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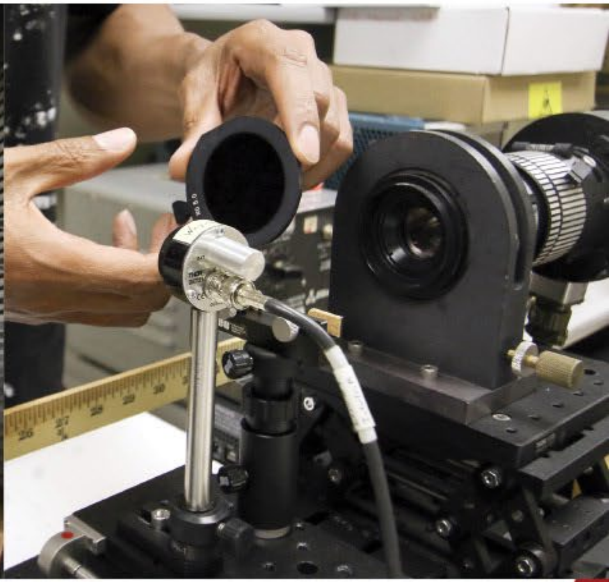
PDV – How Did We Get Here and Why We Care



A mosaic of motivating factors and predecessor diagnostic techniques

Ed Daykin - PDV Workshop Feb 7-8, 2023

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This talk is a *brief survey* of velocimetry techniques prior and leading to PDV with notable contributions from a broad community of talented scientists.

Presented by Ed Daykin

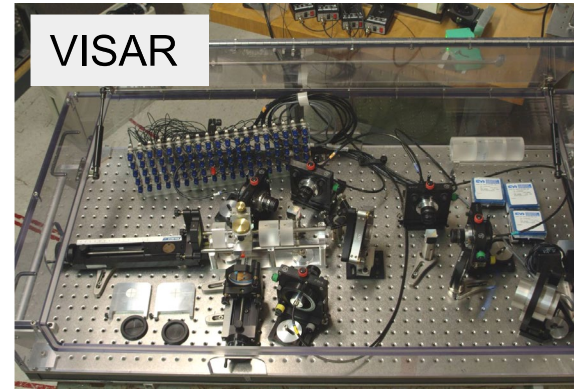
at the PDV Workshop 2023

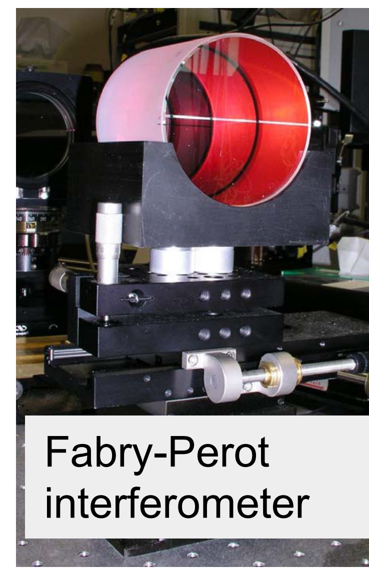
February 7 – 8, 2023

Santa Fe, New Mexico

We will briefly discuss motivation, physical principles, configuration and analysis methods

- ▶ VISAR velocimetry
- ▶ Fabry-Perot velocimetry
- ▶ Segue into PDV and MPDV
- ▶ Bonus material – ‘Asay foiled’





Interferometric velocimetry – why do we care?

- Shocking, melting, and moving metal has weapons relevance
  - High explosives and/or powder and gas gun experiments for shock physics
  - material physics and equation of state
  - For a shock physics perspective, see R.S. Hixson, *Diagnostic development through the decades*, PDV Workshop 2014
- Measurement of Doppler shifted light ~ few ppm change in optical frequency requires interferometry to precisely determine material behaviors

(1) $\frac{\rho_0}{\rho} = 1 - \frac{(u_p - u_{p0})}{(u_s - u_{p0})}$ mass

(2) $P - P_0 = \rho_0 (u_s - u_{p0})(u_p - u_{p0})$ momentum

(3) $E - E_0 = {}^1\!/_2 (P + P_0)(V_0 - V)$ energy

This is a system of 3 equations in 5 unknowns...

P, ρ, E, u_s, u_p ← Measured velocities

$$\Delta v/v = 2\text{v}/c$$

Many other innovative velocimetry applications can be found in the OSU PDV Workshop archive

- Detonation (high explosive) physics
- Pulsed power
- Rail guns
- Powder guns
- Impact welding
- Time of arrival
- Vibrometry
- Making PDV look like a VISAR – Triature PDV

I encourage those new to velocimetry and/or PDV to explore past PDV Workshops, available online at the Ohio State Knowledge Bank, https://kb.osu.edu/handle/1811/52627

VISAR: Velocity Interferometer System for Any Reflector

- VISAR was a revolutionary invention, late 1960s – early 1970s
  - L. M. Barker, R. E. Hollenbach, W. F. Hemsing, J. R. Asay, D. R. Goosman, and many, many others (see Dan Dolan for expertise)
- VISAR uses Wide Angle Michelson Interferometer (WAMI) concept
- Can measure arbitrarily high velocities (some caveats here)
- Push-pull VISAR major advance introduced by W. Hemsing (1978)
- Numerous Point VISAR and Line VISARs designs
- Commercially available and still used today, e.g. Z-machine & NIF

19 channel dual cavity VISAR, Circa 2012, NNSS/NLV
Designed by B. Marshall et al, Special Technologies Laboratory

VISAR Basics: phase measurement = *change* in velocity

- Michelson measures ***change*** in phase due to ***change*** in velocity
- Time domain data → requires healthy SNR
- Typically visible (532nm) laser light
- Four detector 'push-pull' configuration is current baseline design:
  - W. Hemsing, Review of Scientific Instruments, 50:73, 1979
  - Removes ambiguity in sign of acceleration
  - Allows for insensitivity to incoherent light

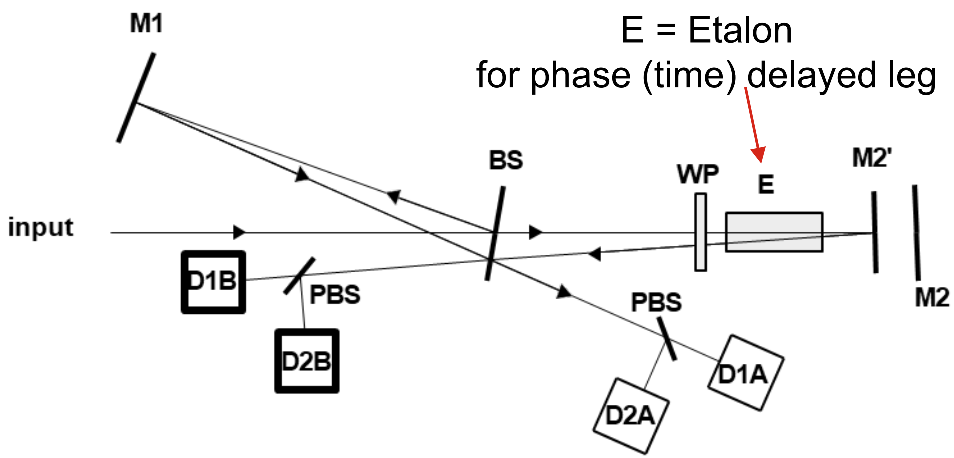


Figure 2.9. The push-pull VISAR.

