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PDV Velocimetry Features as a Glue Layer Diagnostic in Windowed Shock Experiments

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Summary

A series of experiments were conducted using samples with different glue layer thicknesses between a LiF window and HE driven, shocked sample coupons. We completed a total of 13 shots (4 with integrating sphere, 8 with glue and one in vacuum), all with PBX 9501 driving a Sn coupon with a LiF window on the metal sample. Four shots were done with 3.5 mm Sn coupons, 5 mm LiF, and integrating spheres. Two shots of those 4 were done with the glower on to look for changes in emissivity and two were done in the same geometry to measure the radiance of the shock heated sample to measure the correction to the emissivity (if needed). The other 9 shots had LiF windows (6 or 10 mm thick) bonded with Loctite 326 glue of varying thicknesses (of these one was "glueless" – with an attempt at a "glueless" Sn/LiF interface with a rough vacuum). Three shots had thin Cr metal coatings (100 or 200 nm thick) on the Sn coupon.

We observe splitting of the velocity spectrogram trace at shock breakout that appears to be correlated with the glue layer thickness. This resolves a puzzling feature that appeared in several gas gun shots where the glue layer was measured (mechanically using a stack-up method) to be a few microns or less (sometimes negative values resulted). If the data here is interpreted correctly, then those layers were likely thicker – perhaps 2 or 3 times the reported thicknesses measured with mechanical methods.

Shots BB100525 through BB100527-2: Integrating Sphere Shots (with PDV and Cold IR Pyrometer)

These 4 shots were conducted using a single Lightpath collimated probe in the integrating sphere, constructed with a pulsed glower and optical coupling to allow simultaneous radiance measurements in the 1-5 μm wavelength range. Two shots were conducted with the glower on (for dynamic emissivity measurements) and two were conducted with the glower off to measure the self-light of the shock heated target to allow us to correct the emissivity measurement for this effect.

The PDV data were taken with a 40 GS/s digitizer so we could analyze the single PDV channel with higher time resolution that we might normally be able to do. See the appendix for details and figures of these shots.

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All 4 shots used a (nominal) 3.5 mm Sn coupon glued to a (nominal) 5 mm thick LiF window. All targets and LiF windows were measured mechanically and the glue layer thickness was measured using Bruce's white light interferometer.

Shots BB100531-1 through BB100603-2: LiF Windowed Shots using PDV and Armando Pyrometer "Box 2" (aka the "JASPER" Radiometer)

The main purpose of these shots was to study the effect of glue layer thickness, gaps, and thin Cr metal coatings on the radiometry data obtained from shocked Sn. All coupons were nominally 1 mm in thickness with (mostly) 6 mm LiF windows (nominal). Two shots used a thicker 10 mm window. Two were constructed to have no glue joint at all and attempted a vacuum "glueless" coupling. Because of the imperfect flatness of the Sn and LiF, there is still a measureable gap at the metal/window interface. Of the two "vacuum" shots, one was lost due to a detonator malfunction.

The probe was the larger version of the combined PDV/Radiometer probe built by NSTec for use at LANL and JASPER. It contains 3 PDV fibers (on a ~1 mm diameter circle equally spaced in angle) and seven 300 μm radiometry fibers. Thus for all (but two) shots we had 3 separate PDV measurements of the breakout and velocity at the interface. The two shots that had only 2 were because of a weak PDV return at breakout on one channel of each shot.

Because we were limited in recording capability, we recorded all 3 probes at 20 GS/s for each of these shots, resulting in slightly poorer time resolution of the velocity. We were able to compensate for that somewhat by the fact we had 3 independent measurements at (hopefully) the same glue layer thickness, over the ~1 mm diameter circle for the 3 points. This enabled a calculation of a standard deviation for the 3 points that are listed in the Table for each shot. For the two shots were only 2 PDV points were measured, we quote the average and an uncertainty obtained from the FFT analysis parameters.

Results

As one can tell from looking at the PDV spectrogram analyses (see figures in the Appendix), the splitting/ring-down feature is close to the limit of time resolution possible with these data, particularly for the thinner glue layers. Also the placement of the cursors to obtain the annotated times in the figures is somewhat subjective, but I think it is persuasive that there is a trend present. If the data is analyzed in a self consistent way, using similar criteria for choosing the onset and end of the splitting, I think most people would arrive at similar conclusions even if the precise times obtained might differ. The most difficult cases were the thinnest glue layers (Figures A15 and A16 in the Appendix). The vacuum shot (BB100601-1) is shown in Figure A11 in the Appendix and is consistent with no observable splitting.

Figure 1 shows a plot of the uncorrected ring-down times vs. measured glue layer thickness. The vertical error bars are the ±1σ estimate of the time resolution from the FFT analysis parameters for the 4 integrating sphere shots and the two shots were only 2 PDV measurements were obtained. For the remaining 6 shots the uncertainty is a calculated one standard deviation for the 3 independent probe points on each shot. The horizontal error bars are ± 0.5 μm (Bruce's estimated uncertainty of the glue layer thickness measurement). There is good reason to think this uncertainty is smaller than this, but let's use 0.5 μm for now.

Figure 2 shows the same results, corrected for the estimated time resolution of the measurements. I assume that the observed splitting (Figure 1) is the quadrature sum of the "true" splitting time and the estimated time resolution (from the FFT parameters). This is an assumption, but I hope a reasonable one. The linear fit (Figure 2) results in a slope of 0.45 ± 0.09 with an intercept of 1.38 ± 1.08 ns with a $\chi^2=0.92$. Adding a constraint to intercept the origin does not significantly change the results.

Figure 3 shows the corrected ringdown vs. glue thickness but with a quadratic fit. The fit is slightly better (as one would expect) with an intercept of 0.44 ns, a linear slope of 0.66 and a quadratic coefficient of -0.007. Again, adding an origin constraint doesn't appreciably change the fit results. There is no physics reason I can muster that argues for a quadratic dependence of the ringdown times on thickness – linear makes more sense to me. The uncertainties on the quadratic fit parameters are also rather large, also indicating that the additional degree of freedom is not compelled by the fit.

The glue thicknesses, corrected and uncorrected times are summarized in Table 1.

Summary

Using the white light interferometry (thank you, Bruce!) has provided confirming insight into a phenomenon that has been observed for some time. We had interpreted this feature in the PDV breakout velocity as the ring-up across the glue layer, but did not have any concrete evidence that the finite glue layer thickness was the cause.

Now I think we have such evidence.

We should be able to apply these results to estimate the glue layer thickness on the earlier gun shots where we may not have had as precise a glue layer thickness measurement as can be achieved interferometrically.

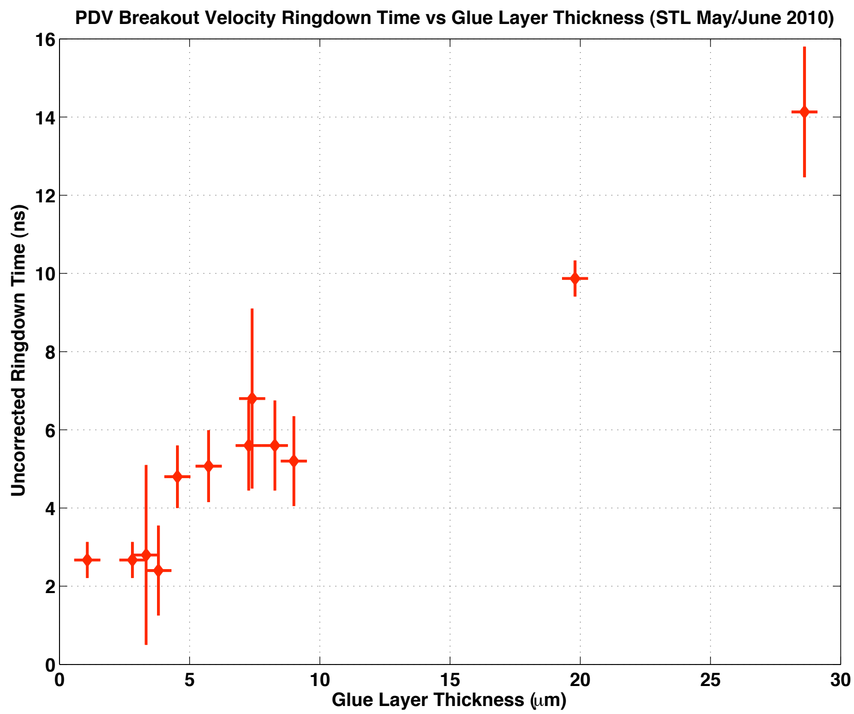


Figure 1: Plot of Uncorrected Ring Down Time (ns) vs. Glue Layer Thickness (μm)

