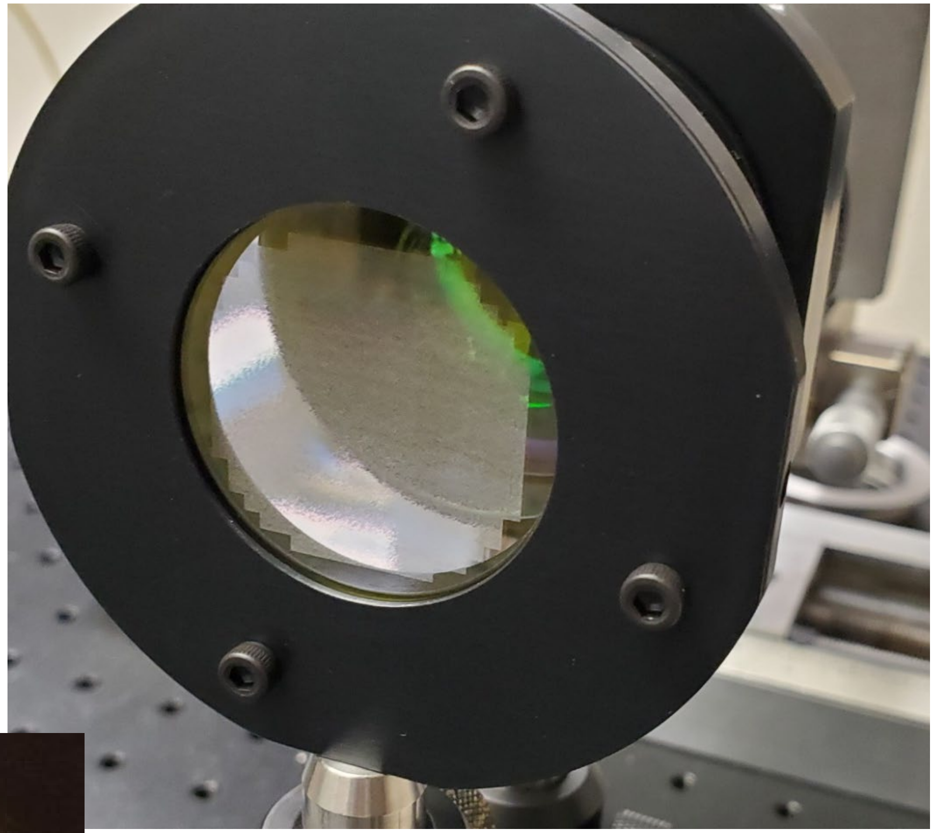
Beam Shaping Optical Assembly

- Initially in the project we used a Pi-shaper to obtain a top hat uniform laser beam.

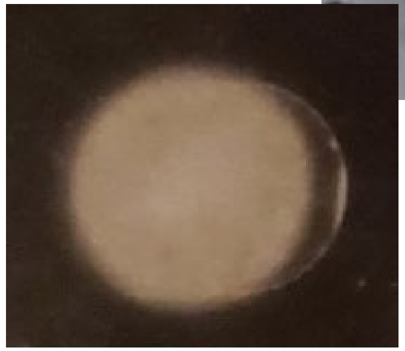


SILIOS Integration

- The Silios Diffractive Optical Element (DOE) replaced the Pi-shaper during the project.



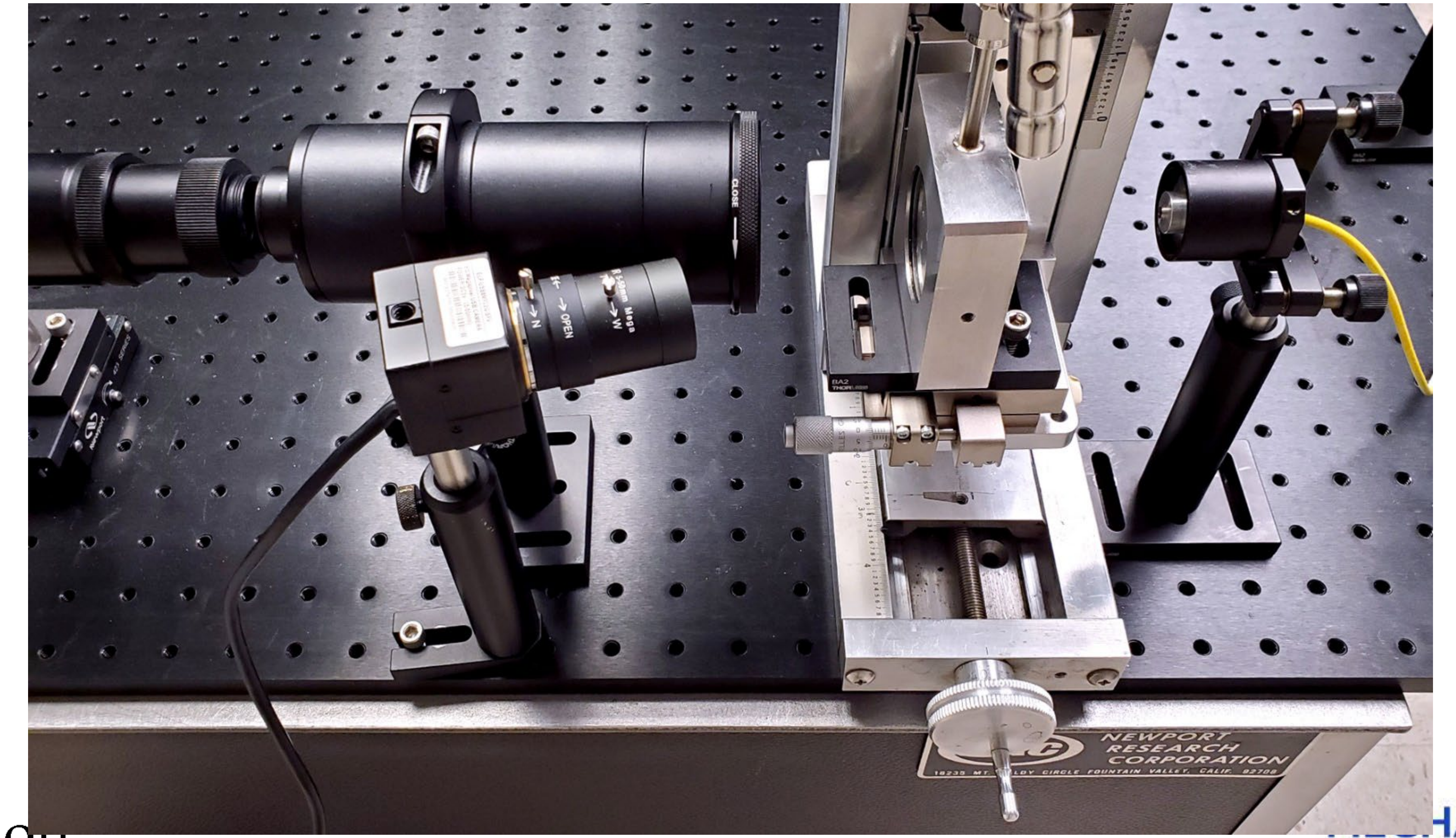
SILIOS DOE



SILIOS DOE spot

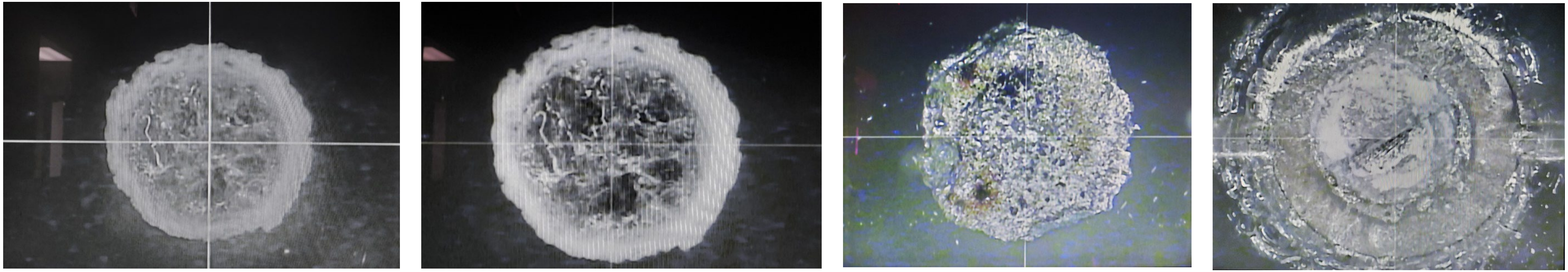
Siting Camera and PDV Probe

- Siting camera in front allows alignment of impact point using software.
- PDV probe located at the back.



Laser Launched Flyer Generation

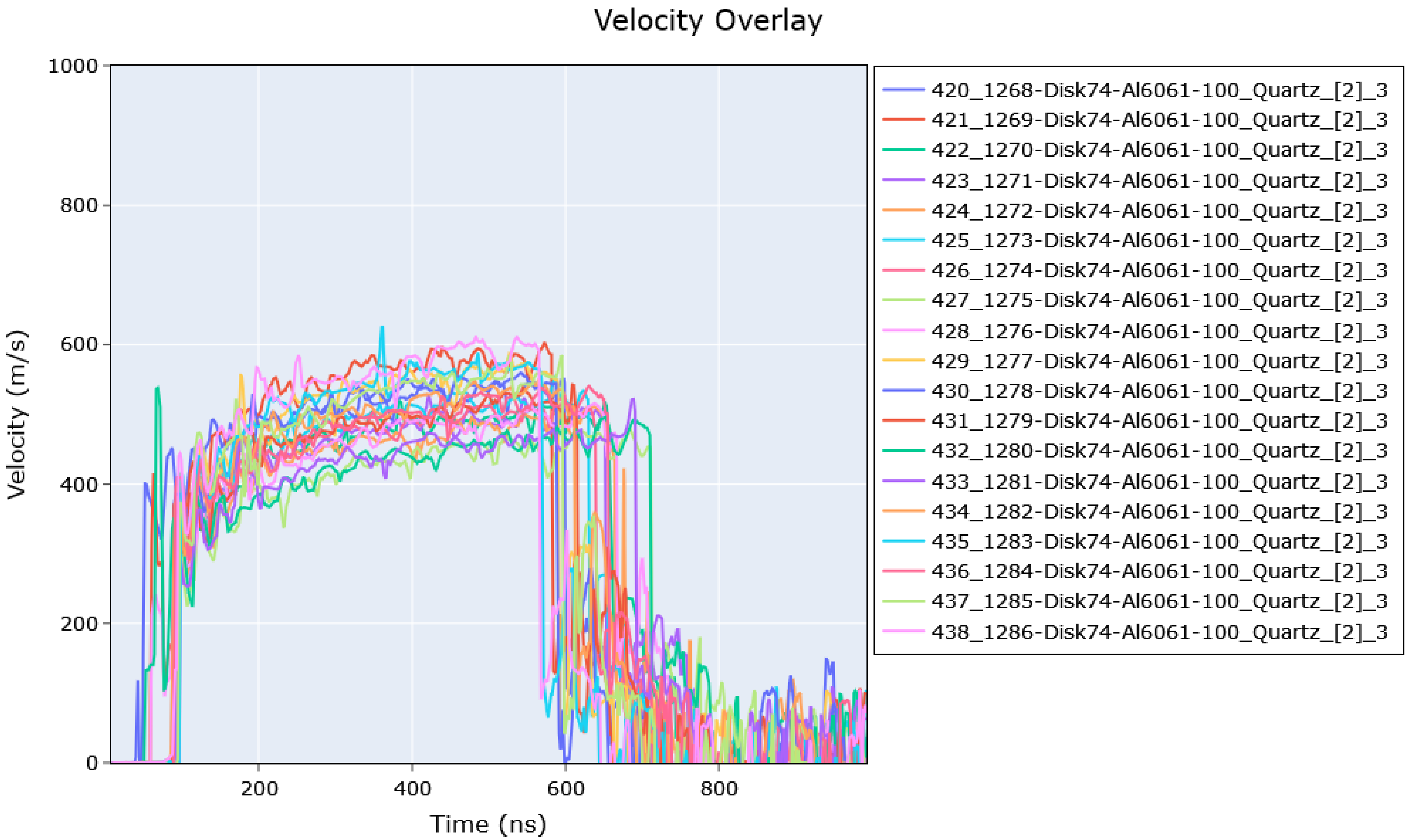
- Successfully generated 2 mm laser driven flyers



Foil impact on glass: flyers were intact and generally symmetric, only slight carbonization on the back of the flyers observed. Impact craters were generally symmetric and uniformly formed.