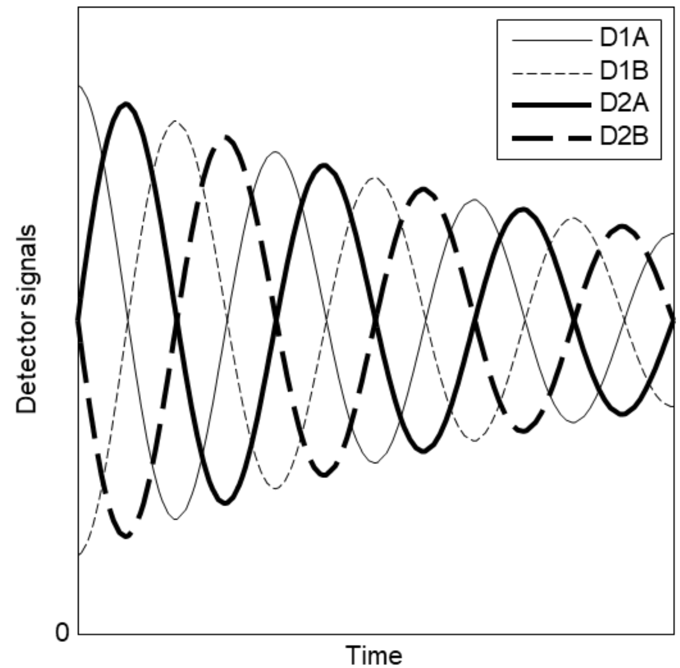


Figure 2.10. Push-pull VISAR signals.

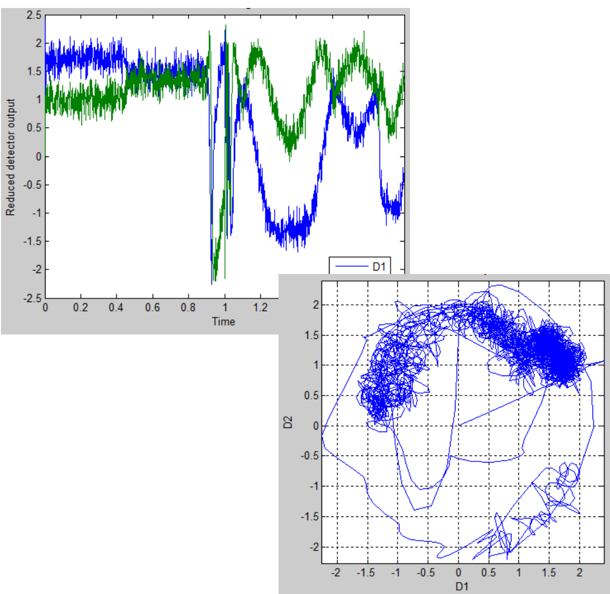
D. Dolan, *Foundations of VISAR analysis*, Sandia Report, April 2006

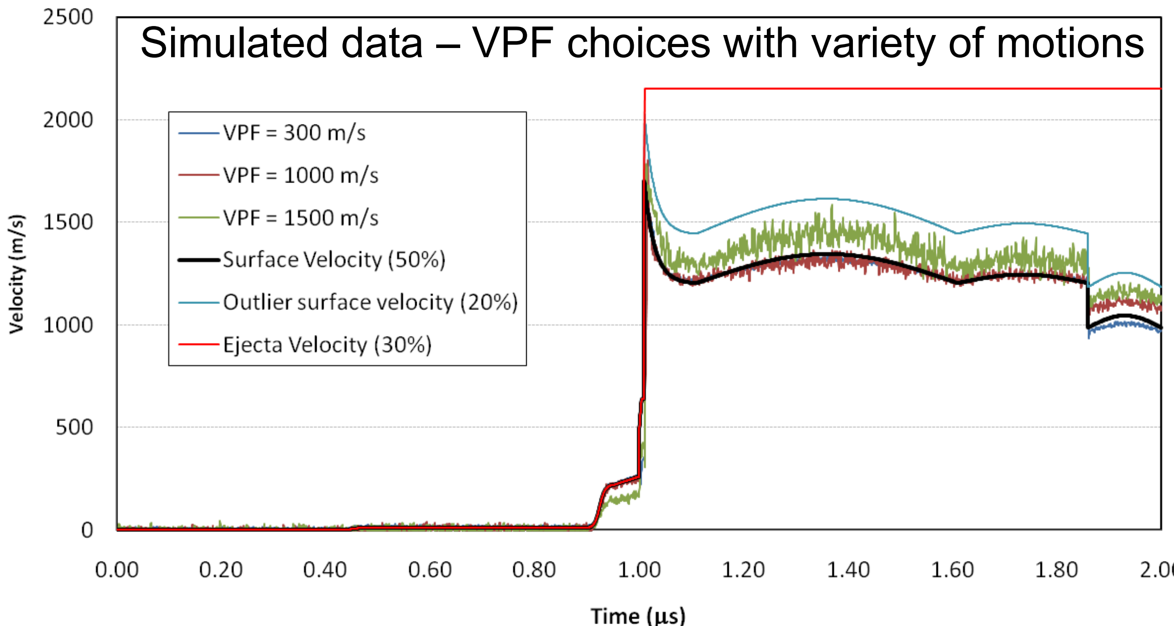
VISAR Basics: VPF and data analysis

- VPF (Velocity per fringe, mm/µs) ∝ delay τ (typically ~ Etalon length)
- Select etalon appropriate to anticipated velocities
- Analysis typically done using Lissajous methodology

$$VPF = \frac{\lambda}{2\tau(n - \frac{1}{n})(1 + \delta)}$$

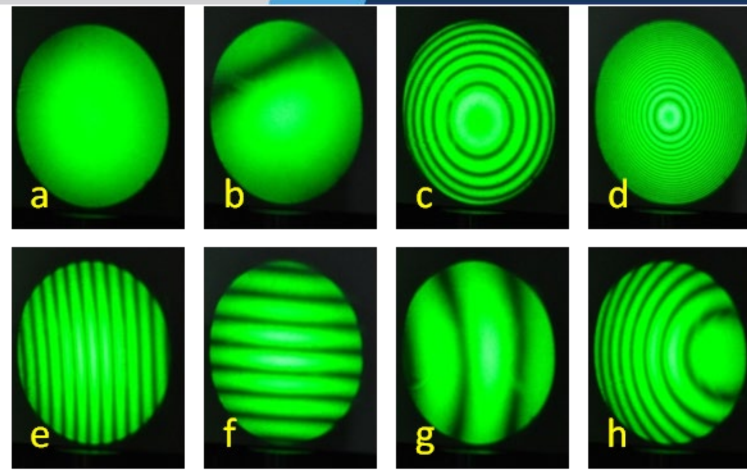
$$\text{Velocity} = \frac{VPF}{2\pi} tan^{-1} (\frac{D2A - D2B}{D1A - D1B})$$