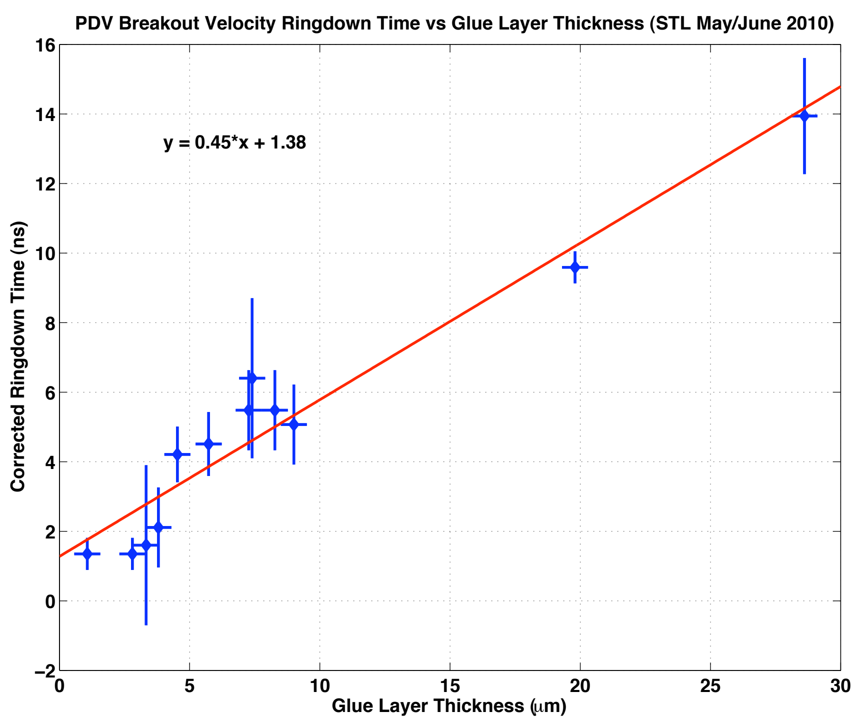


Figure 2: Plot of Corrected Ring Down Time (ns) vs. Glue Layer Thickness (μm) with a linear fit

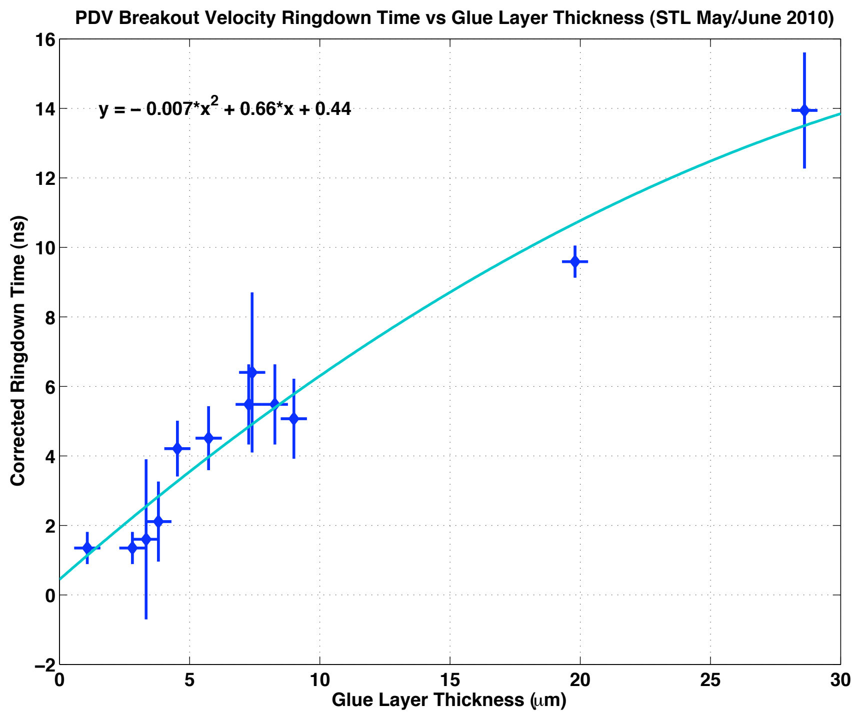


Figure 2: Plot of Corrected Ring Down Time (ns) vs. Glue Layer Thickness (μm) with a quadratic fit

Table 1: Measured Glue Layer Thicknesses from Integrating Sphere and Shots using the Large PDV/Radiometry Probes

Shot Number	Target Number	Target/LiF Configuration	Glue Layer Thickness★	Raw Ringdown Time (ns)	Corrected Ringdown Time (ns)
BB100525	100506-1	Sphere/3.5 mm Sn/5 mm LiF	7.27 µm	5.60 ± 1.15 ns†	5.48 ± 1.15 ns†
BB100526	100506-2	Sphere/3.5 mm Sn/5 mm LiF	8.27 µm	5.60 ± 1.15 ns†	5.48 ± 1.15 ns†
BB100527-1	100506-3	Sphere/3.5 mm Sn/5 mm LiF	3.80 µm	2.40 ± 1.15 ns†	2.11 ± 1.15 ns†
BB100527-2	100506-4	Sphere/3.5 mm Sn/5 mm LiF	9.00 µm	5.20 ± 1.15 ns†	5.07 ± 1.15 ns†
BB100531-1	100504-1	1 mm Sn/6 mm LiF	4.53 µm	4.80 ± 0.80 ns‡	4.21 ± 0.80 ns‡
BB100531-2	100505-1	1 mm Sn/100 nm Cr/6 mm LiF	5.73 µm	5.07 ± 0.92 ns‡	4.51 ± 0.92 ns‡
BB100601-1	100504-4	1 mm Sn/6 mm LiF	"Vacuum"	Not observed	Not observed
BB100601-2	100504-2	1 mm Sn/6 mm LiF	3.33 µm	2.80 ± 2.30 ns†	1.60 ± 2.30 ns†
BB100601-3	100504-3	1 mm Sn/6 mm LiF	7.40 µm	6.80 ± 2.30 ns†	6.40 ± 2.30 ns†
BB100602-1	100525-1	1 mm Sn/10 mm LiF	28.61 µm	14.13 ± 1.67 ns‡	13.94 ± 1.67 ns‡
BB100602-2	100505-2	1 mm Sn/100 nm Cr/6 mm LiF	1.07 µm	2.67 ± 0.46 ns‡	1.35 ± 0.46 ns‡
BB100602-3	100505-3	1 mm Sn/200 nm Cr/6 mm LiF	2.80 µm	2.67 ± 0.46 ns‡	1.35 ± 0.46 ns‡
BB100603-1	100504-5	1 mm Sn/6 mm LiF	"Vacuum"	Lost	Lost
BB100603-2	100602-1	1 mm Sn/10 mm LiF	19.80 µm	9.87 ± 0.46 ns‡	9.59 ± 0.46 ns‡

★ Uncertainty in thickness measurement estimated to be ± 0.5 µm.
† Uncertainty in time estimated from PDV analysis parameters.
‡ Uncertainty from standard deviation of 3 PDV measurements.

Appendix: Discussion of Details of Each Shot and Figures

Shot BB100525: 3.5 mm Sn + 5 mm LiF with Integrating Sphere with Glower On

Table 1 shows the glue layer thicknesses measured at the center of each coupon. For this shot the layer was 7.36 μm. Figures A1 and A2 show the velocity spectrogram and a zoom of the breakout region with annotations.

The PDV data was taken at 40 GS/s and was analyzed with a 256 point FFT, zero padded by x2 (for spectral resolution). The shift per analysis step was 1/16 (i.e. overlap was 15/16). These analysis factors translate into an estimated 1 σ time resolution of the velocity of 1.15 ns, with a velocity time bin size of 0.4 ns.

Shot BB100526: 3.5 mm Sn + 5 mm LiF with Integrating Sphere with Glower On

Figures A3 and A4 are the spectrogram and zoom of the PDV data from shot BB100526. The measured glue layer thickness was 8.38 μm.