Laser Launched Flyer Velocity

- Flyer average velocity over 19 shots was 528 m/s with a standard deviation of 38 m/s
- Velocities ranged from 454 m/s to 601 m/s



Test Matrix

Test Setup							
Config	Material	Case	#Discs	Flyer Material	Ideal Flyer Thickness (um)	Target Material	Target Thickness (um)
A1	AA-6061-T6	HEL/Spall	7	AA-1100-O	50.8	AA-6061-T6	100
A2	AA-6061-T6	HEL/Spall	1	AA-1100-O	50.8	AA-6061-T6	150
C1	IN-718	HEL/Spall	3	AA-1100-O	50.8	IN-718	127

Los Alamos Shock Hugoniot Data

ALUMINUM , 6061

Average ρ_0 = 2.703 g/cm³ .

Sound velocities longitudinal 6.40 km/s .
shear 3.15 km/s .

ρ_0 (g/cm³)	U_s (km/s)	U_p (km/s)	P (GPa)	V (cm³/g)	ρ (g/cm³)	V/Vo	Exp
2.703	5.266	0.000	0.000	.3700	2.703	1.000	ssp ×
2.703	5.928	.442	7.082	.3424	2.921	.925	im1 o
2.703	5.975	.497	8.027	.3392	2.948	.917	im1 o
2.703	6.176	.657	10.968	.3306	3.025	.894	im1 o
2.703	6.652	.999	17.962	.3144	3.181	.850	im1 o
2.703	6.956	1.198	22.525	.3062	3.265	.828	im1 o
2.703	7.655	1.741	36.024	.2858	3.499	.773	im1 o
2.703	7.963	1.925	41.434	.2805	3.565	.758	im1 o
2.703	7.970	1.935	41.686	.2801	3.570	.757	im1 o
2.703	8.431	2.288	52.141	.2696	3.710	.729	im1 o
2.703	8.663	2.473	57.908	.2643	3.783	.715	im1 o
2.703	9.146	2.752	68.034	.2586	3.866	.699	im1 o
2.703	9.069	2.780	68.148	.2566	3.898	.693	im1 o
2.703	9.289	2.886	72.462	.2550	3.921	.689	im1 o
2.703	9.529	3.120	80.361	.2488	4.019	.673	im1 o
2.703	9.830	3.151	83.724	.2514	3.978	.679	im1 o
2.703	9.649	3.376	88.050	.2405	4.158	.650	im1 o
2.703	9.969	3.435	92.560	.2425	4.124	.655	im1 o
2.703	9.843	3.449	91.763	.2403	4.161	.650	im1 o
2.703	10.269	3.470	96.317	.2449	4.083	.662	im1 o

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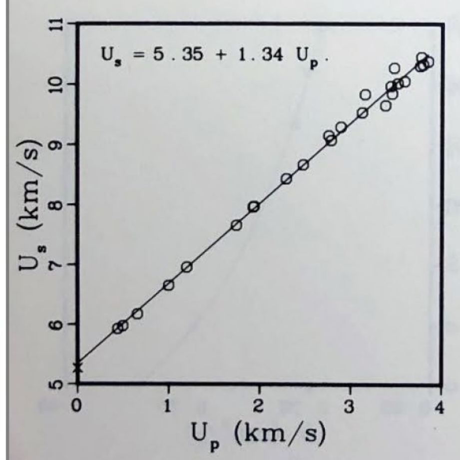
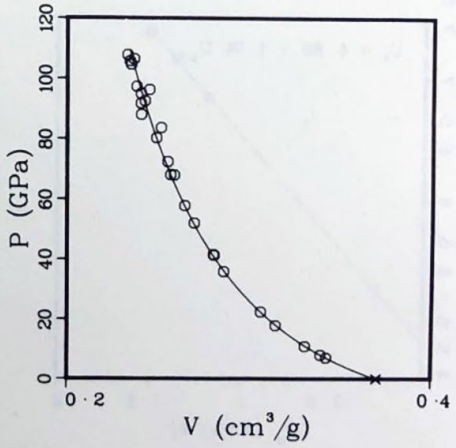




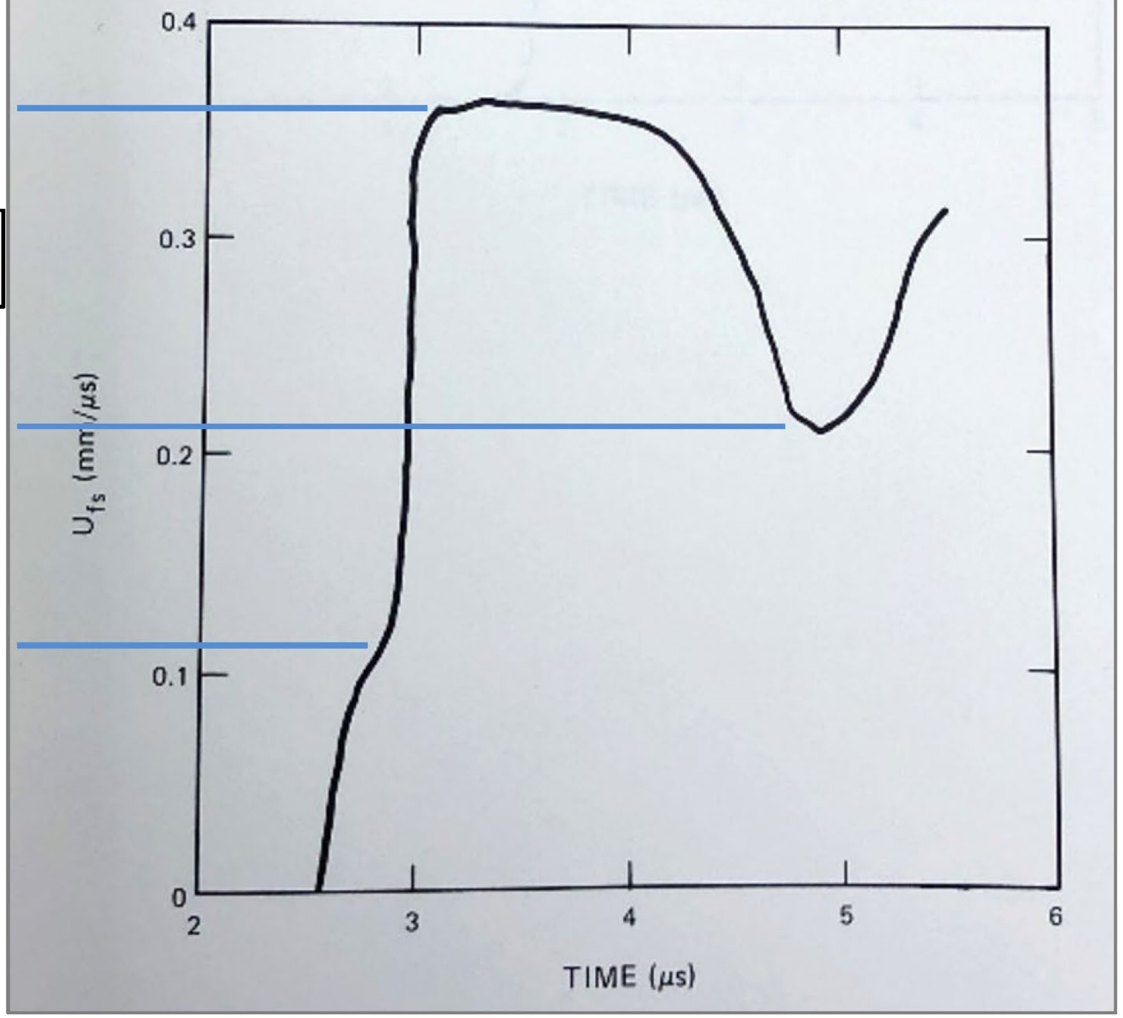
IMPACTOR	6061 aluminum, 6.08 mm thick, mounted on 51-mm-diam aluminum alloy projectile Impact velocity: 0.390 mm/µs
TRANSDUCER	Free-surface capacitor Time: Relative

Peak: 370 m/s

Spall: 150 m/s

Valley: 220 m/s

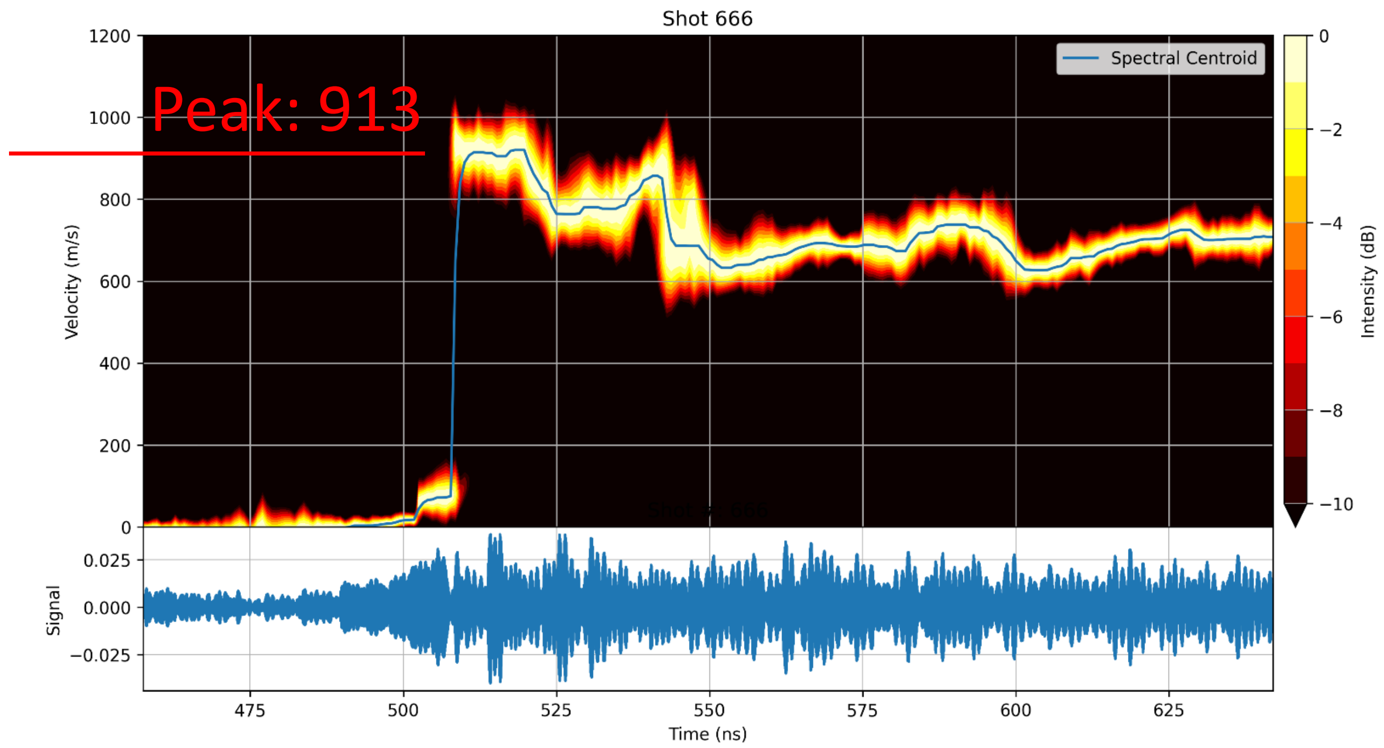
HEL: 110 m/s



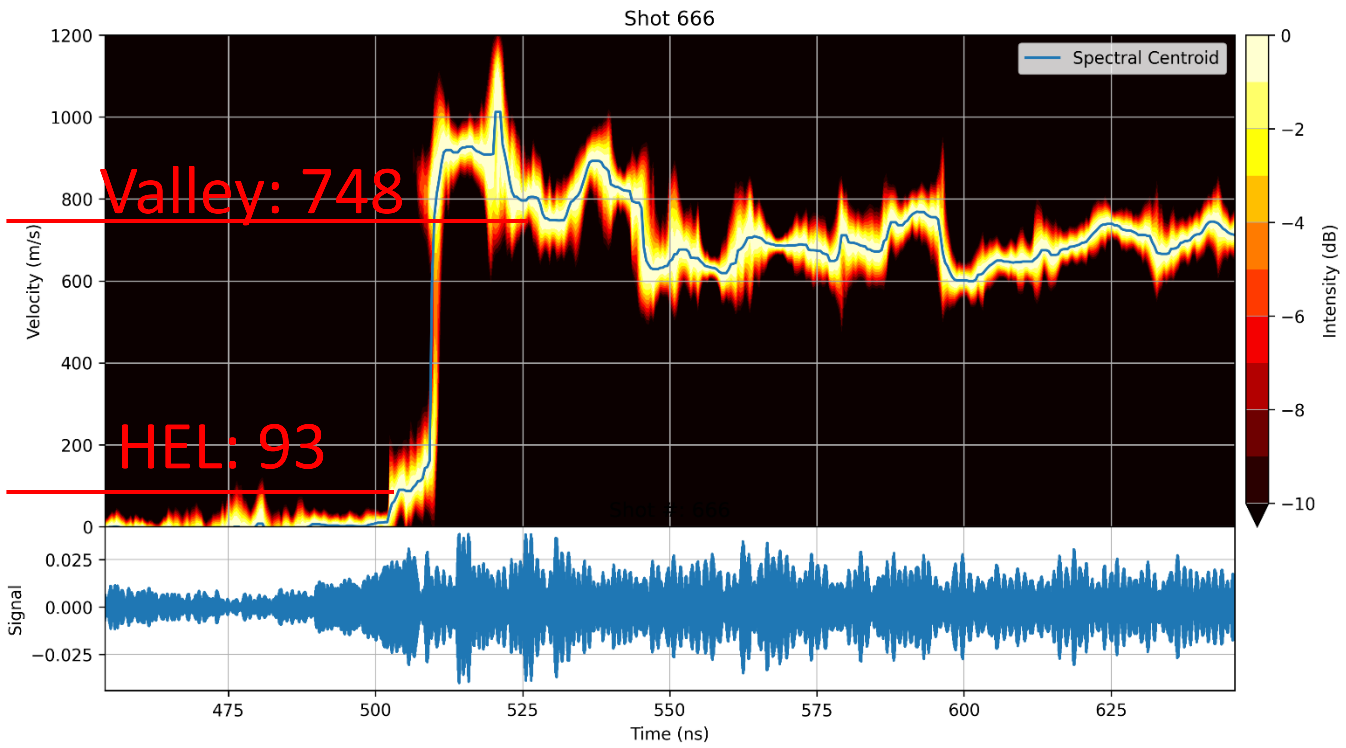
arsh, "LASL Shock Hugoniot Data," Los Alamos Ser. Dyn. Mater. Prop., p. 150, 1980.