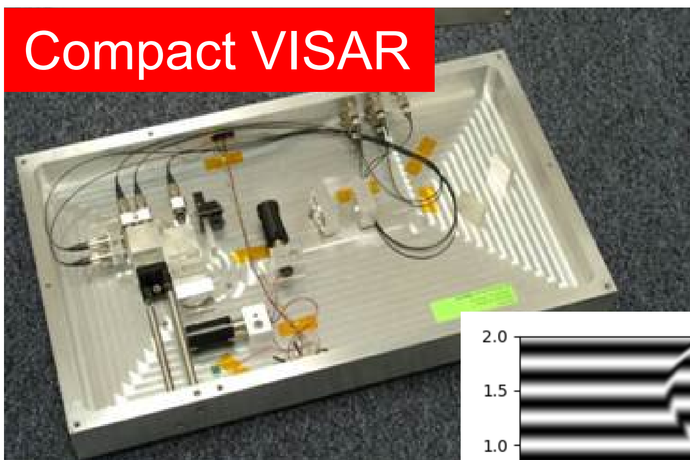




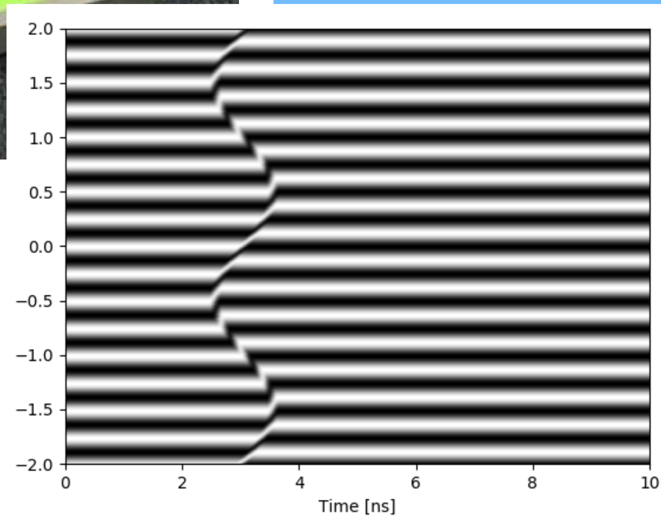
VISAR – some expertise required

- Relatively straightforward to build and align ***with interferometric expertise***
- Require multiple etalons to resolve jump (shock-front) discontinuities
- Requires calibration of VPF (nontrivial)





For a thorough treatment of point VISAR, I recommend: D. Dolan, *Foundations of VISAR analysis*, Sandia Report SAND2006-1950, April 2006

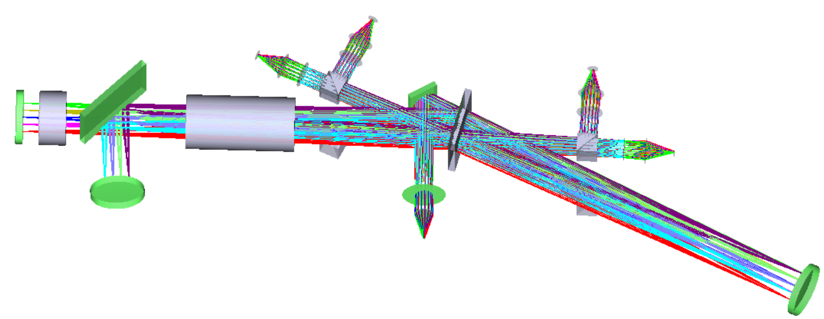


A brief comment on Line VISAR: same physical principles, provides spatial resolution (e.g. NIF), uses streak camera recording, requires spatial analysis

VISAR – Roundup of pros and cons

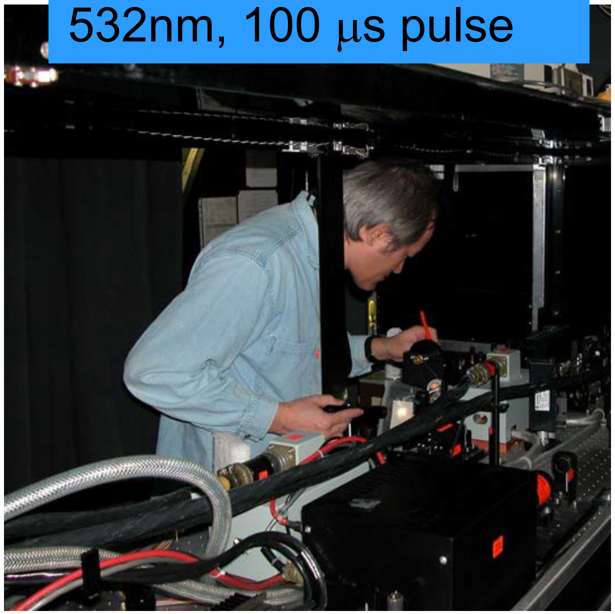
- High precision, high temporal resolution velocimetry still in use today (point and line)
- Can resolve jump-off ambiguity with use of two cavities
- Data analysis somewhat nuanced but straightforward and well understood.

- ***Single frequency measurement only.*** Cannot resolve multiple discrete frequencies or dispersive environments, e.g. ejecta
- Difficult and expensive to expand beyond a 'few' channels. Eighteen channel VISAR a notable accomplishment.
- Requires expertise, 4 digitizer channels per point, and continuous care and feeding for alignment and experimental operations.



Fabry Perot velocimetry – exquisite and complex

- Able to measure multiple discrete velocities and dispersive signals
- Unlimited maximum velocity, also measures ***change*** in velocity
- If VISAR required dedicated expertise, Fabry-Perot required Seal Team 6.

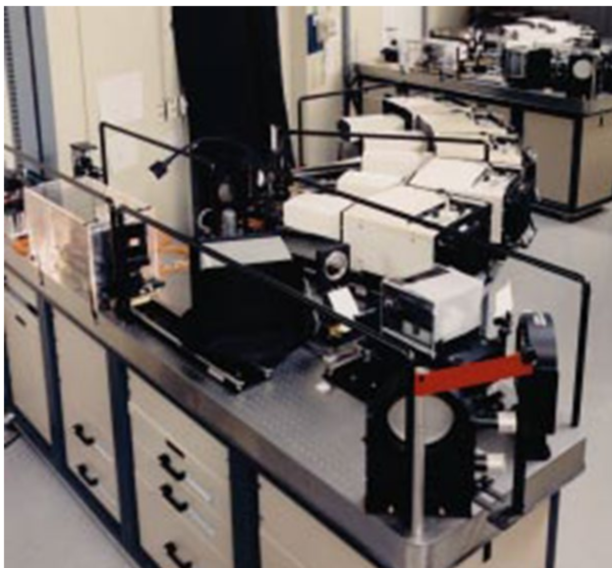


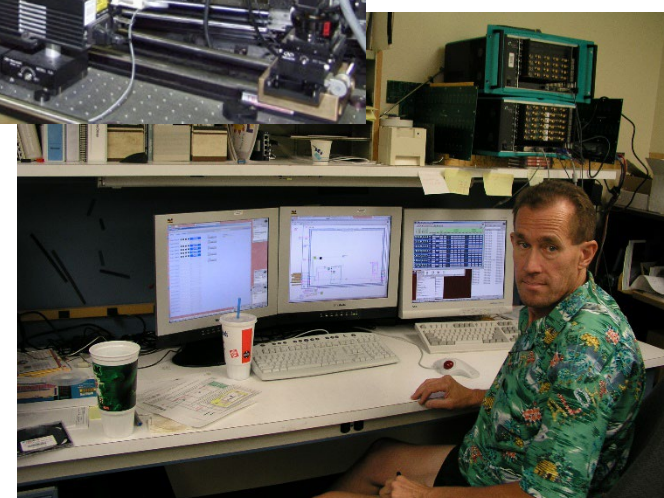
2 kW Pulsed YAG laser
532nm, 100 μs pulse