Shot BB100527-1: 3.5 mm Sn + 5 mm LiF with Integrating Sphere with Glower Off

Figures A5 and A6 are the spectrogram and zoom of the PDV data from shot BB100527-1. The measured glue layer thickness was the thinnest of the 4 integrating sphere shots – at 3.85 μm.

Shot BB100527-2: 3.5 mm Sn + 5 mm LiF with Integrating Sphere with Glower Off

Figures A7 and A8 are the spectrogram and zoom of the PDV data from shot BB100527-2. The measured glue layer thickness was the thickest of the 4 integrating sphere shots – 9.12 μm.

Shot BB100531-1: 1 mm Sn + 6 mm LiF

Figure A9 is of zooms of the 3 PDV points from shot BB100531-1. The measured glue layer thickness at the center was 4.53 μm.

Shot BB100531-2: 1 mm Sn + 100 nm Cr + 6 mm LiF

Figure A10 is of zooms of the 3 PDV points from shot BB100531-2. This tin target had a 100 nm Cr coating applied. The measured glue layer thickness at the center was 5.73 μm (between the Cr and LiF).

Shot BB100601-1: 1 mm Sn + 6 mm LiF – Glueless and Mostly Evacuated

Figure A11 is of zooms of the 3 PDV points from shot BB100601-1. This target was mounted in a small, evacuated (to < 1 mtorr) shot package. The measured gap at the center was 3.70 μm (between the Sn and LiF). There was no glue used. Note that in Figure A11 there are little or no detectable ringdown splitting, at least none comparable to glued interfaces of similar thickness. This is consistent with the near vacuum gap across the interface. The free surface velocity with 9501 and 1 mm Sn has been observed in the past to be ~2.25 – 2.3 km/s, so the gap would be closed in ~1.6 ns and may have been too fast to be observed distinctly with this PDV setup.

Shot BB100601-2: 1 mm Sn + 6 mm LiF

Figure A12 is of zooms of the 2 PDV points from shot BB100601-2. The measured glue layer thickness at the center was 3.33 μm. One of the PDV signals was so weak at breakout that no decent determination of splitting time was possible, so only 2 measurements were obtained on this shot.

Shot BB100601-3: 1 mm Sn + 6 mm LiF

Figure A13 is of zooms of the 2 PDV points from shot BB100601-3. The measured glue layer thickness at the center was 7.40 μm. One of the PDV signals was so weak at breakout that no decent determination of splitting time was possible, so only 2 measurements were obtained on this shot.

Shot BB100602-1: 1 mm Sn + 10 mm LiF Thick Glue Layer #1

Figure A14 is of zooms of the 3 PDV points from shot BB100602-1. The measured glue layer thickness at the center was 28.61 μm. This was one of the two deliberately thick glue layer shots. It is worth noting that these spectrograms are qualitatively similar to what Lynn Veeser has modeled with WONDY with a much thicker glue layer.

Shot BB100602-2: 1 mm Sn + 100 nm Cr + 6 mm LiF

Figure A15 is of zooms of the 3 PDV points from shot BB100602-2. The measured glue layer thickness at the center was 1.07 μm. This was perhaps the thinnest glue layer obtained in these experiments. The velocity splitting is correspondingly difficult to measure reliably – I think I can argue that the symmetry indicates a very short splitting. On the other hand, one can argue (probably convincingly) that this splitting looks the same as the vacuum case (Figure A11 above), but I include it here for the sake of our spirited arguments to come.

Shot BB100602-3: 1 mm Sn + 200 nm Cr + 6 mm LiF

Figure A16 is of zooms of the 3 PDV points from shot BB100602-3. The measured glue layer thickness at the center was 2.80 μm. It also was the thickest (200 nm) Cr coated sample we shot during this series. The splitting here is slightly more convincing than the previous shot, although also near the limit of what is measureable with this PDV configuration.

Shot BB100603-1: 1 mm Sn + 6 mm LiF Vacuum Package #2 (Lost)

This shot was lost due to a detonator malfunction.

Shot BB100603-2: 1 mm Sn + 10 mm LiF Thick Glue Layer #2

Figure A17 is of zooms of the 3 PDV points from shot BB100603-2. The measured glue layer thickness at the center was 19.80 μm. This was the second shot with a deliberately thick glue layer. Some pyrometry data was lost due to a triggering problem.