Al6061-T6 Tests

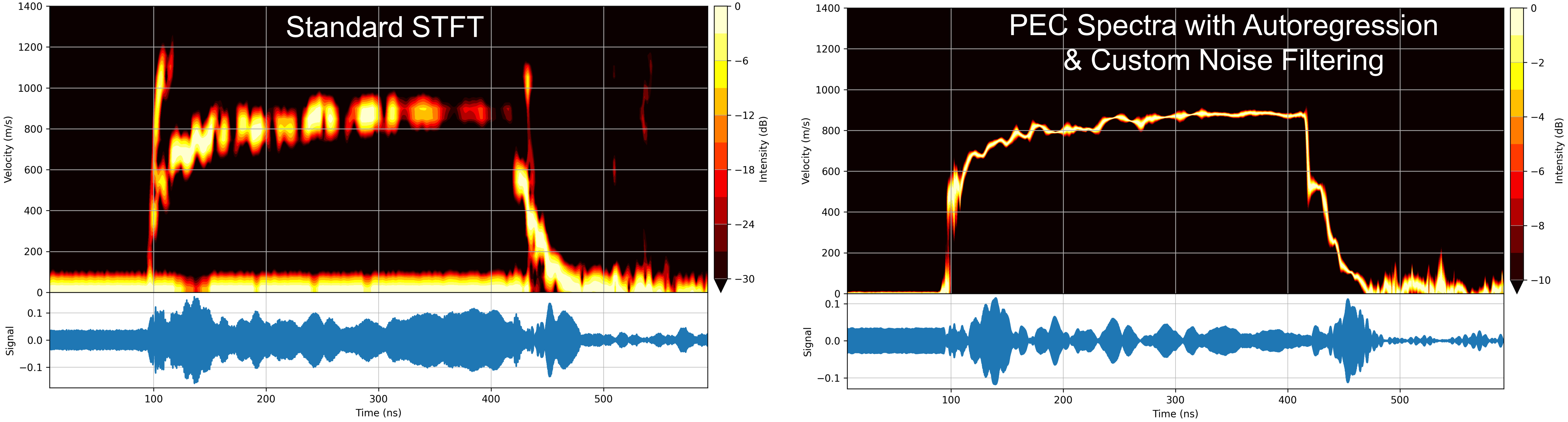
15ns window



8ns window

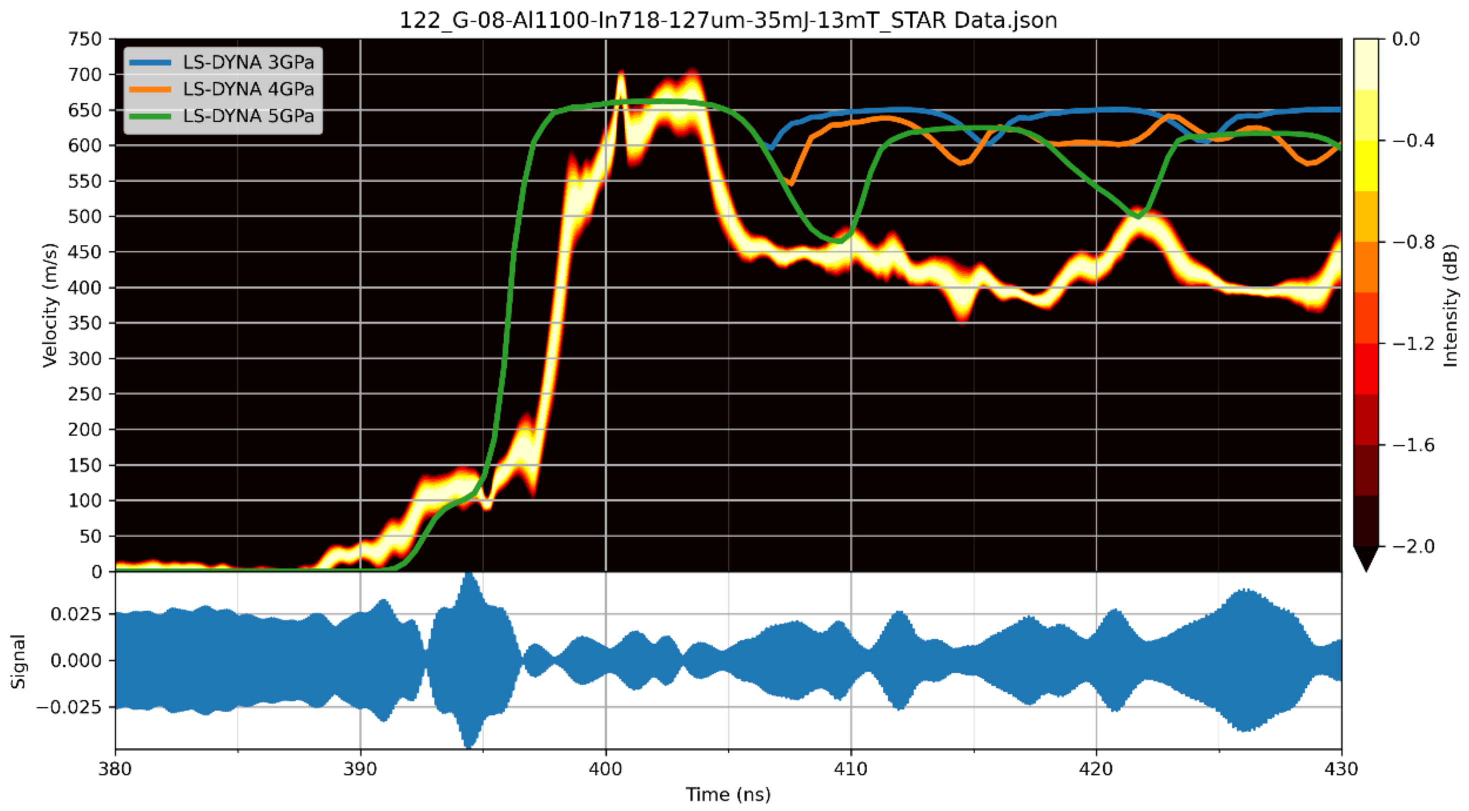


Data Processing with PEC Spectra

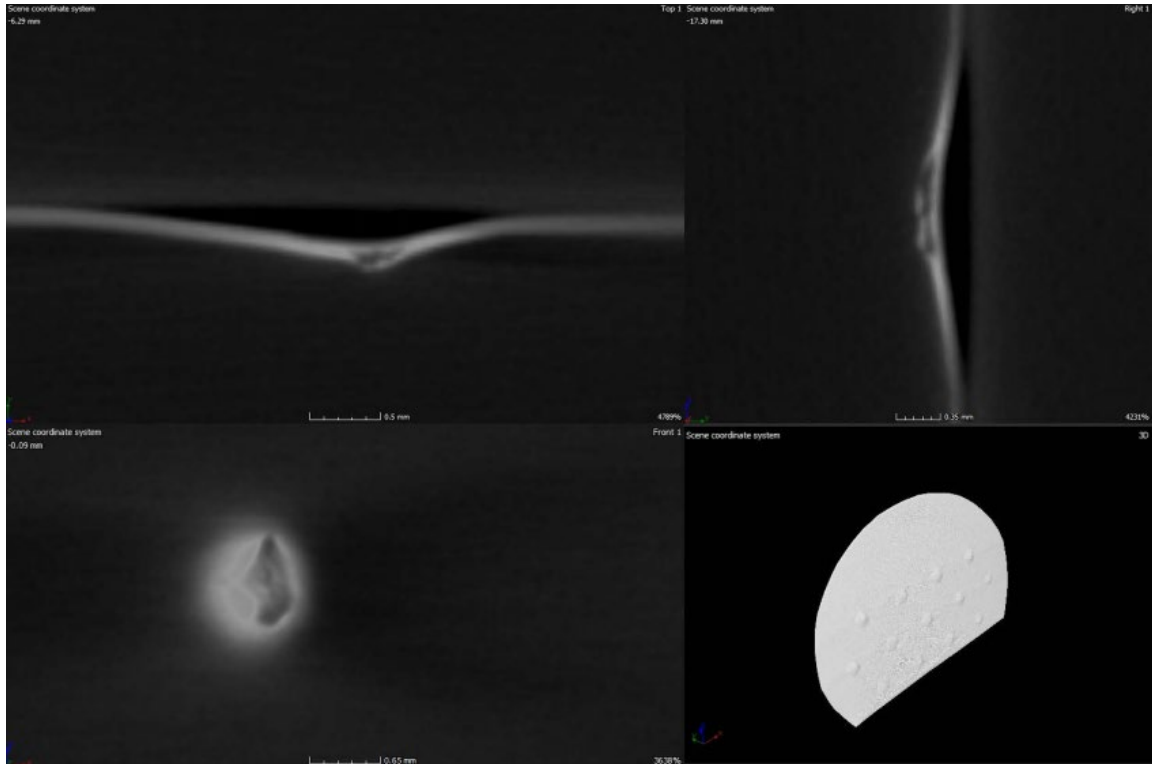


In718 Tests Compared to Hydrocode Simulations

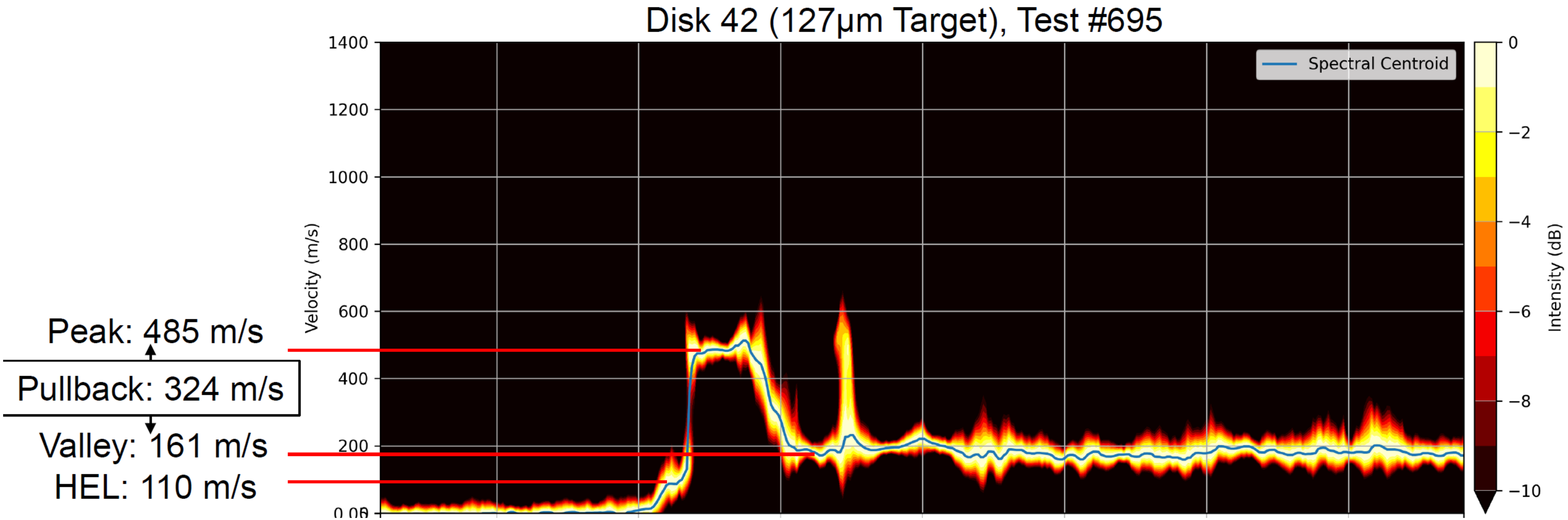
Measurement of HEL and Spall



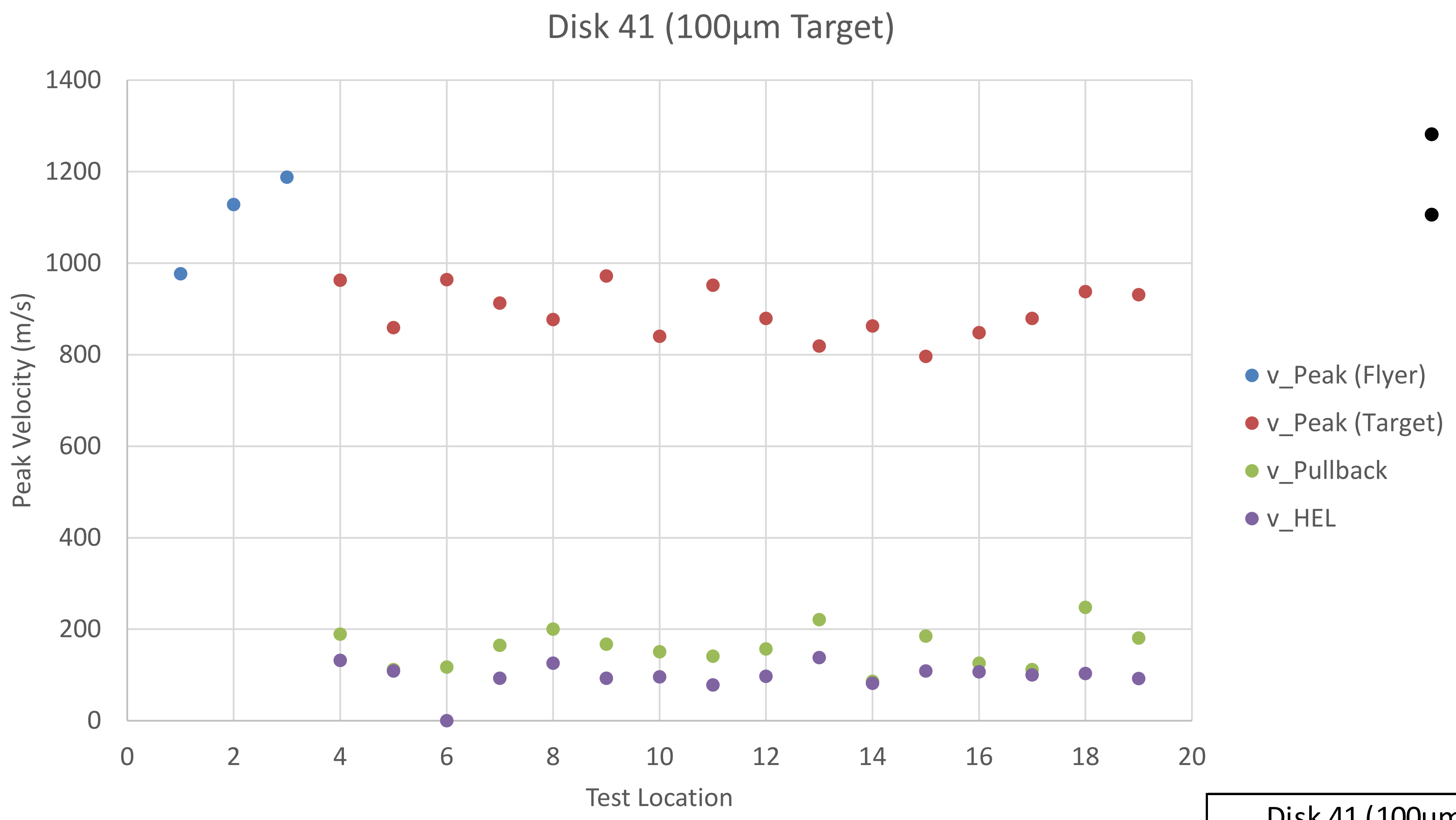
Spalled Foil Specimen



Inconel Tests