15 Channel Fabry-Perot system, circa 2000
Shown as fielded at U1a for SCEs

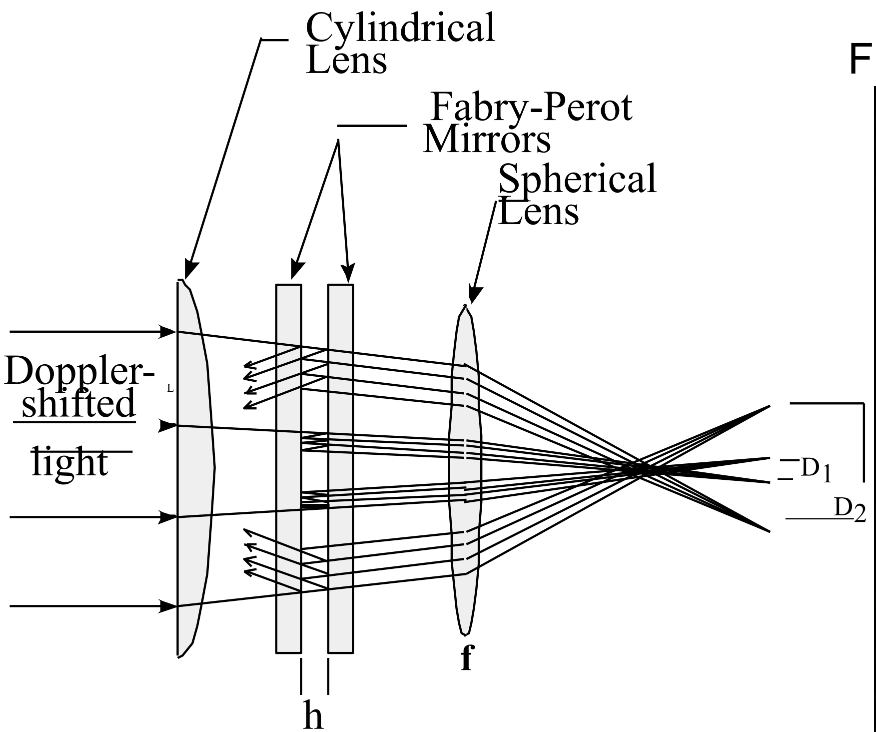
Fabry Perot velocimetry developed in the early 1990s, and fielded through ~ 2010

1. D.R. Goosman, *Formulas for Fabry-Perot velocimeter performance using both stripe and multifrequency techniques*, Appl. Opt. 30 (27), 1991
2. D. R. Goosman et al, *Manybeam velocimeter for fast surfaces*, SPIE proceedings 22nd Int. Congress on High Speed Photography and Photonics, 2869, 1996

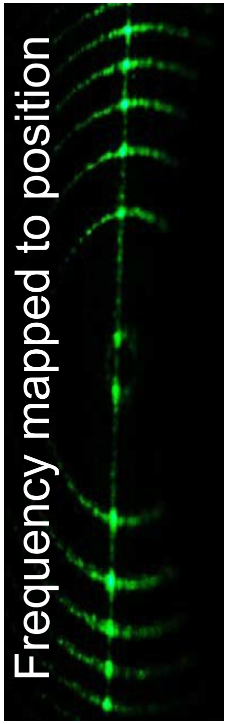




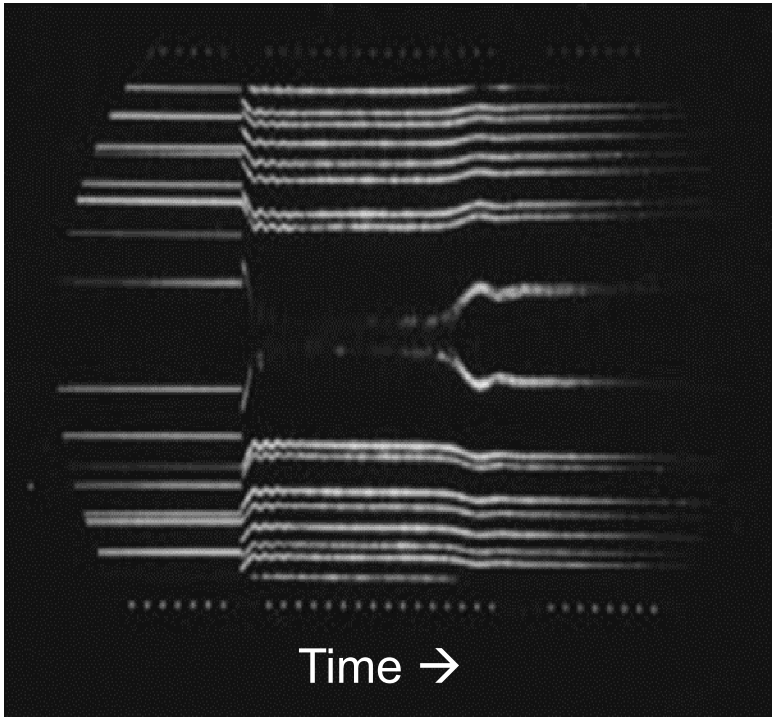
Fabry-Perot Principles: fringe spacing ∝ velocity. Data is recorded using streak cameras onto film