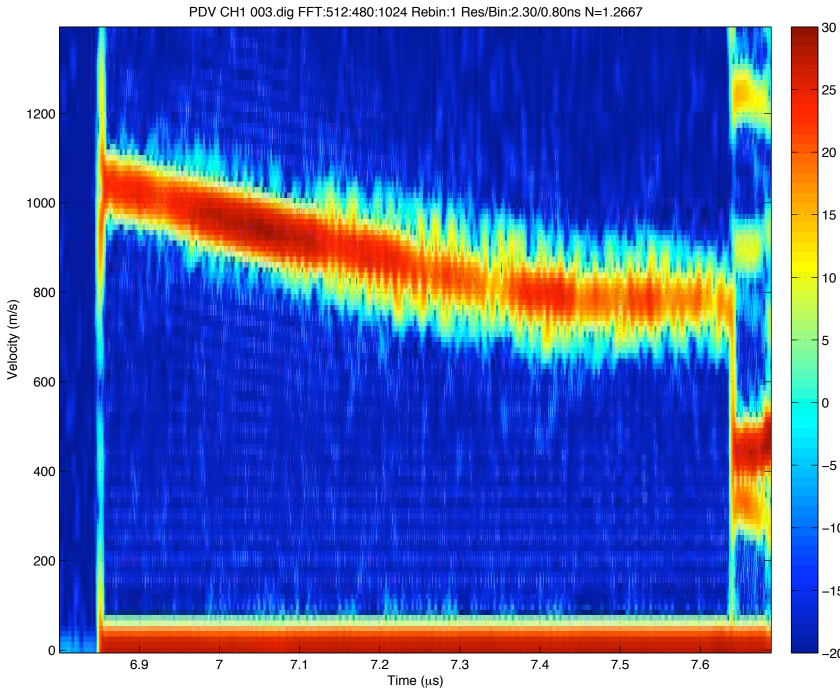


Figure A1: Spectrogram of velocity for shot BB100525

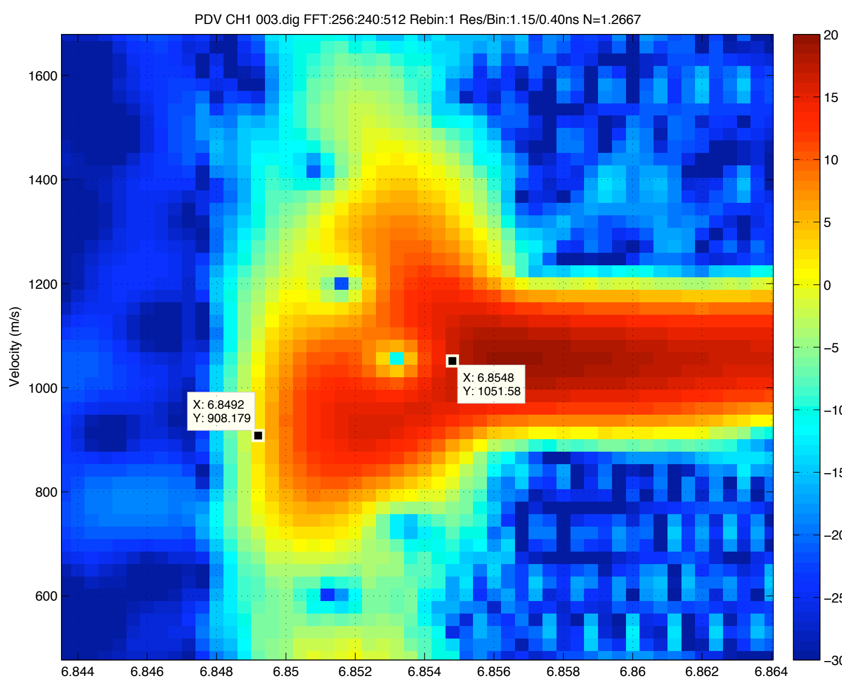


Figure A2: Spectrogram zoom of velocity for shot BB100525

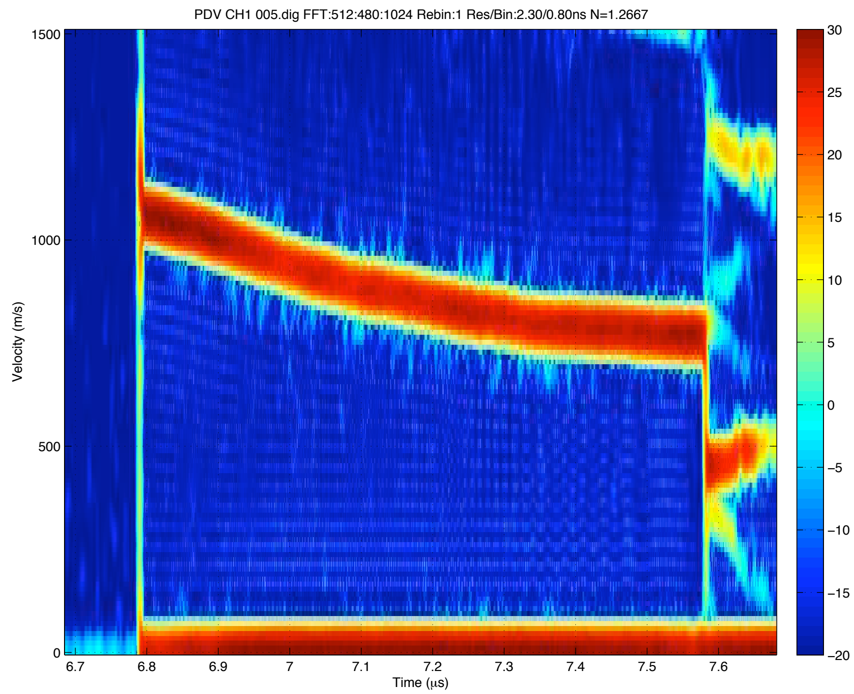


Figure A3: Spectrogram of velocity for shot BB100526

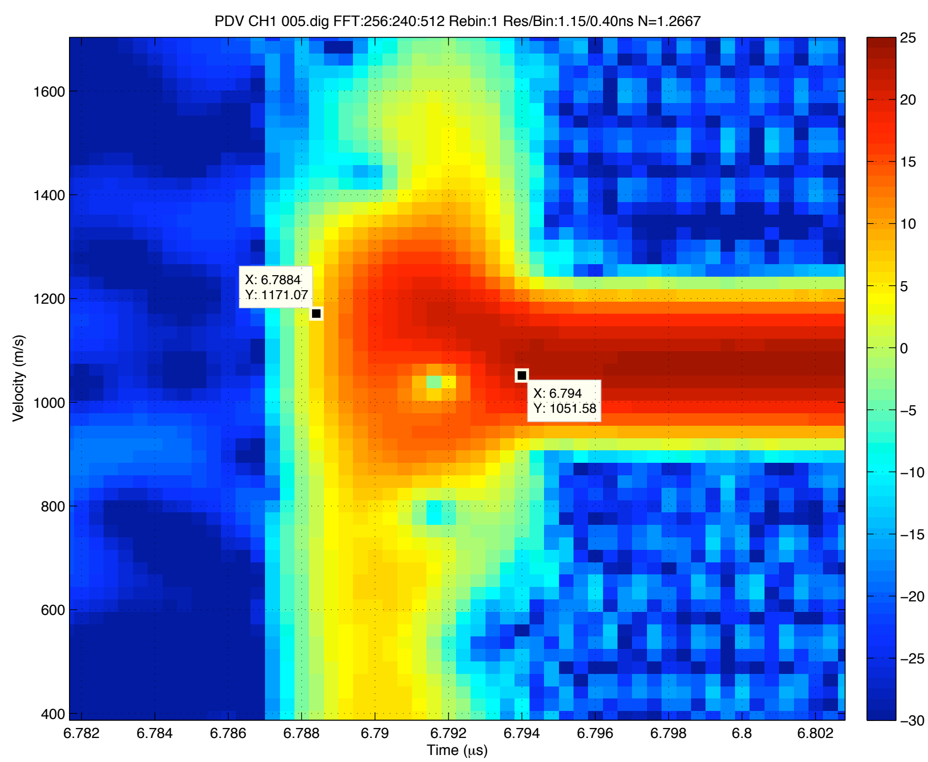


Figure A4: Spectrogram zoom of velocity for shot BB100526

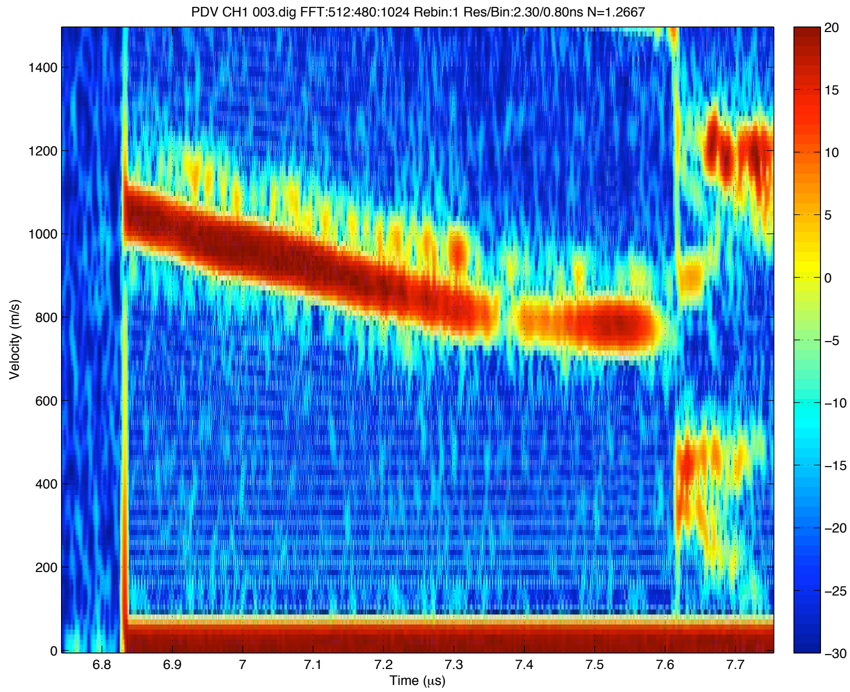