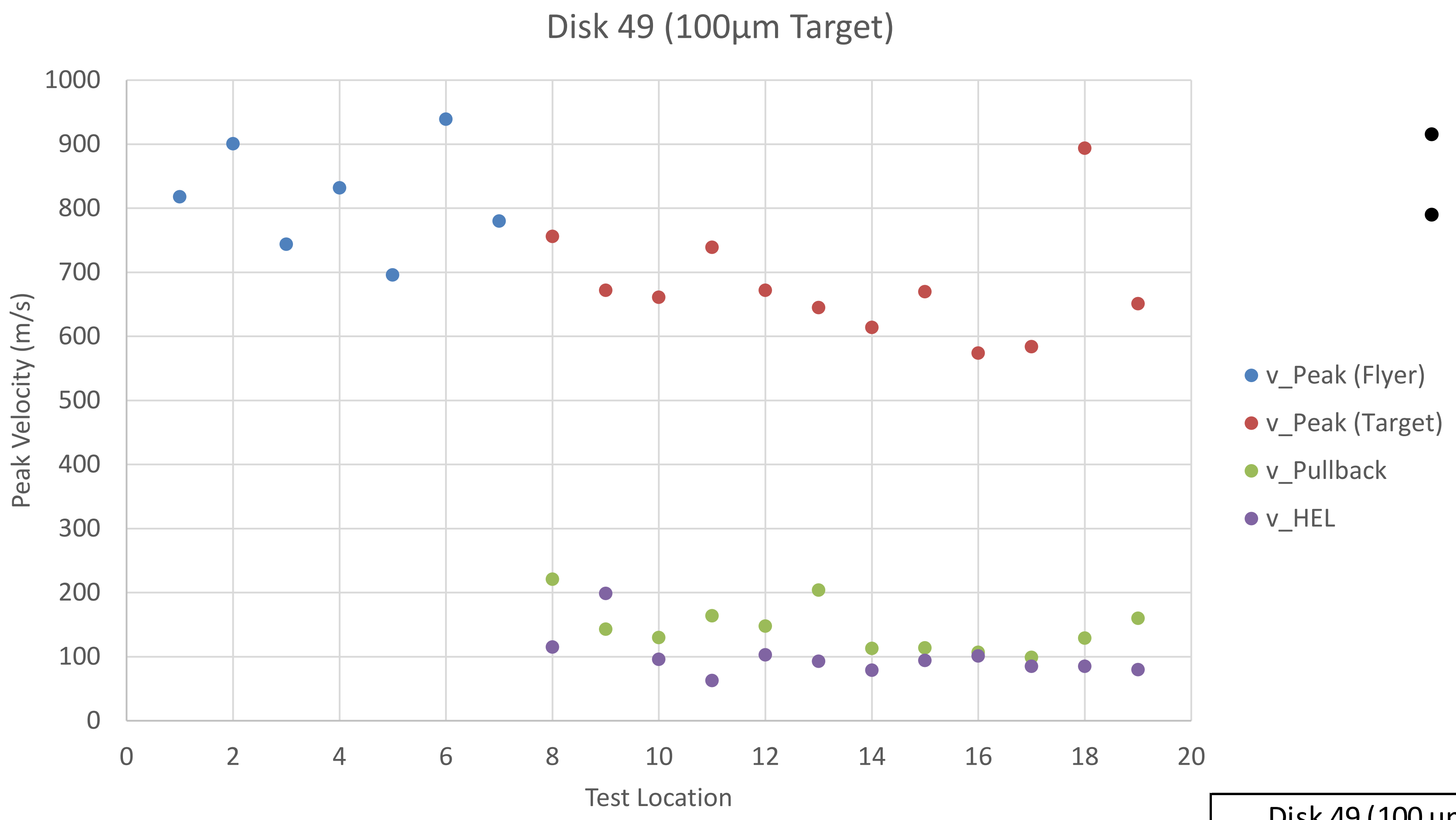
Disk 41 (AL 6061-T6) Velocities



- HEL readable in 15/16 tests
- Peak & Pullback readable in 16/16 tests

Disk 41 (100µm)	[m/s]	[m/s]	[m/s]	[%]	[m/s]	[%]
Free Surface Velocities	Mean	Median	Standard Deviation		1/2 Interquartile Range	
Peak Flyer	1098	1128	89	8%	52.75	5%
Peak Target	893	879	54	6%	42.625	5%
Pullback	160	161	42	26%	31.125	19%
HEL	104	100	17	16%	8	8%