Static Fringe Pattern



Streak Camera Data Record

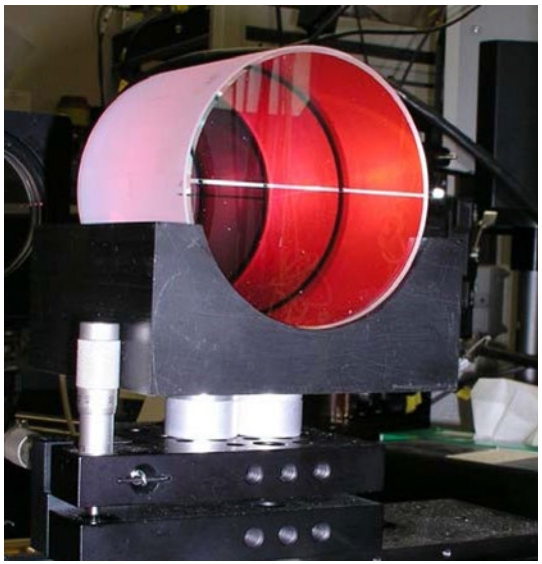


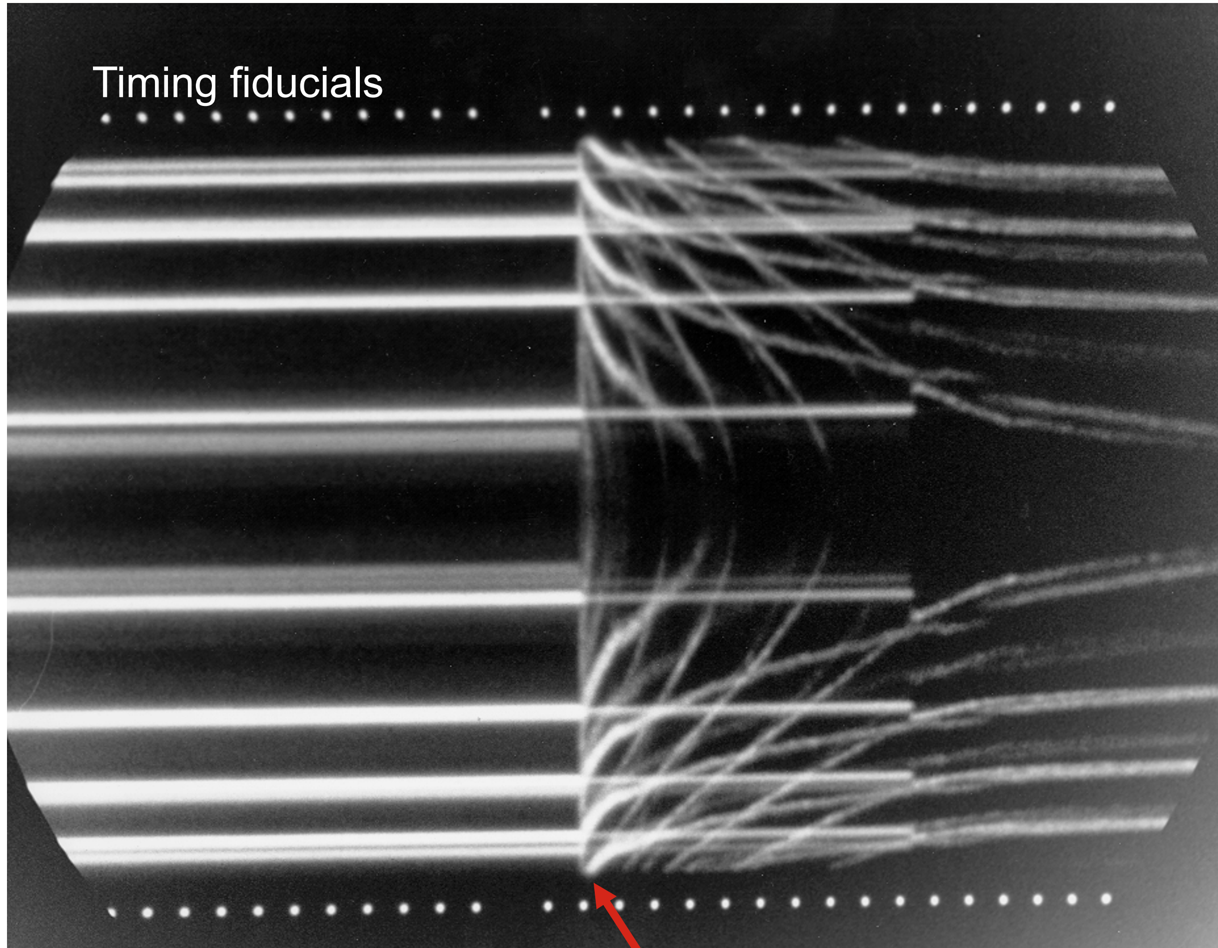
Similar to VISAR VPF, the Fabry-Perot fringe constant $\mathbf{f_c}$ is related to etalon spacing and determines velocity resolution.

$$f_c = \frac{c\lambda}{4h} \quad \left(\frac{mm}{\mu s}\right)$$

$$velocity = \frac{c\lambda}{4h}\frac{D_1^2(t) - D_1^2}{D_2^2 - D_1^2} + n$$

Fabry-Perot advantage: multi-frequency capability

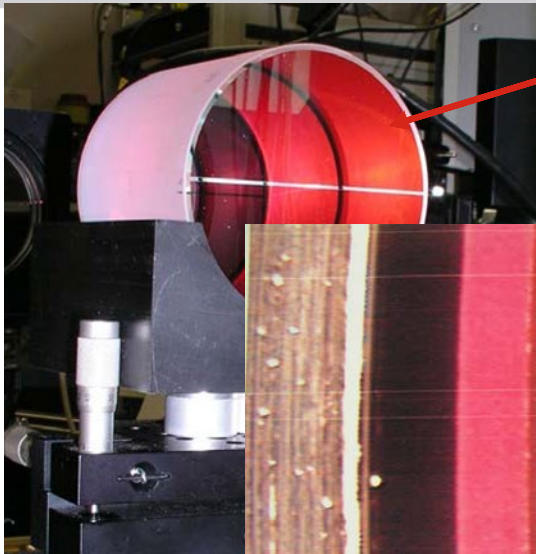




$$velocity = \frac{c\lambda}{4h} \frac{D_1^2(t) - D_1^2}{D_2^2 - D_1^2} + n$$

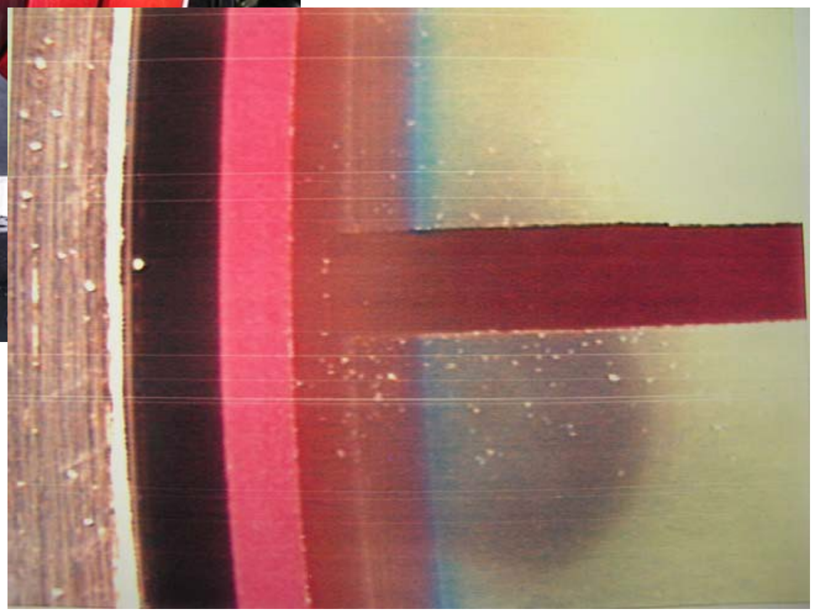
Similar to VISAR, Fabry required multiple cavities to resolve jump-off ambiguity

… and yes, we did horrible things to exquisite optics



An tremendous accomplishment of optical fabrication!