Figure A5: Spectrogram of velocity for shot BB100527-1

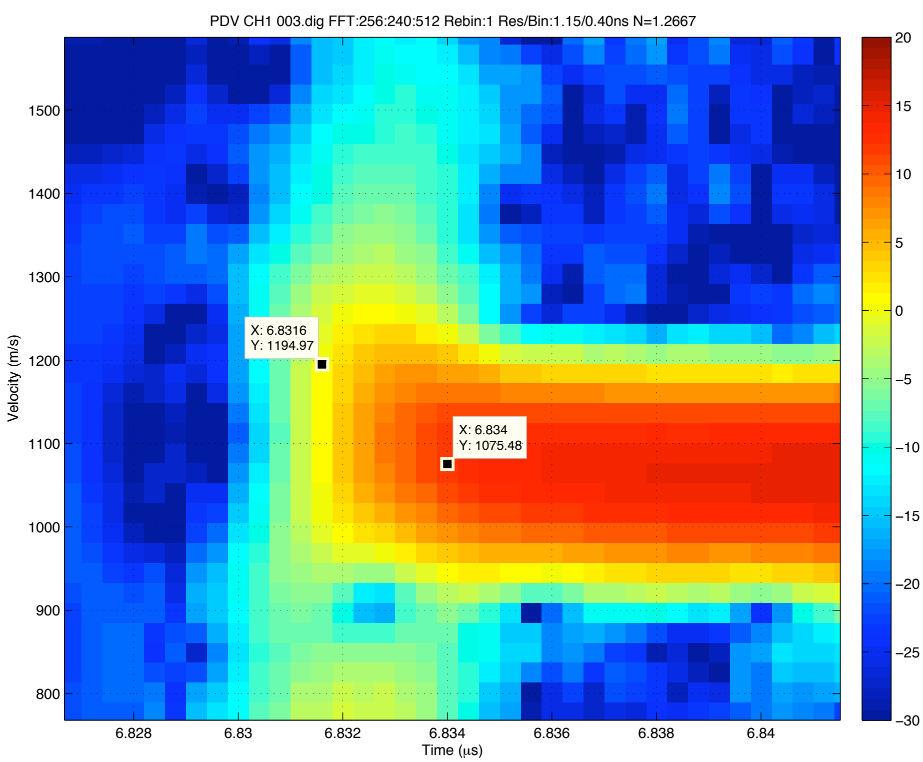


Figure A6: Spectrogram zoom of velocity for shot BB100527-1

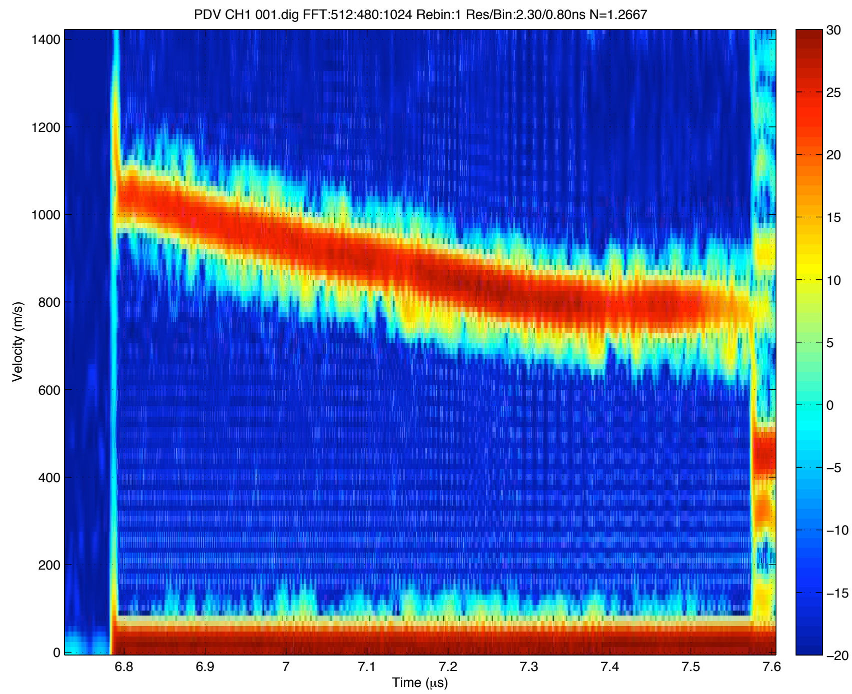


Figure A7: Spectrogram of velocity for shot BB100527-2

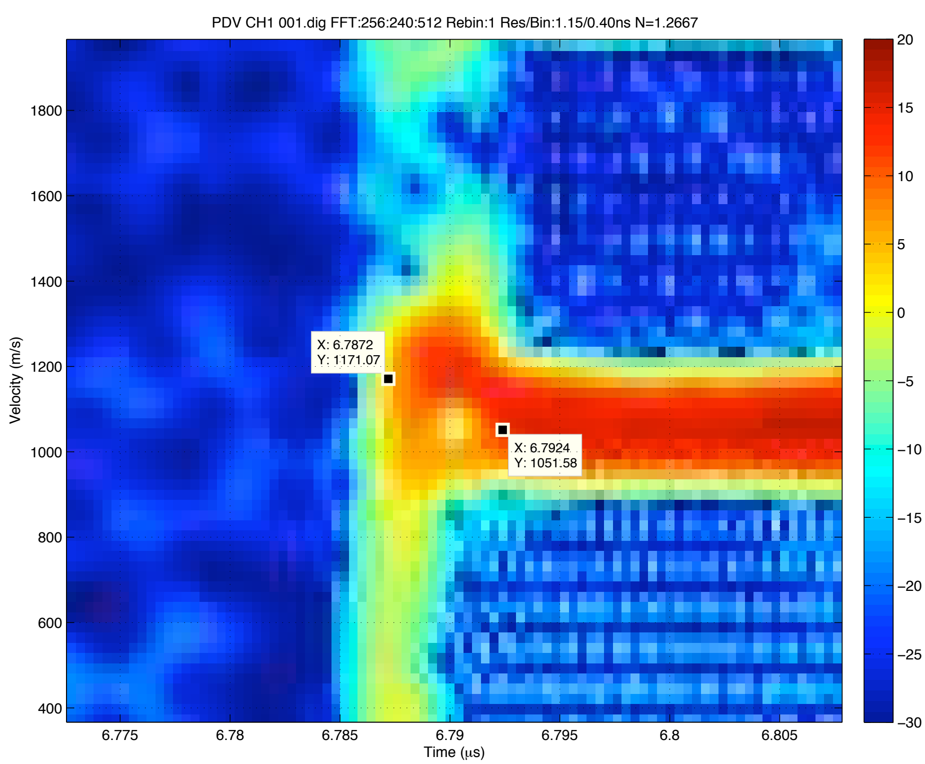


Figure A8: Spectrogram zoom of velocity for shot BB100527-2

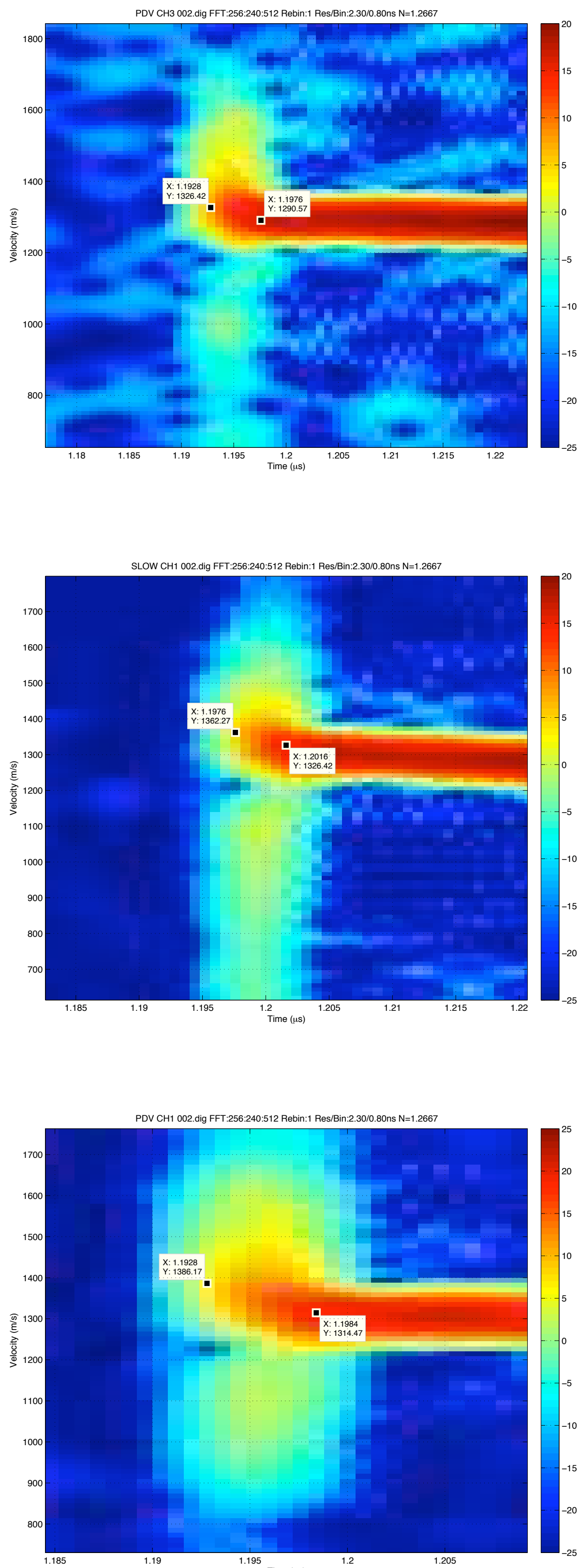


Figure A9: Spectrogram zooms of the PDV points for shot BB100531-1.