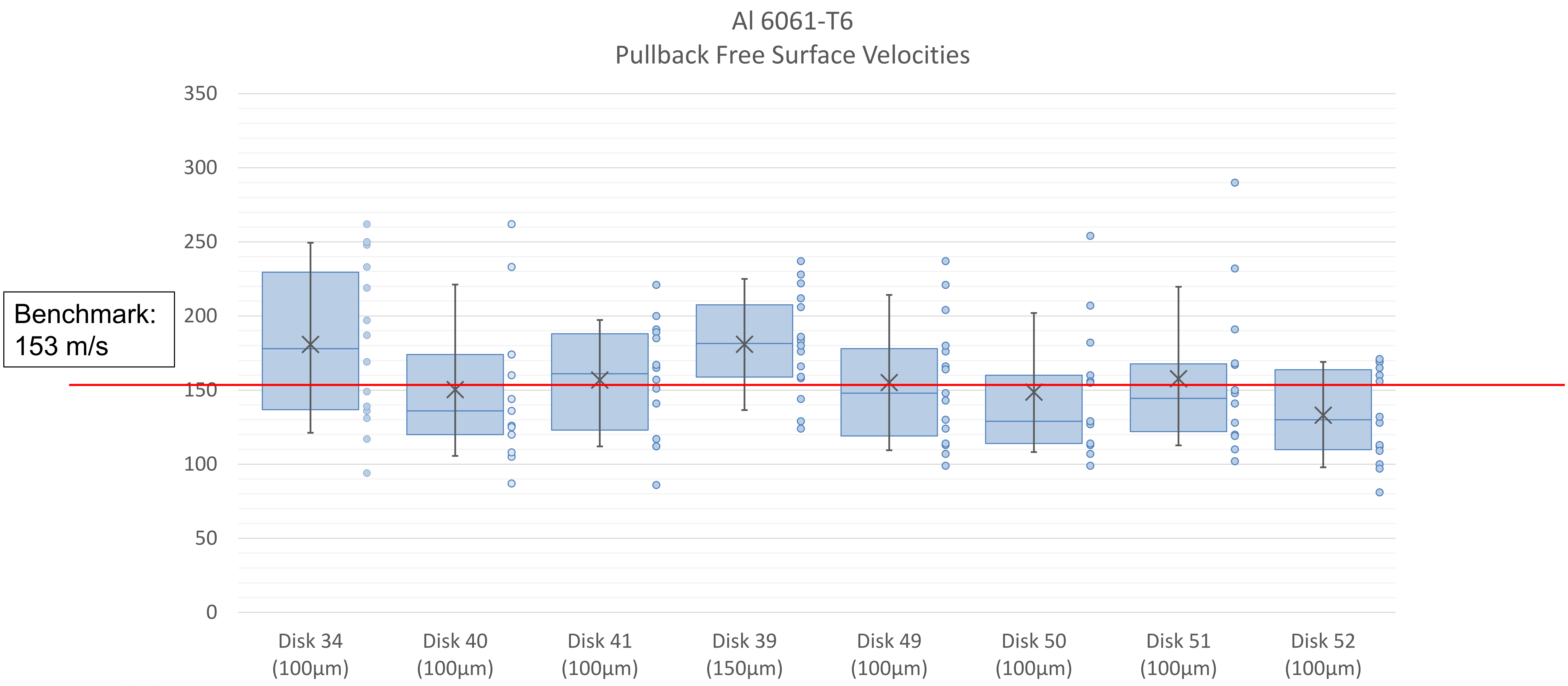
Disk 49 (AL 6061-T6) Velocities



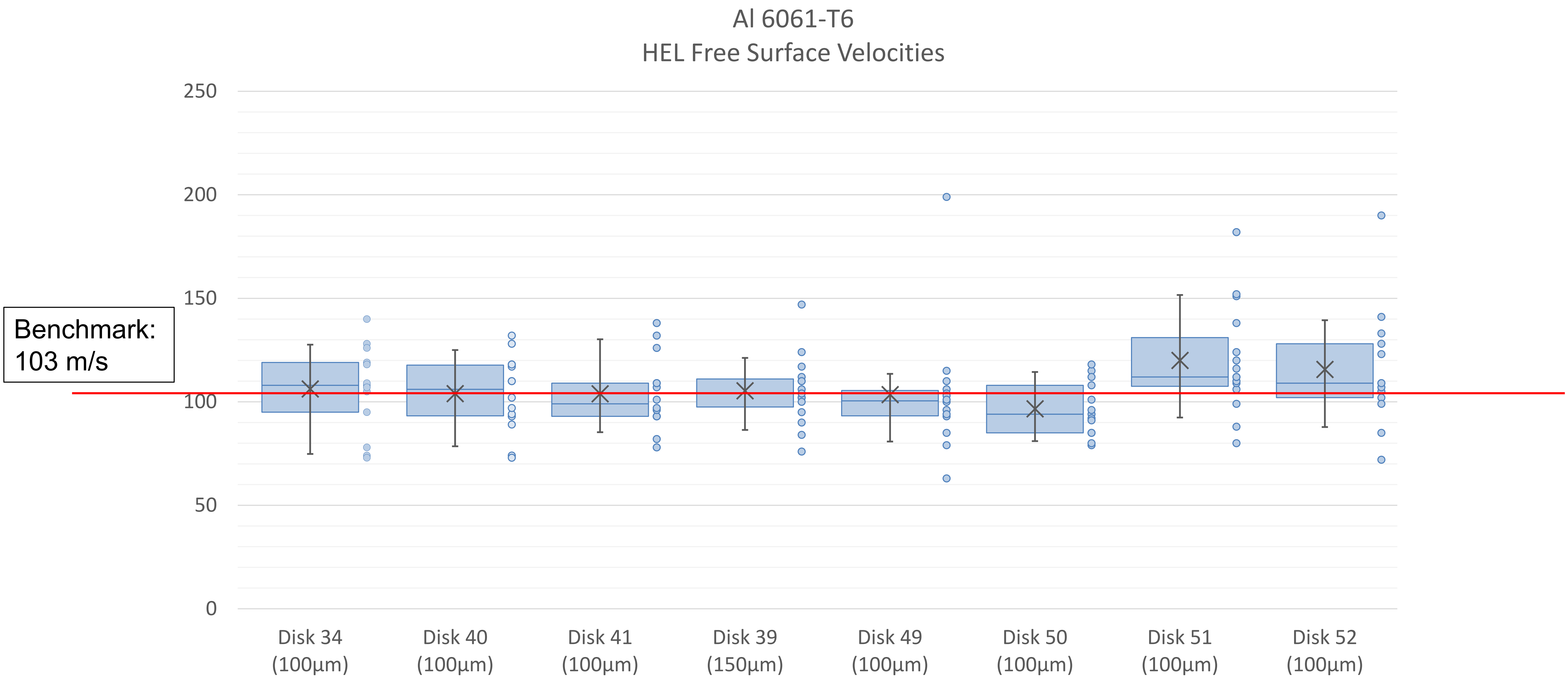
- HEL readable in 12/12 tests
- Peak & Pullback readable in 12/12 tests

Disk 49 (100 µm)	[m/s]	[m/s]	[m/s]	[%]	[m/s]	[%]
Free Surface Velocities	Mean	Median	Standard Deviation		1/2 Interquartile Range	
Peak Flyer	816	818	79	10%	52.25	6%
Peak Target	678	665.5	83	12%	25.75	4%
Pullback	144	136.5	36	25%	23.625	16%
HEL	99	93.5	33	33%	8.875	9%

Aluminum 6061-T6 Pullback Velocities



Aluminum 6061-T6 HEL Velocities



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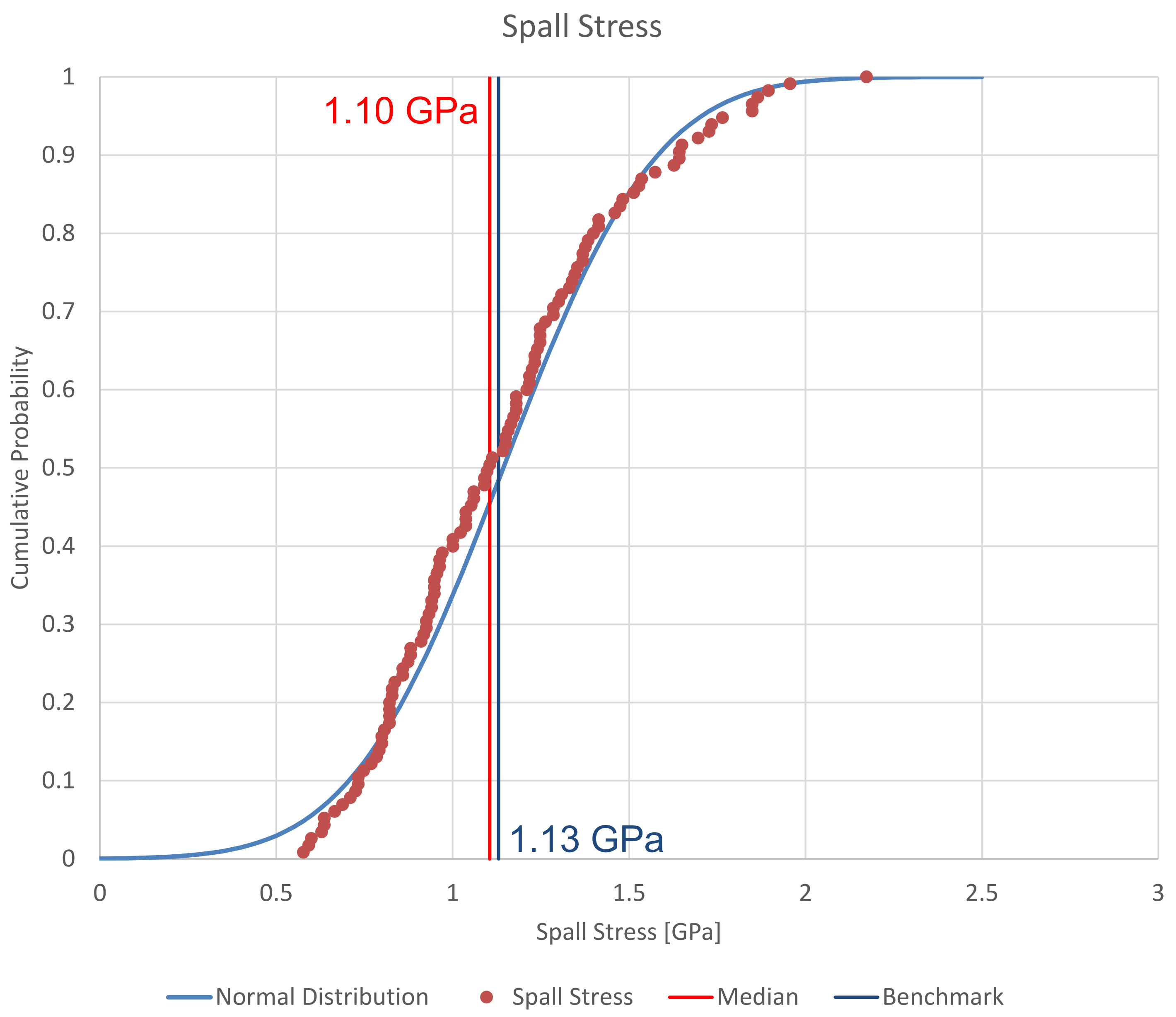
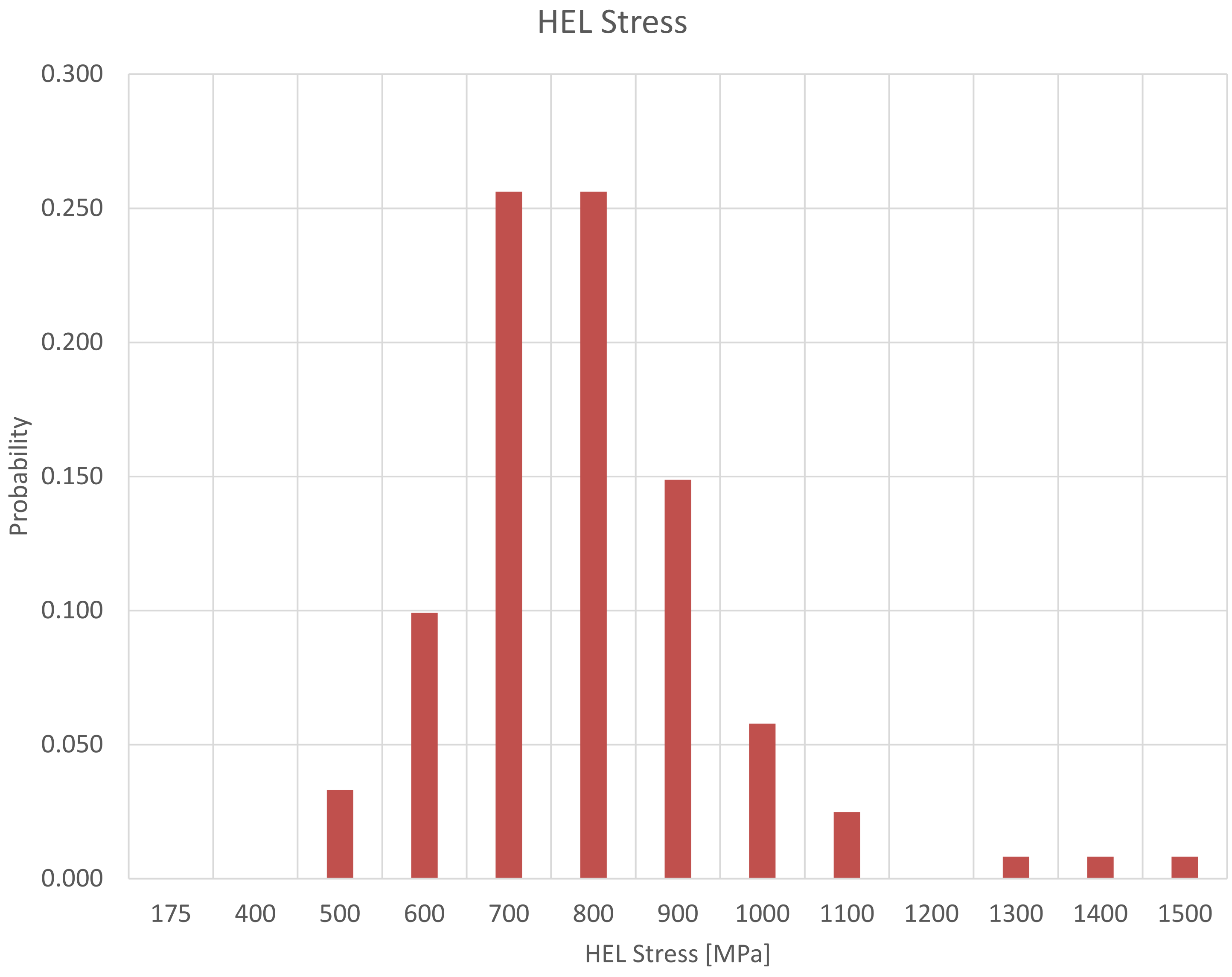
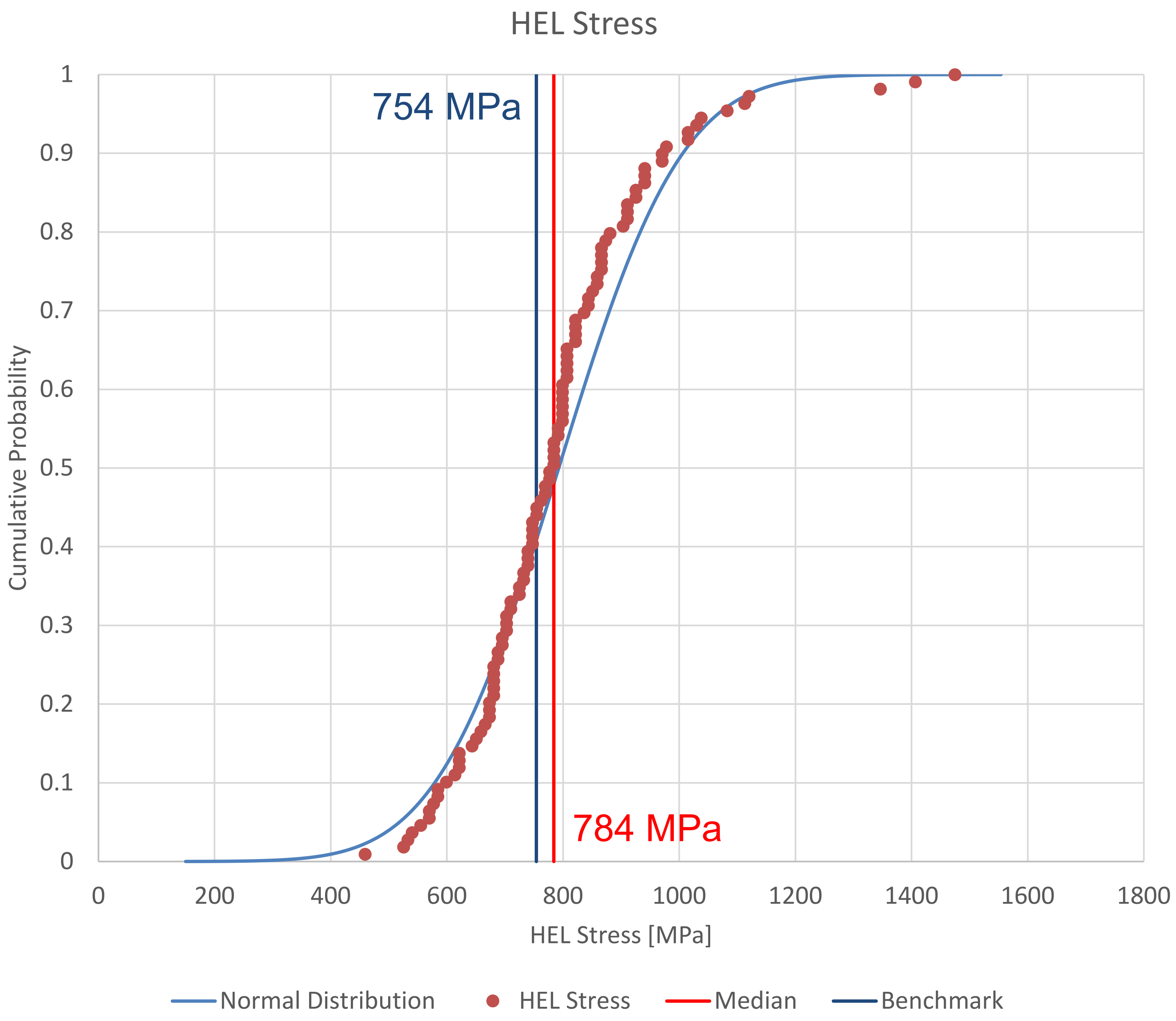
Aluminum 6061-T6 Spall Stress