A ‘good’ Fabry-Perot etalon could be better than $\lambda/100$ across the majority of the 4” diameter clear aperture



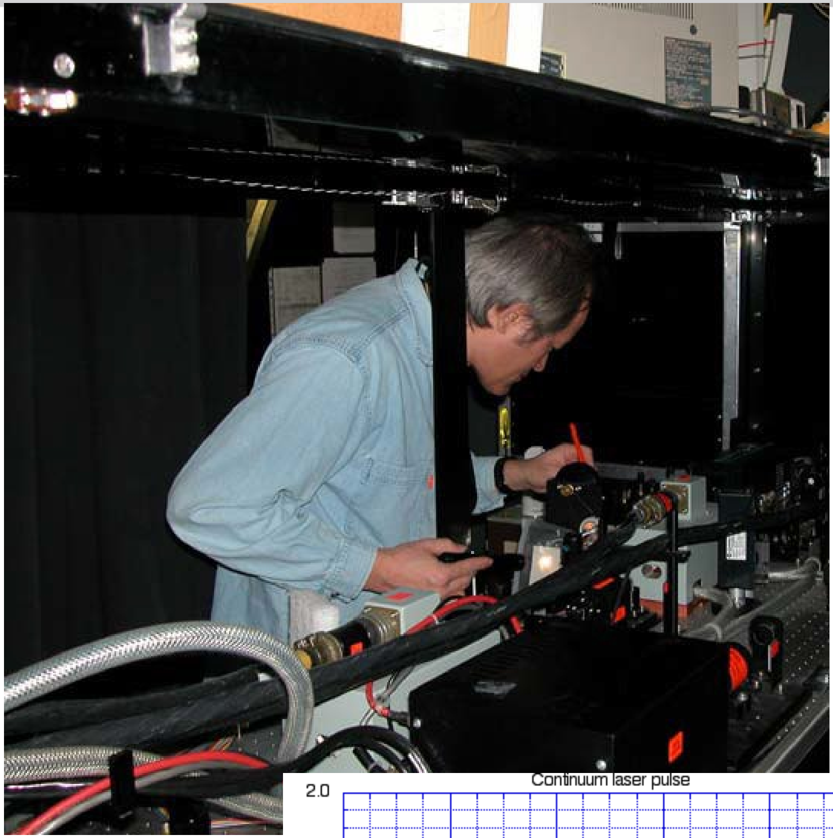
Picture of Etalon input stripe. A stripe of dielectric reflective coating has been removed by mechanical means. Stripe width is approximately 0.5 mm.

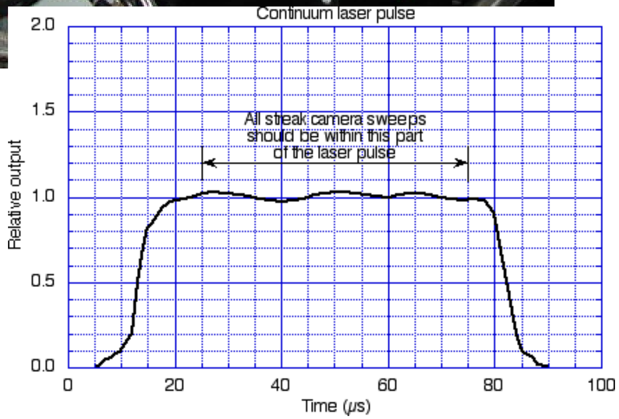
For typical values of reflectivity and absorption, the peak intensity of a striped etalon is theoretically ~ 50 times greater than that of a normal etalon.

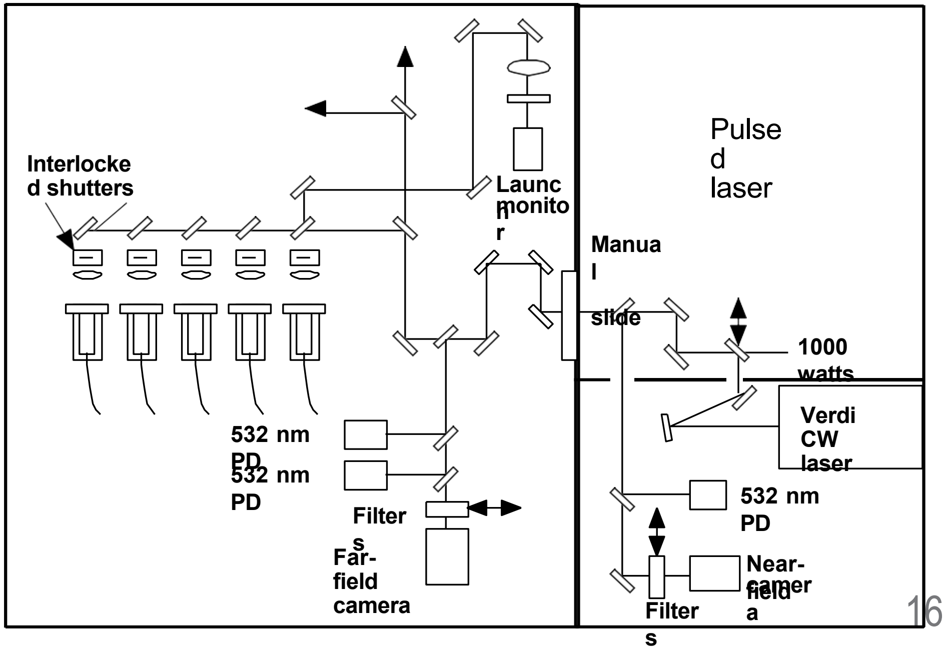
$$I_{normal} = \left(1 - \frac{A}{1-R}\right)^2 \frac{1}{1 + \frac{4R\sin^2 \delta/2}{(1-R)^2}}$$

$$I_{striped} = \left(1 - \frac{A}{1-R^2}\right)\frac{1+R}{1-R}\frac{1}{1 + \frac{4R\sin^2 \delta/2}{(1-R)^2}}$$

Fabry-Perot required a custom 'long pulse' doubled YAG laser (532nm)