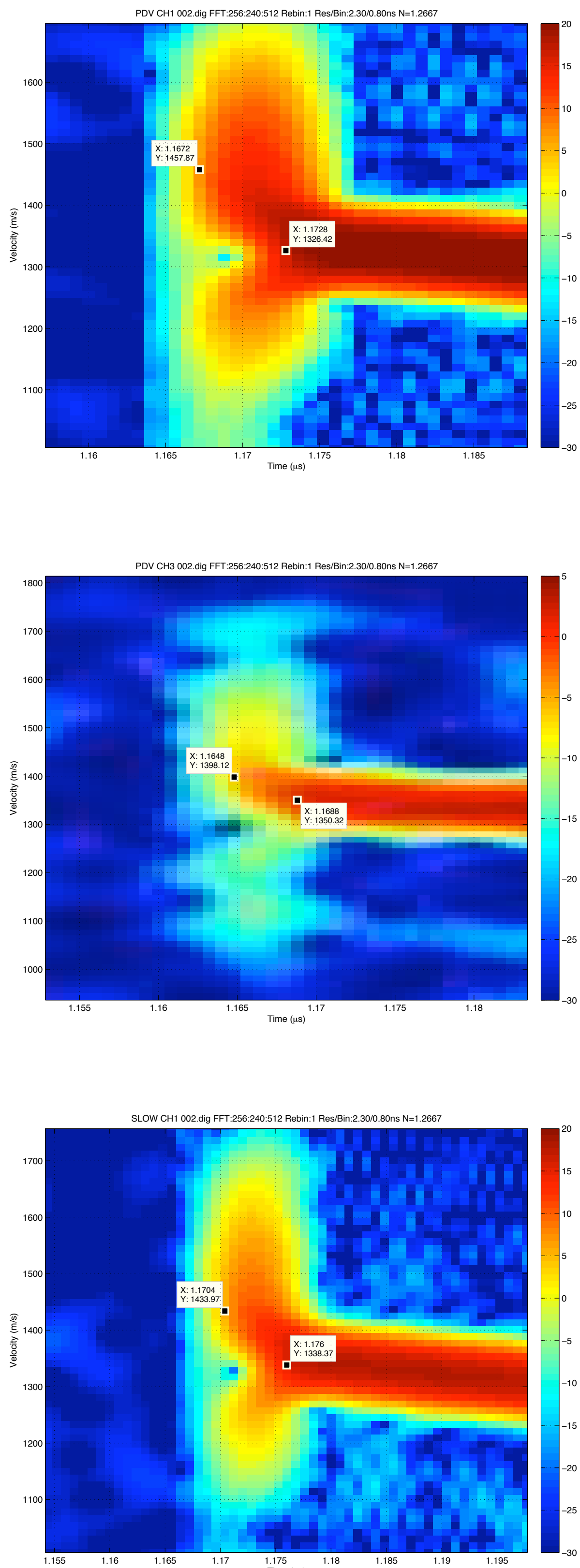


Figure A10: Spectrogram zooms of the PDV points for shot BB100531-2.

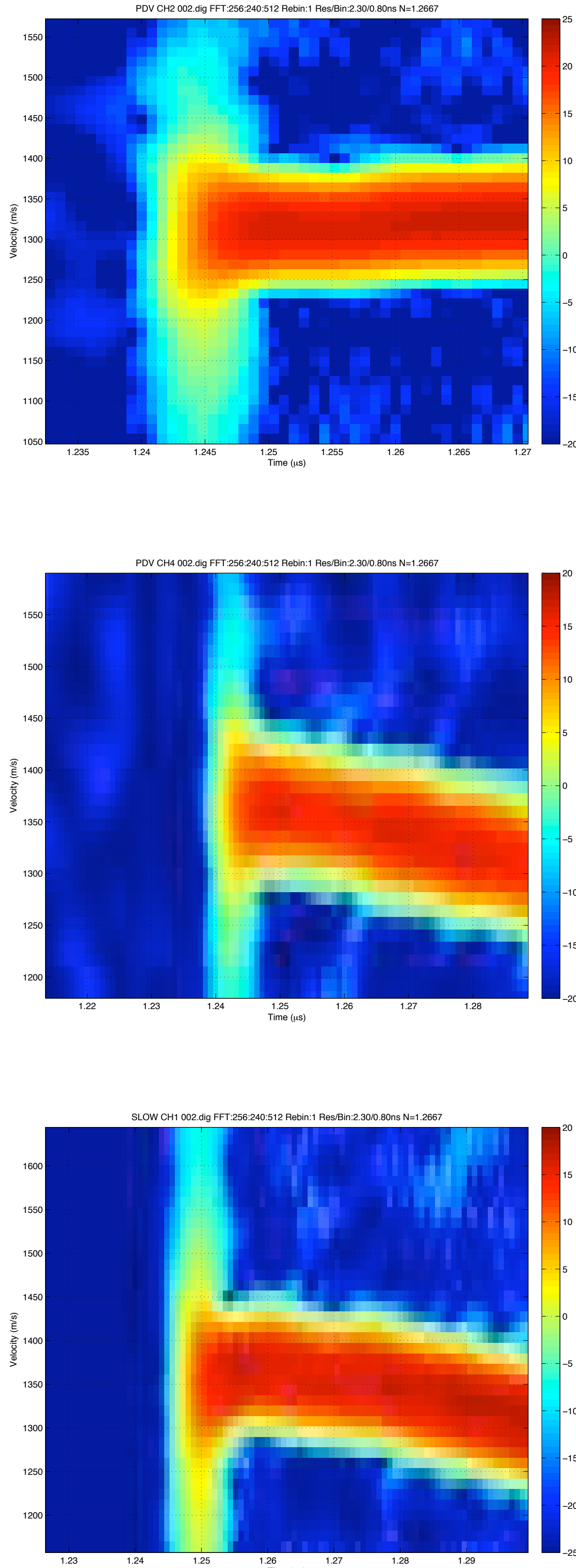
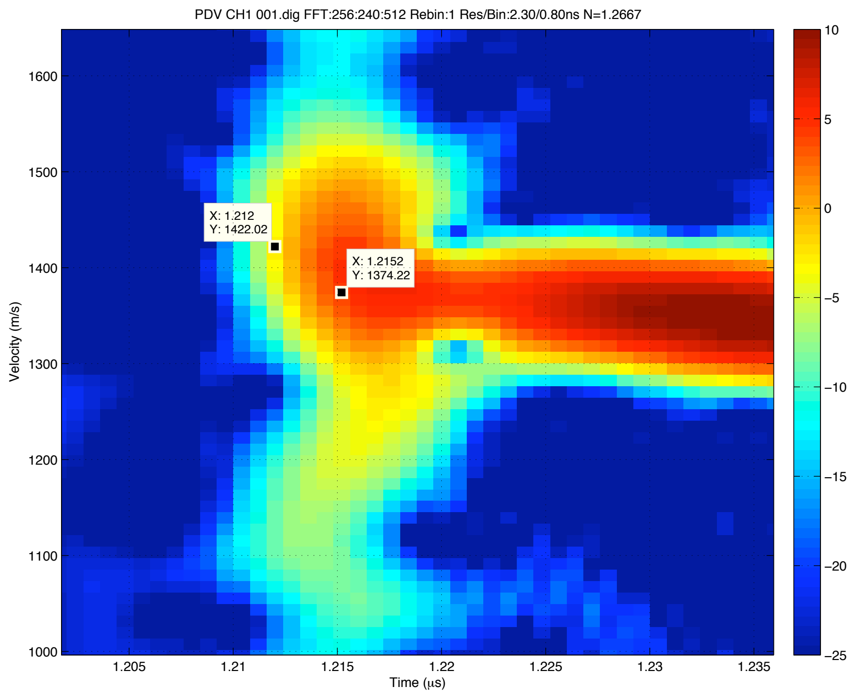


Figure A11: Spectrogram zooms of the PDV points for shot BB100601-1.



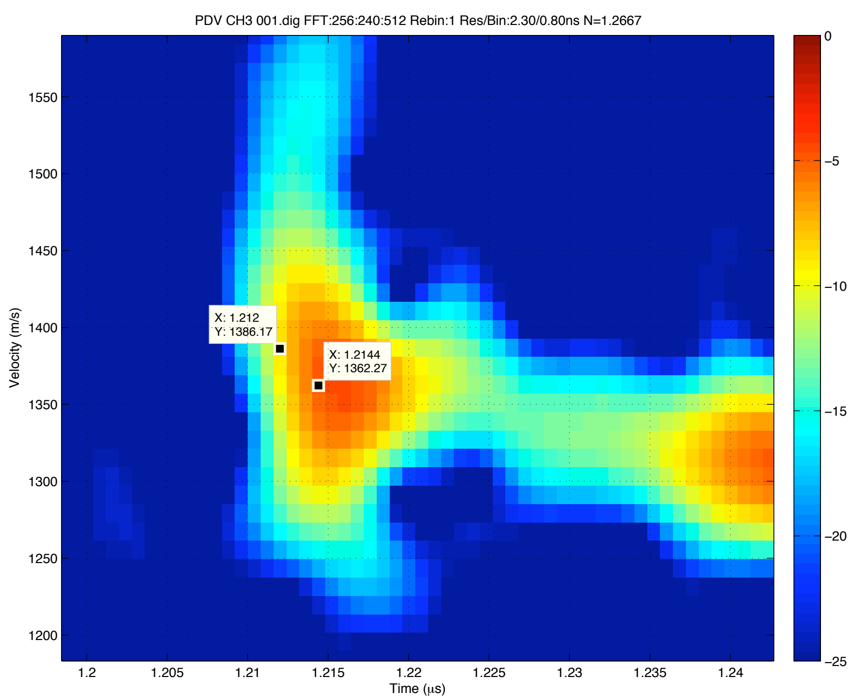


Figure A12: Spectrogram zooms of the PDV points for shot BB100601-2.