Aluminum 6061-T6 HEL Stress





AL 6061-T6 Results Summary

AL-6061 T6	All Targets		Benchmark	Mean	Median	Standard Deviation		1/2 Interquartile Range	
Free Surface Velocity	Peak	[m/s]		749	768	126	17%	86	11%
	Pullback	[m/s]	153	155	150	45	29%	32	20%
	HEL	[m/s]	103	108	107	22	21%	12	11%
Shock Velocity	Peak	[m/s]		5852	5865	84	1%	58	1%
Hugoniot Pressure		[GPa]		5.94	6.09	1.07	18%	0.74	12%
Spall Stress		[GPa]	1.13	1.14	1.10	0.34	30%	0.24	21%
HEL Stress		[MPa]	754	793	784	167	21%	89	11%
Dynamic Strength		[MPa]		402	398	85	21%	45	11%

Total Readings	
Peak	117
Pullback	115
HEL	109

Conclusions

- The laser-driven flyer technique has recently been implemented at SwRI by the team PEC/SwRI.
- It is successfully providing reliable HEL and spall stress on selected foil materials like Al6061 T6 and Inconel 718.
- Equation of state data is in development.
- This test may supplement the tests performed in the large gun systems.

Thank You!

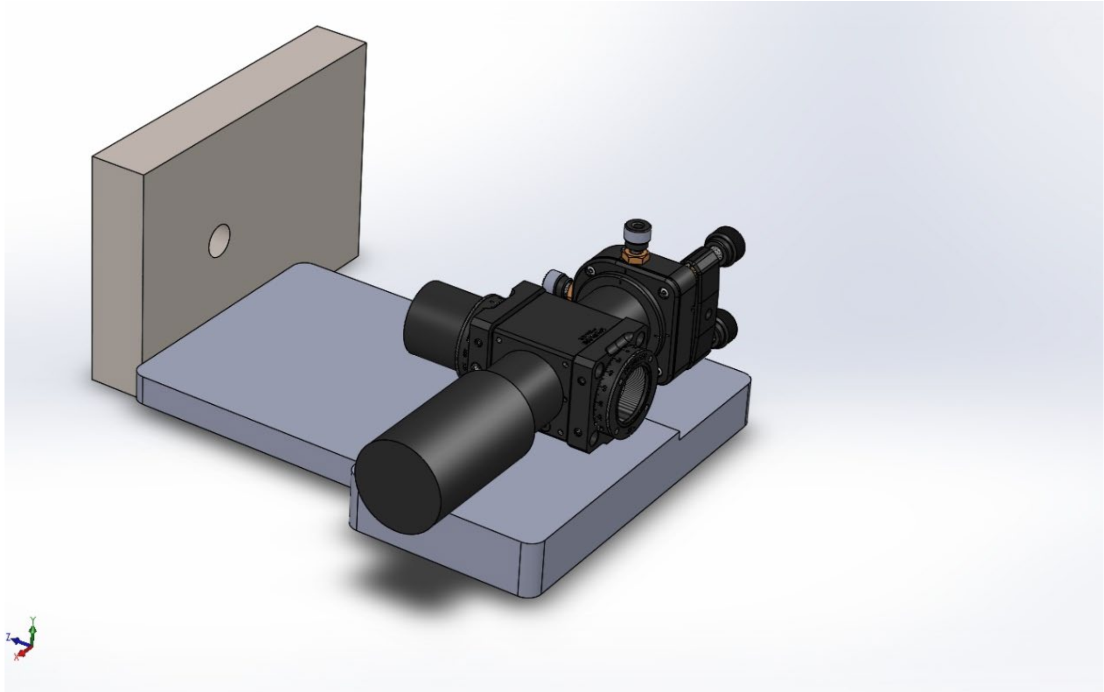
Questions?