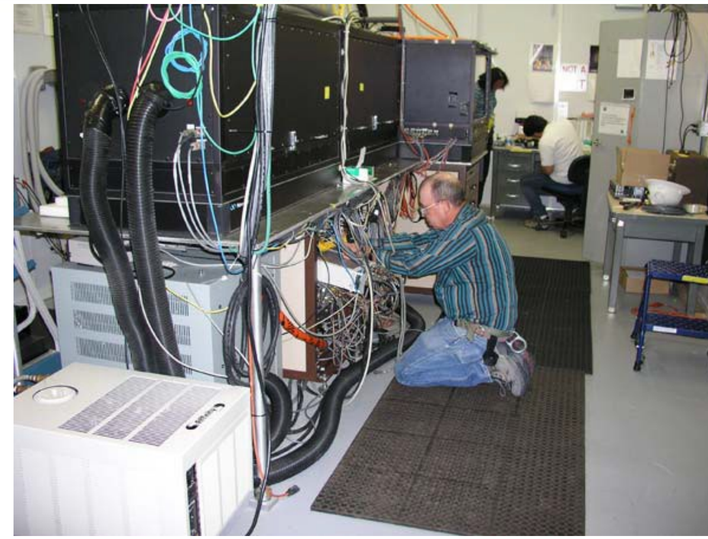






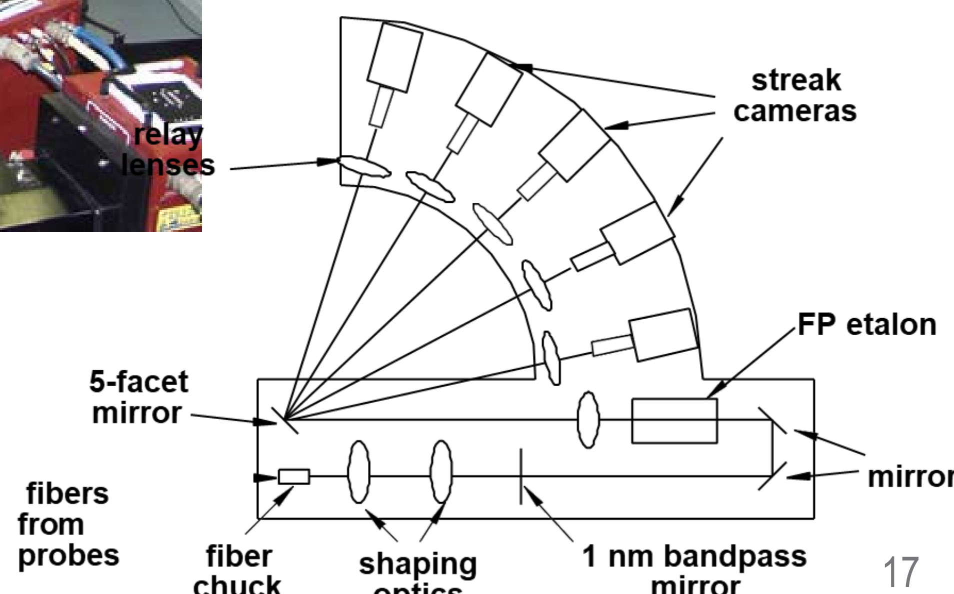
Fabry-Perot system: all major elements were manually aligned and remotely controlled on SCEs

FPV Analyzer System Lab at NTS/U1a

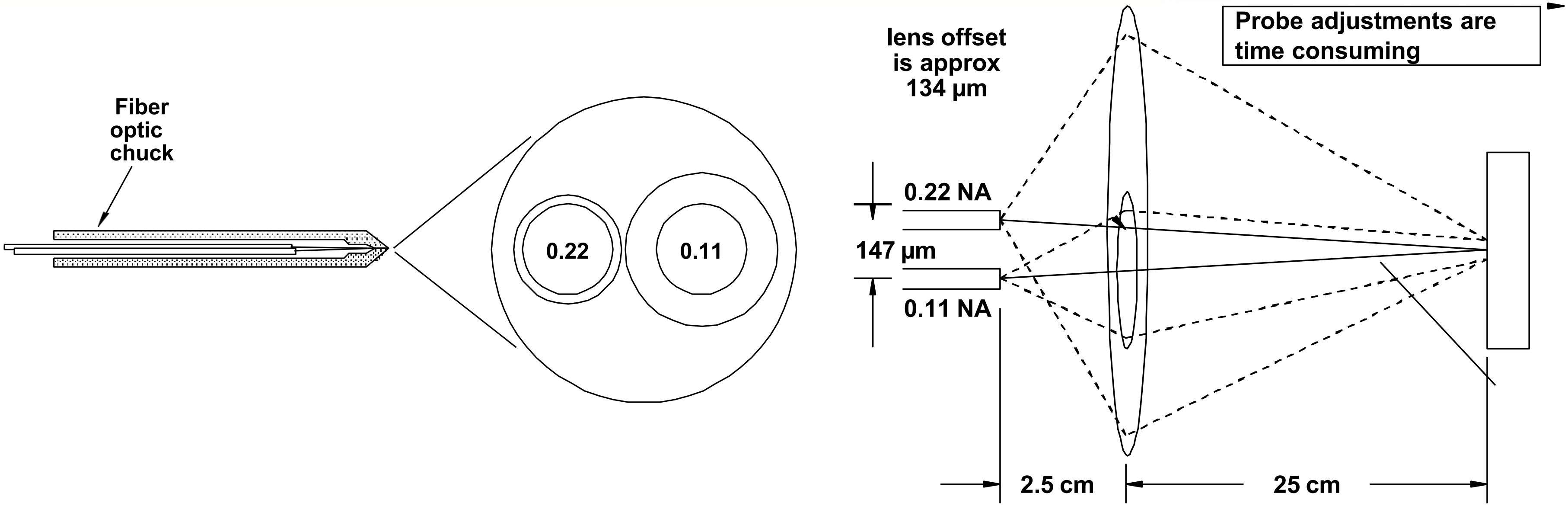


FPV Laser Lab at U1a

57 total adjustments (degrees of freedom) per optical tau table



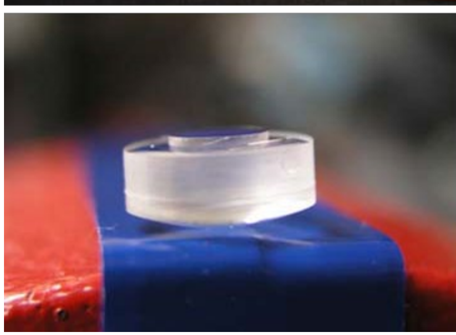
Probes are also a major element of velocimetry