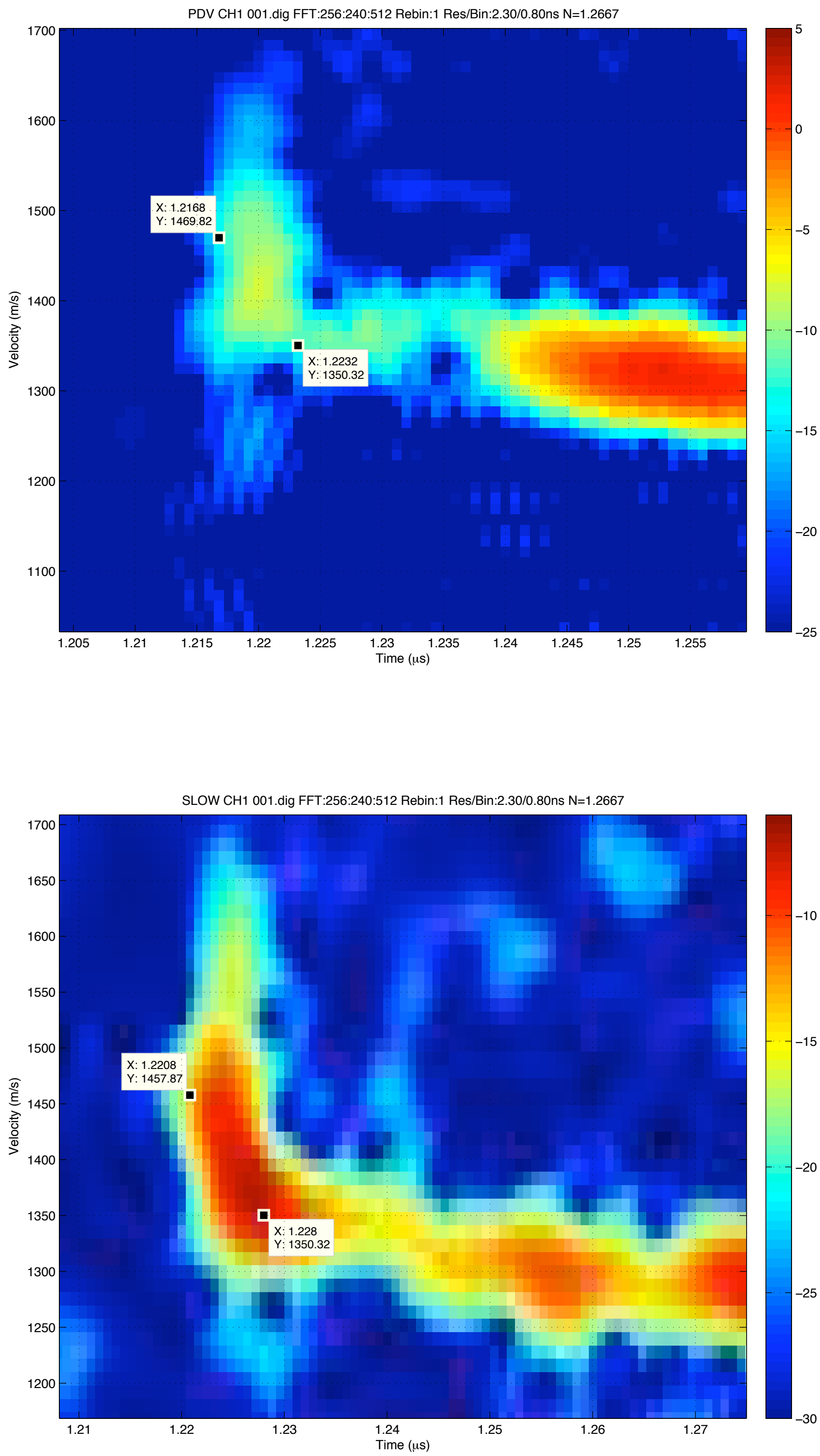


Figure A13: Spectrogram zooms of the PDV points for shot BB100601-3.

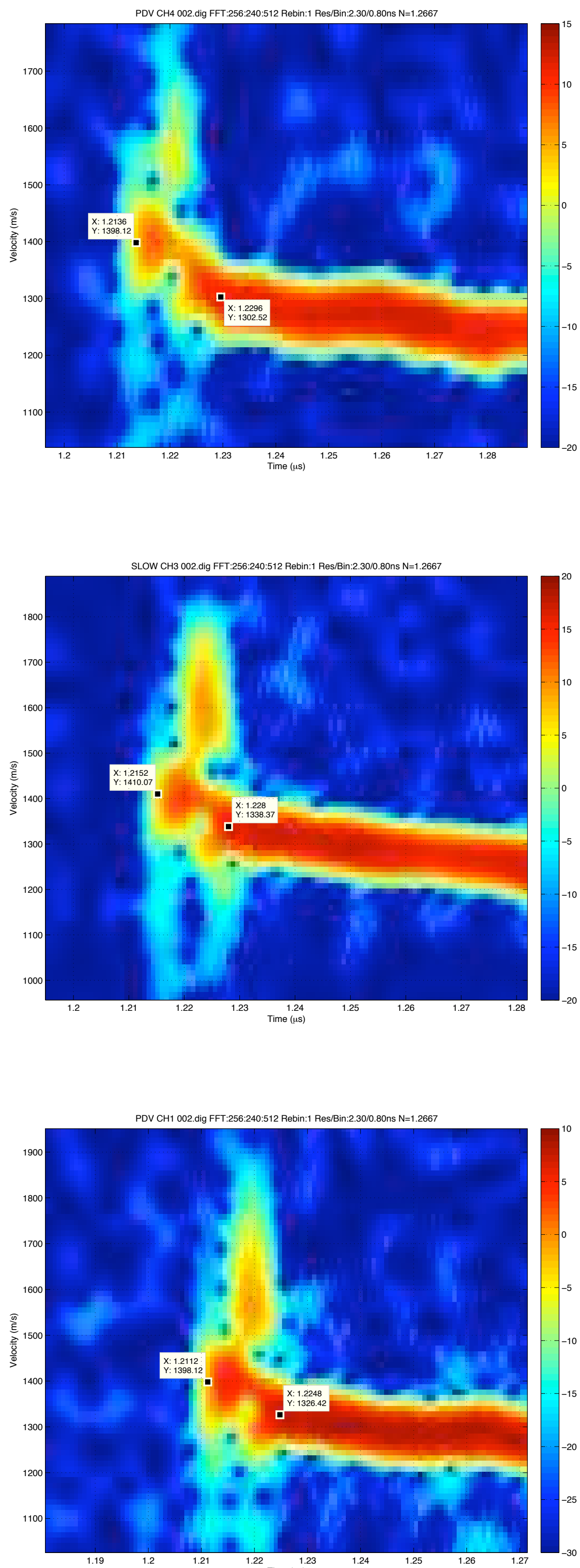


Figure A14: Spectrogram zooms of the PDV points for shot BB100602-1.