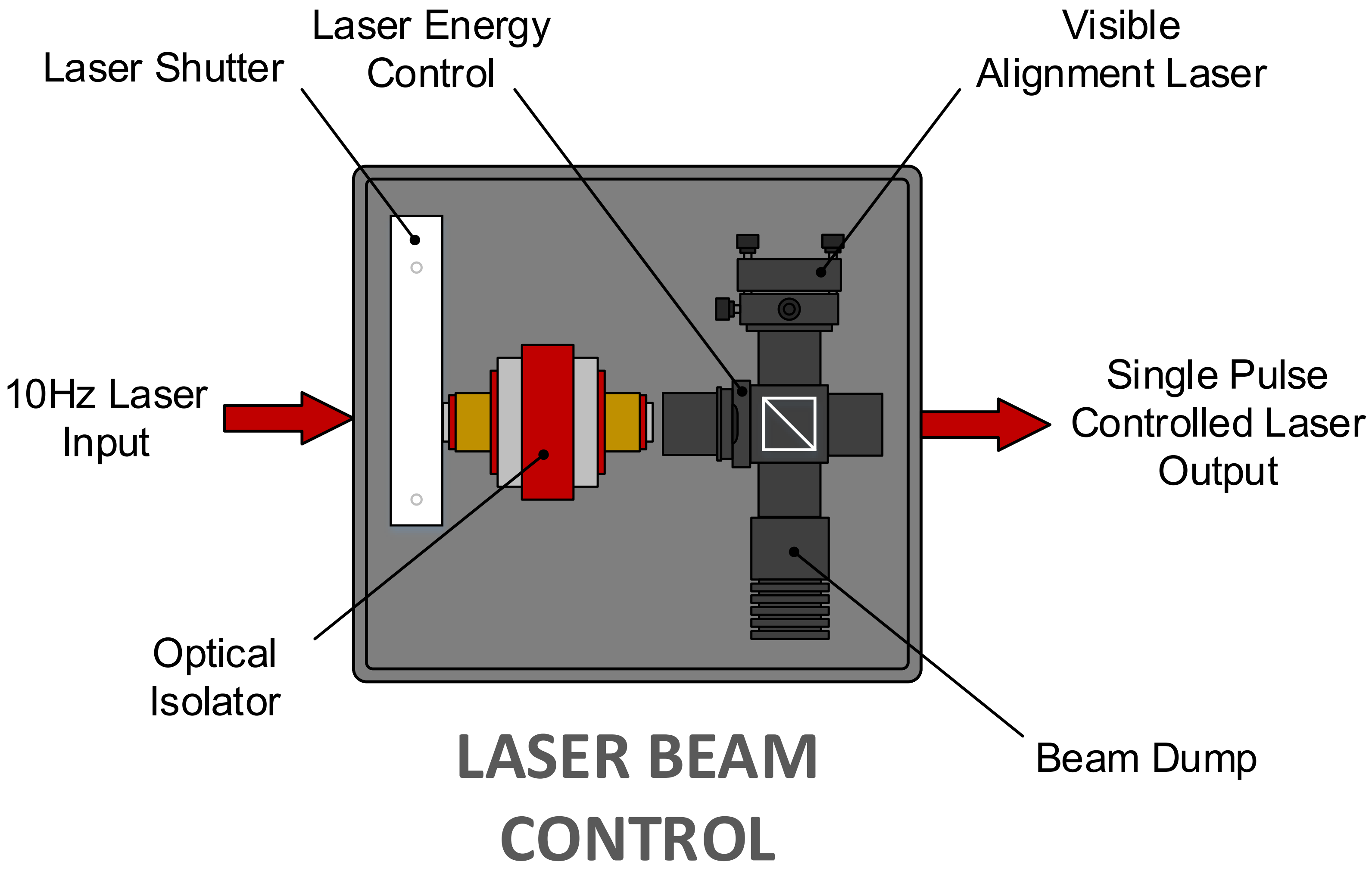
daniel.portillo@swri.org

sidney.chocron@swri.org

mbarsotti@protection-consultants.com

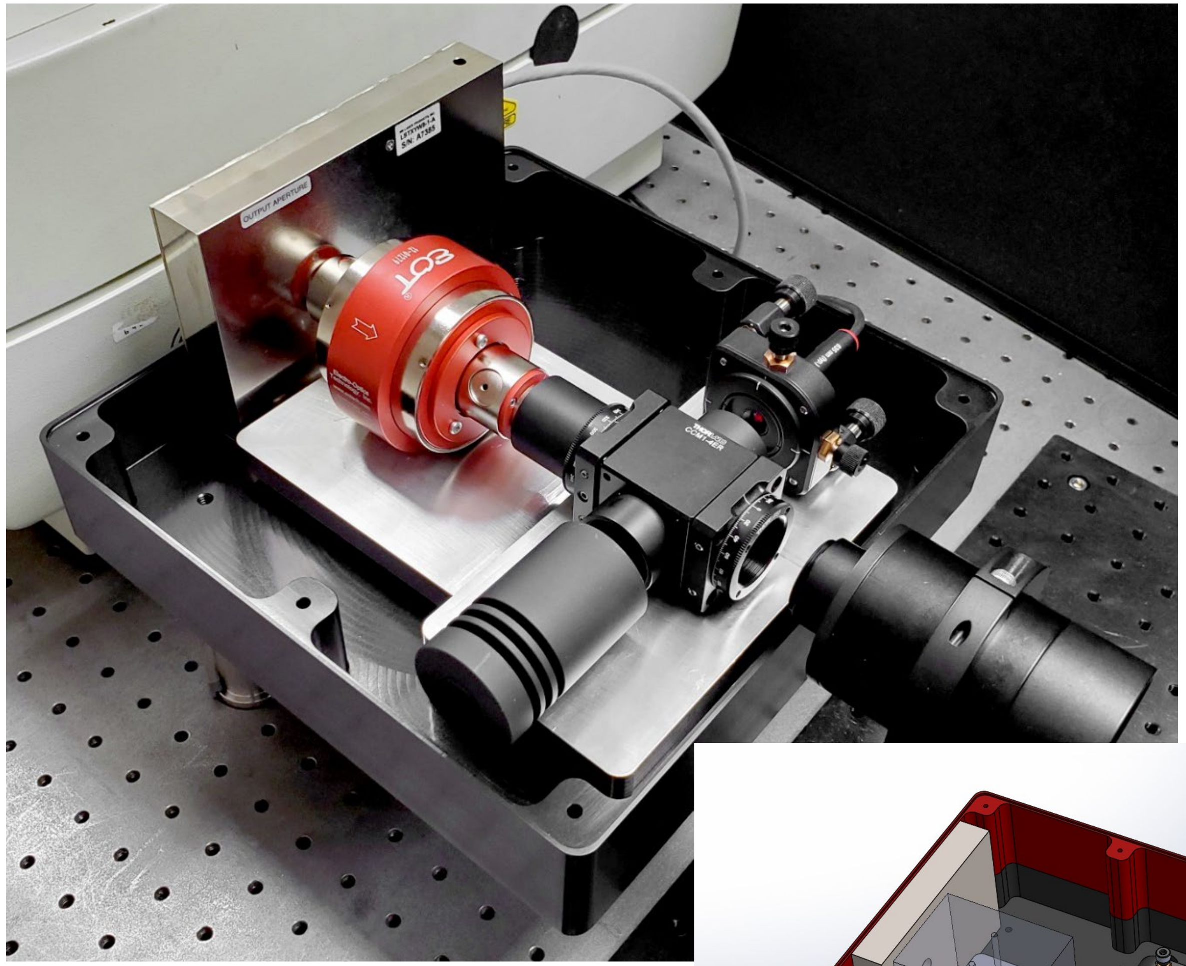
Laser Beam Control

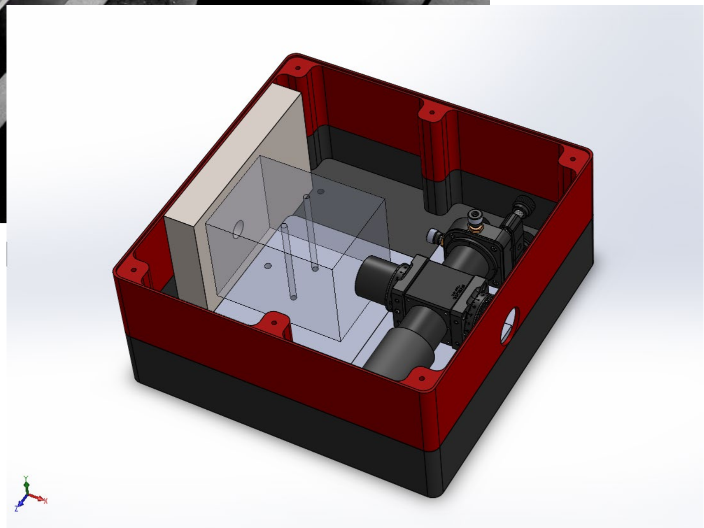




Laser Beam Control Assembly

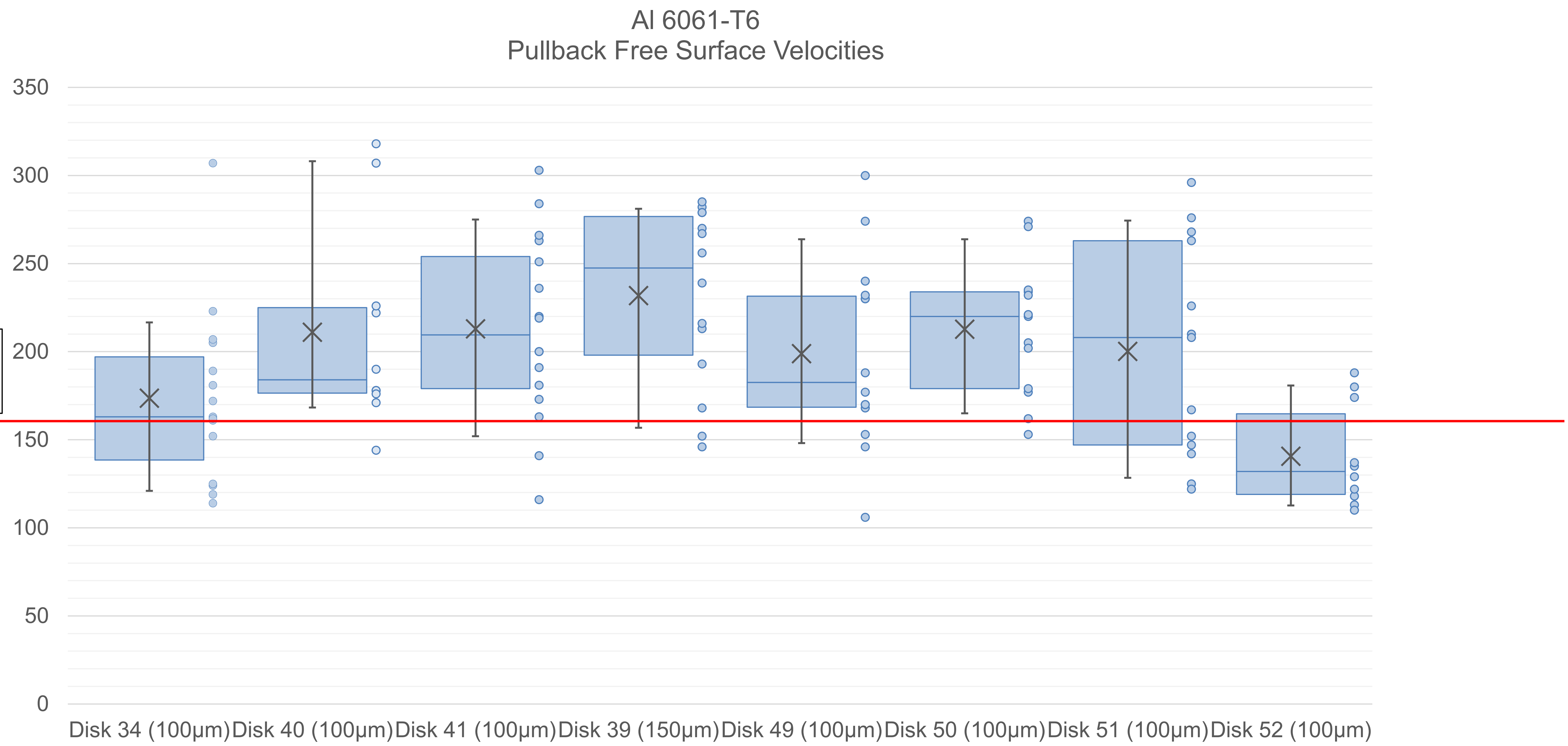
- Modular beam control assembly & alignment completed.
- Shutter moved inside the laser



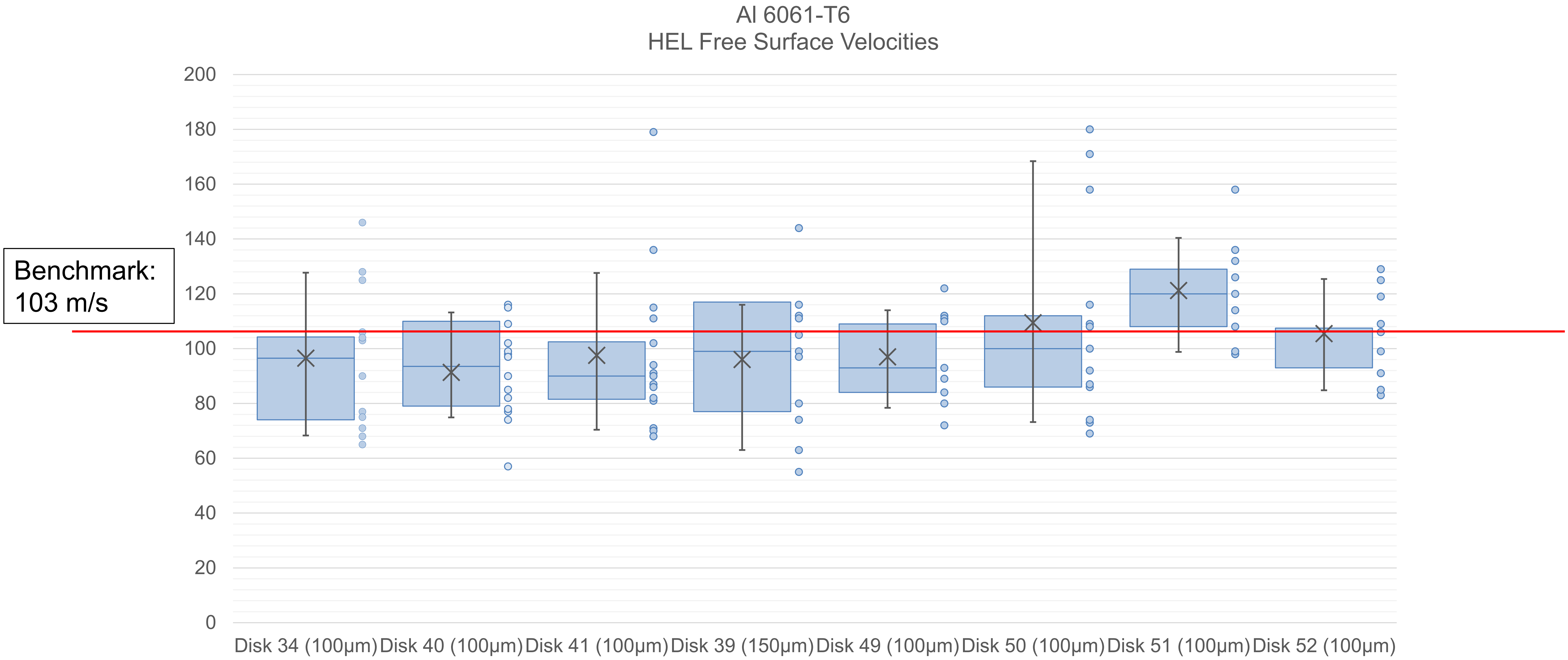


Aluminum 6061-T6 Pullback Velocities (Old Analysis)