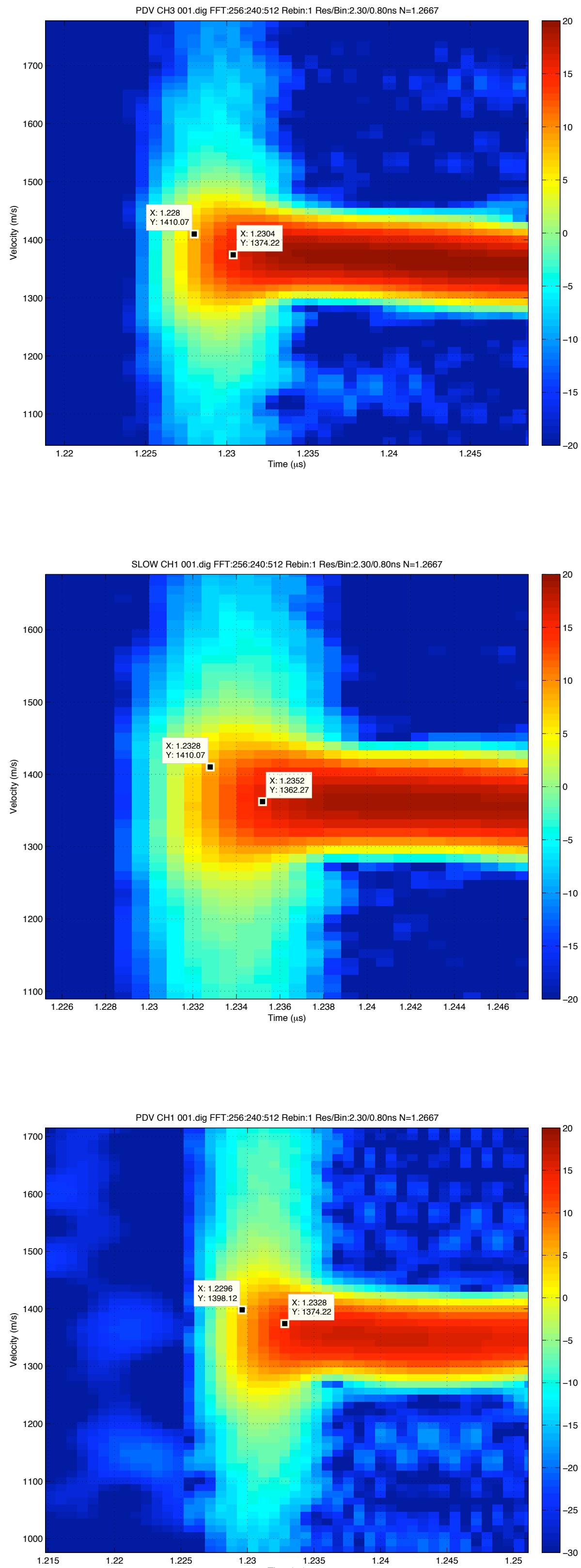


Figure A15: Spectrogram zooms of the PDV points for shot BB100602-2.

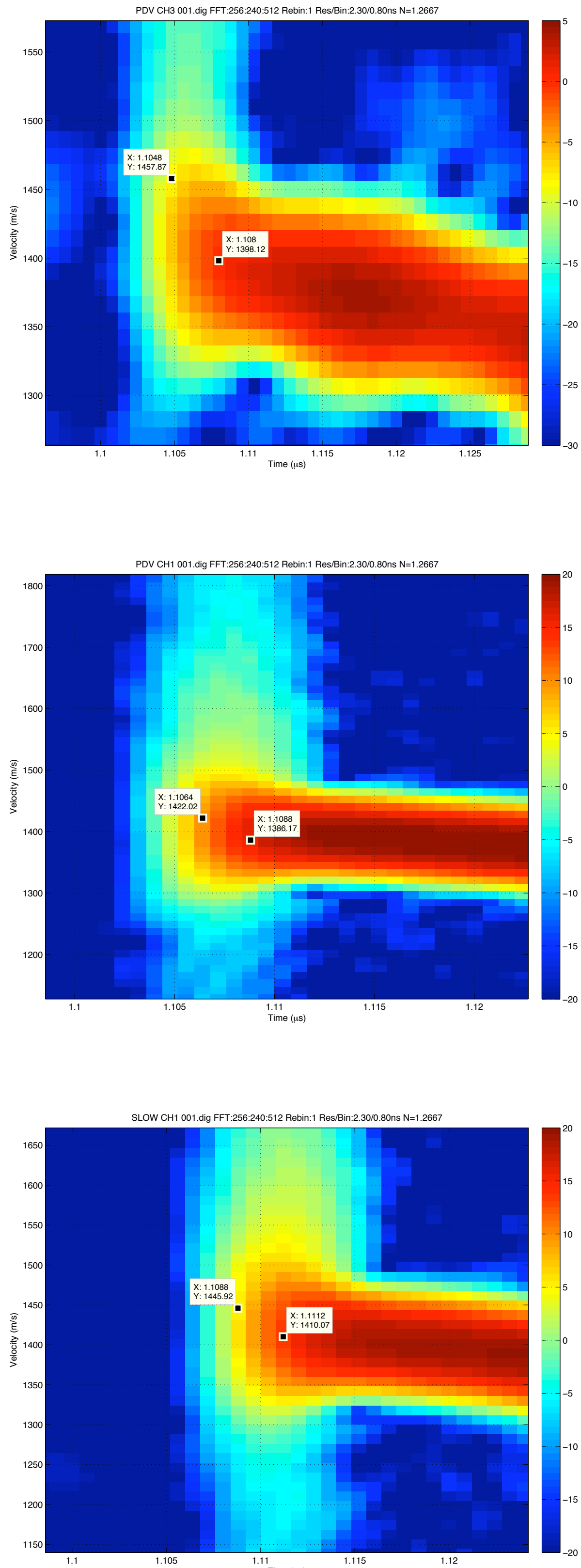


Figure A16: Spectrogram zooms of the PDV points for shot BB100602-3.

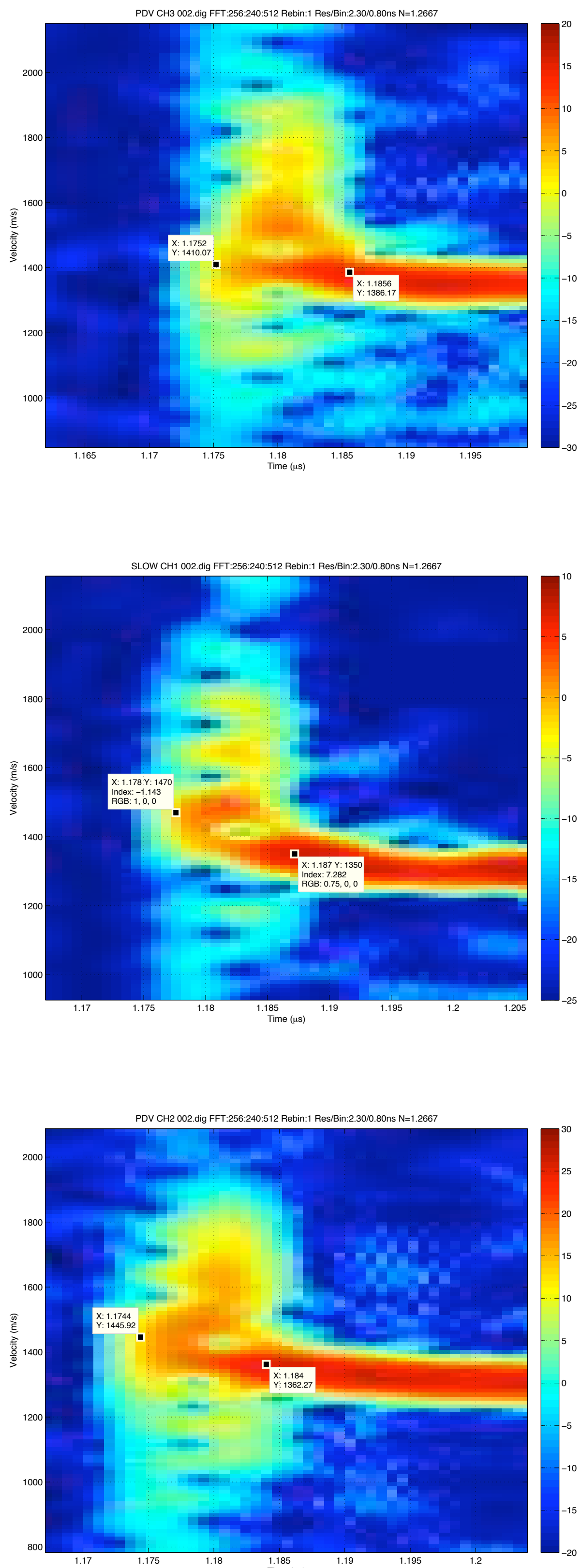


Figure A17: Spectrogram zooms of the PDV points for shot BB100603-2.