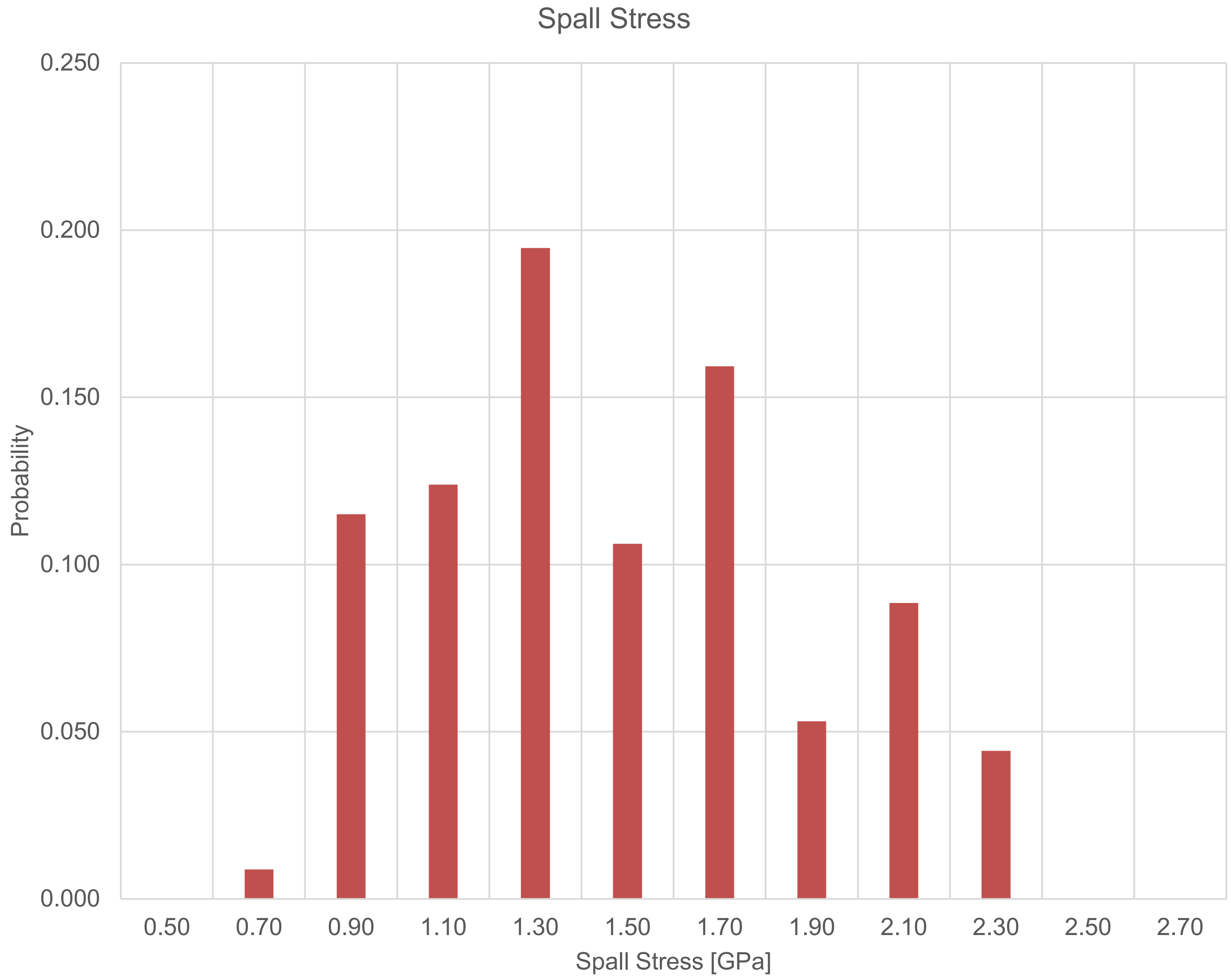
Benchmark:
153 m/s

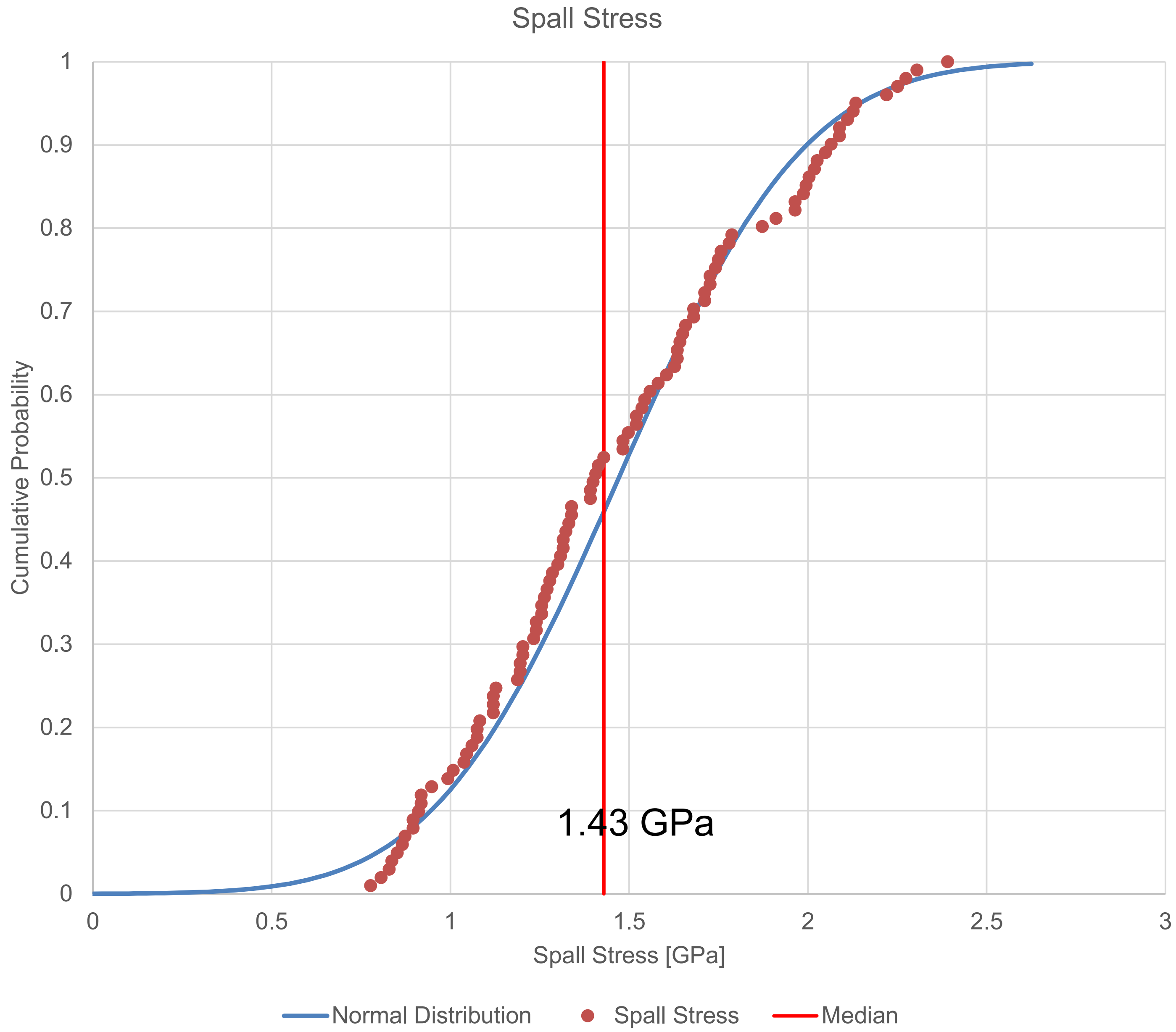


Aluminum 6061-T6 HEL Velocities (Old Analysis)



Aluminum 6061-T6 Spall Stress (Old Analysis)





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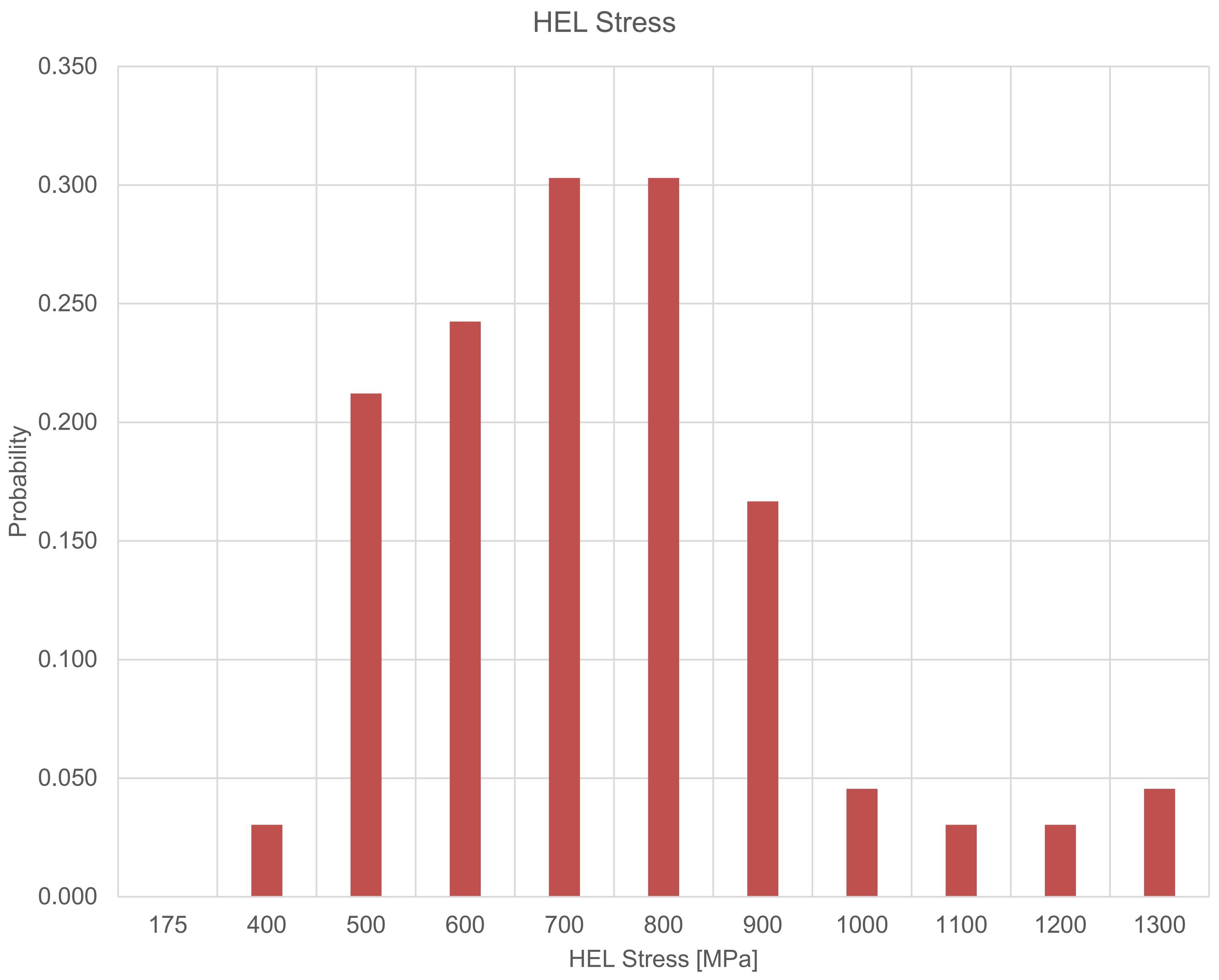
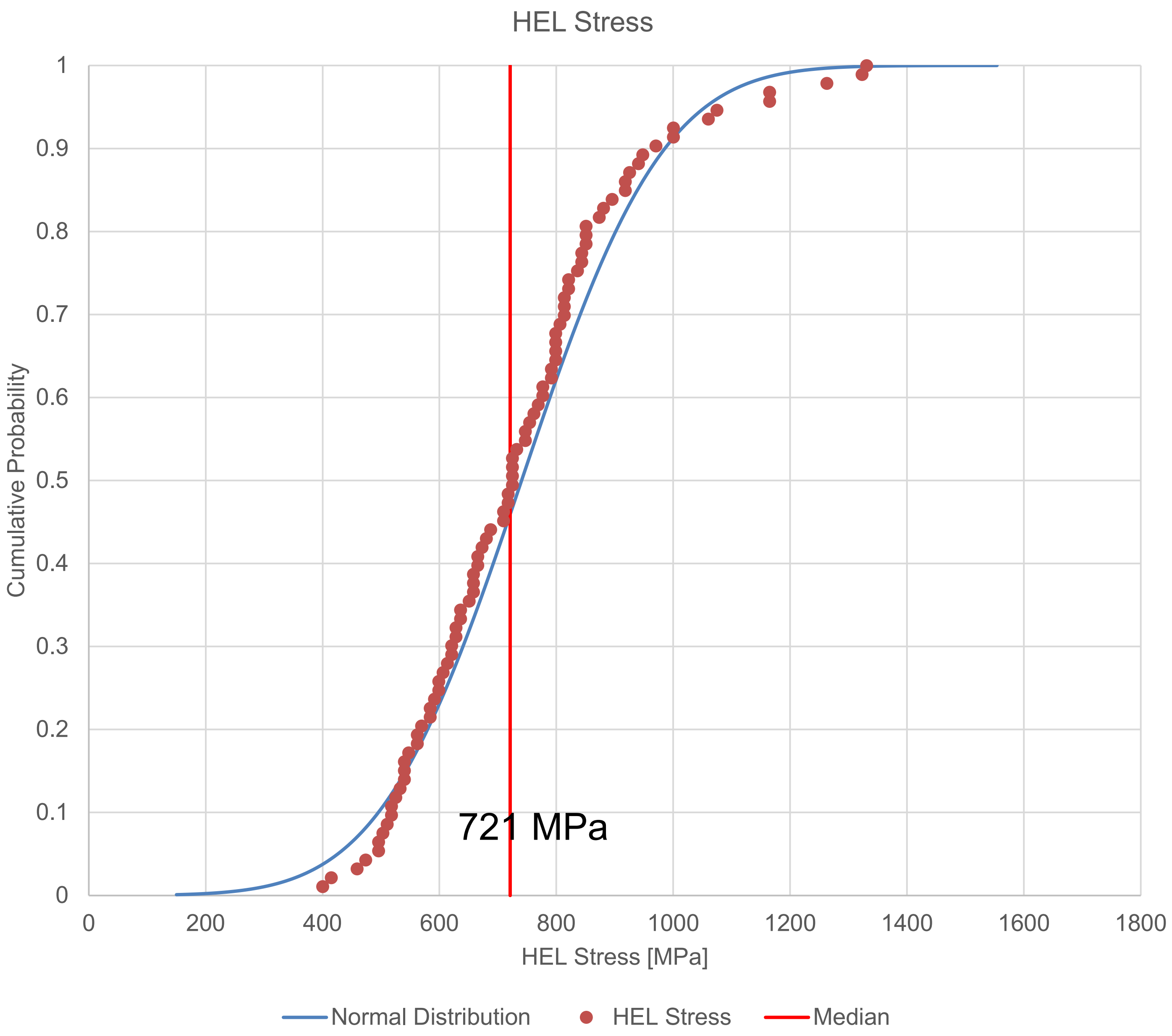
Aluminum 6061-T6 HEL Stress (Old Analysis)





Aluminum 6061-T6 Spall Tests (Old Analysis)

- The summary values indicate that the micro flyer tests did well at matching the benchmark HEL stress
- The tests over-predicted the spall stress. However, it is unclear whether the benchmark data was artificially smoothed

AL-6061 T6	All Targets		Benchmark	Mean	Median	Standard Deviation		1/2 Interquartile Range	
Free Surface Velocity	Peak	[m/s]		788	813	125	16%	79	10%
	Pullback	[m/s]	153	198	193	54	27%	37	18%
	HEL	[m/s]	103	101	99	26	25%	16	16%
Shock Velocity	Peak	[m/s]		5878	5896	84	1%	53	1%
Hugoniot Pressure		[GPa]		6.28	6.49	1.07	17%	0.68	11%
Spall Stress		[GPa]	1.13	1.47	1.43	0.41	28%	0.28	19%
HEL Stress		[MPa]	754	741	721	191	26%	119	16%
Dynamic Strength		[MPa]		376	366	97	26%	60	16%