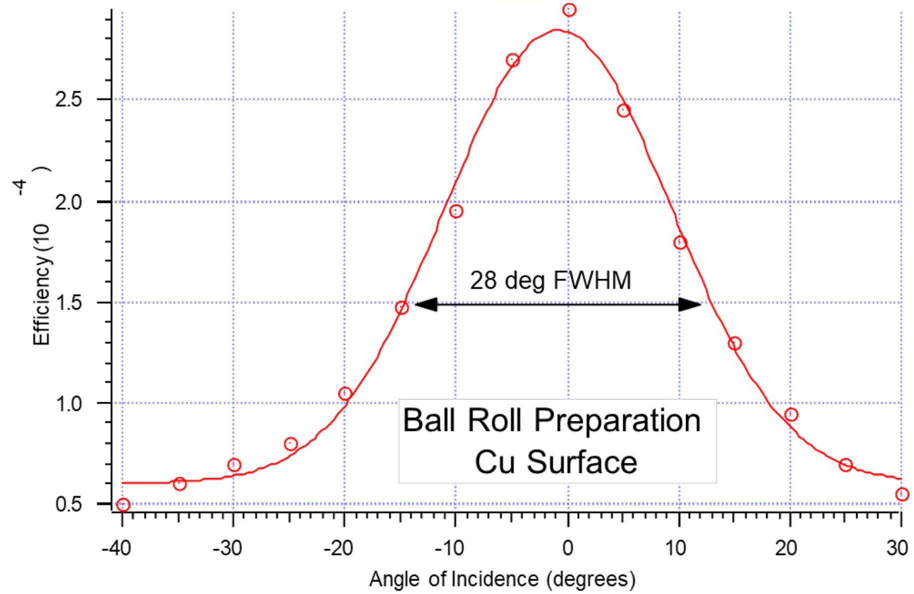


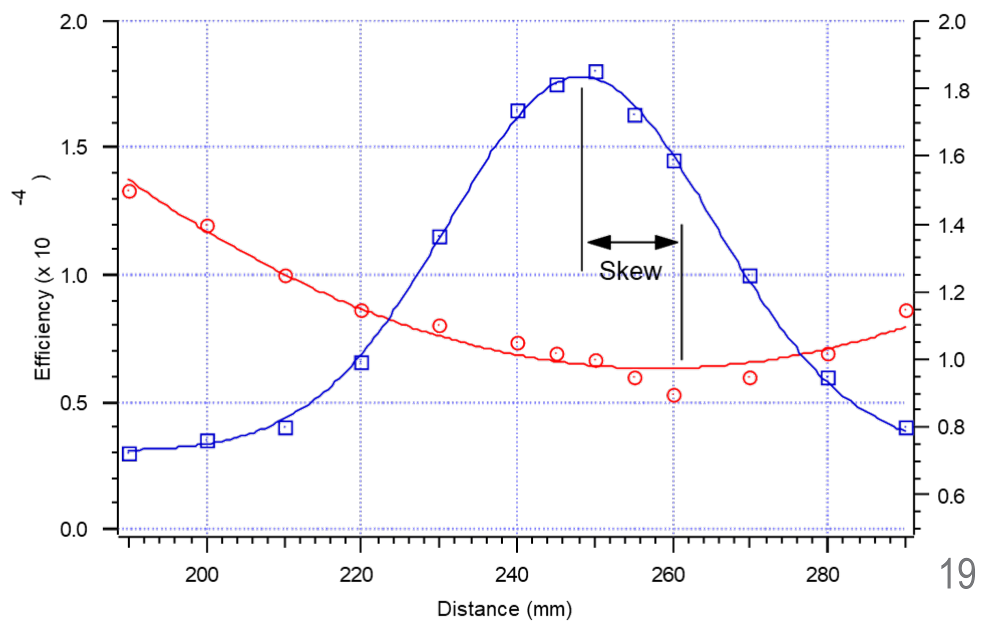
- Two fiber probes – launch & receive – used for both VISAR and Fabry-Perot required careful design and assembly/alignment
- Probe collection efficiency ~ 10^{-4} necessitated high power lasers
- 25cm working distance allowed for large depth of field (10's of mm) and clearance for other diagnostics (e.g. high speed video)

Single fiber probes sure would have made life a lot easier, but it's notable that two-fiber probes are still useful today for specific PDV applications

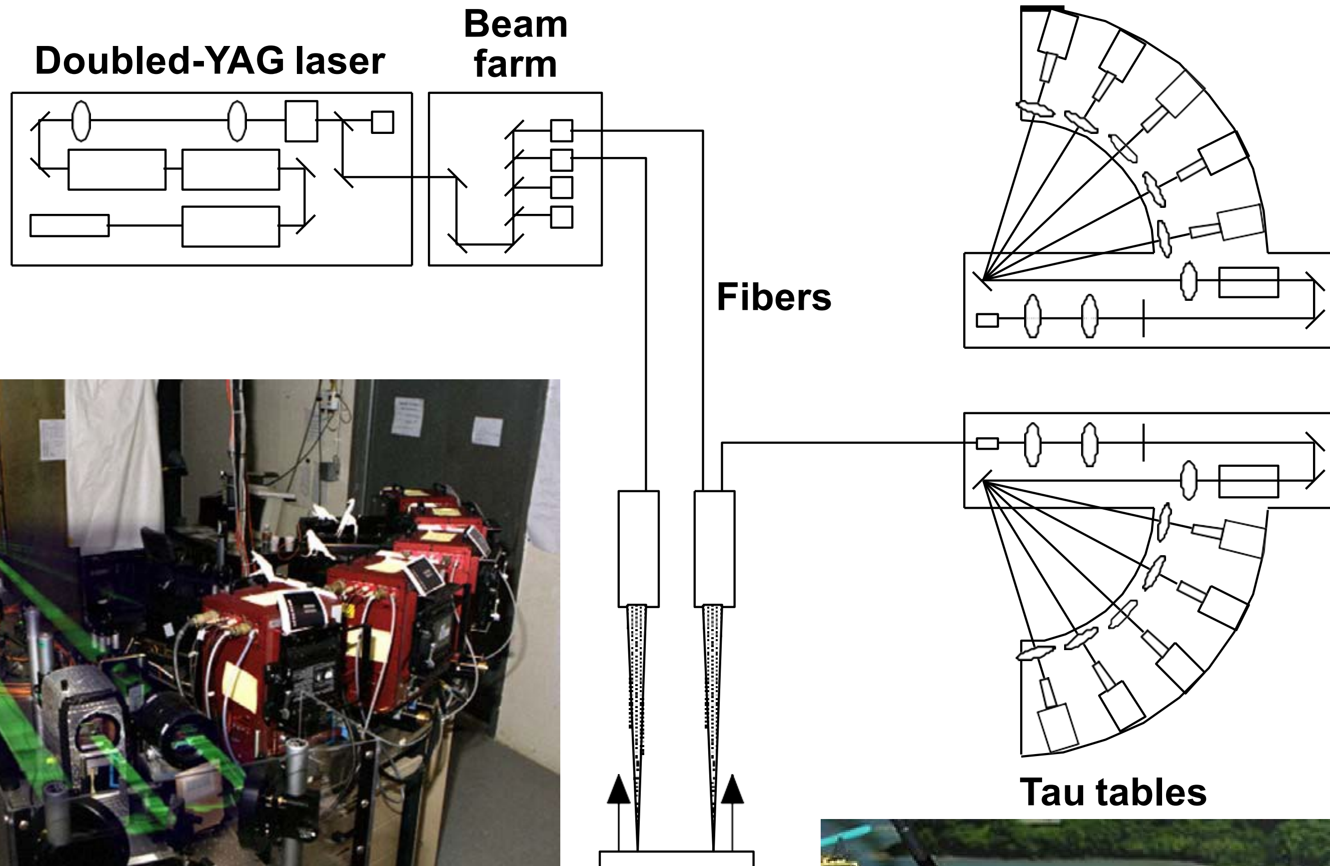
Probe performance depends on probe optical design AND material surface preparation

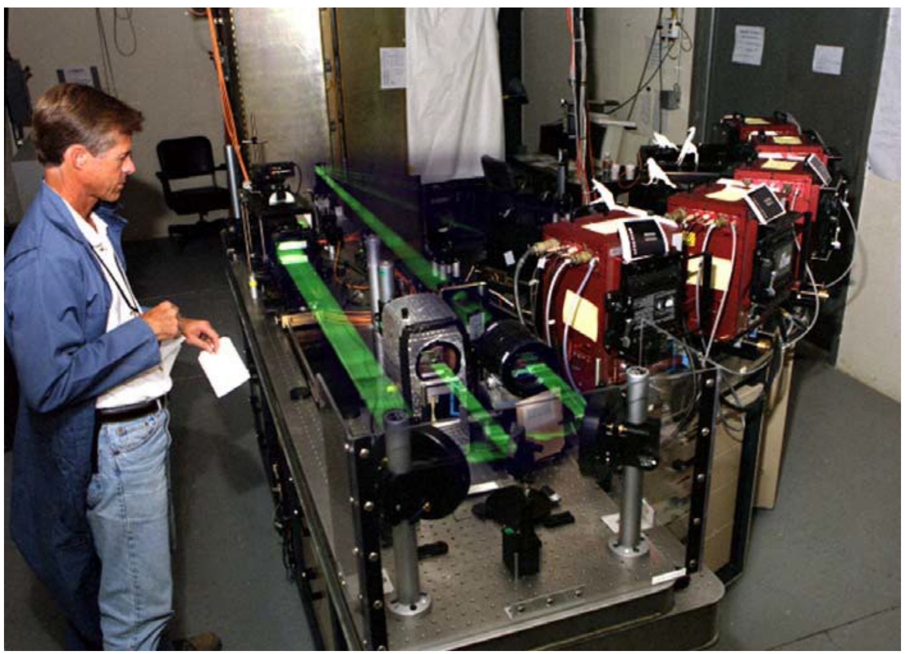






Fabry-Perot system alignments/tuning required many weeks and a highly skilled & experienced team



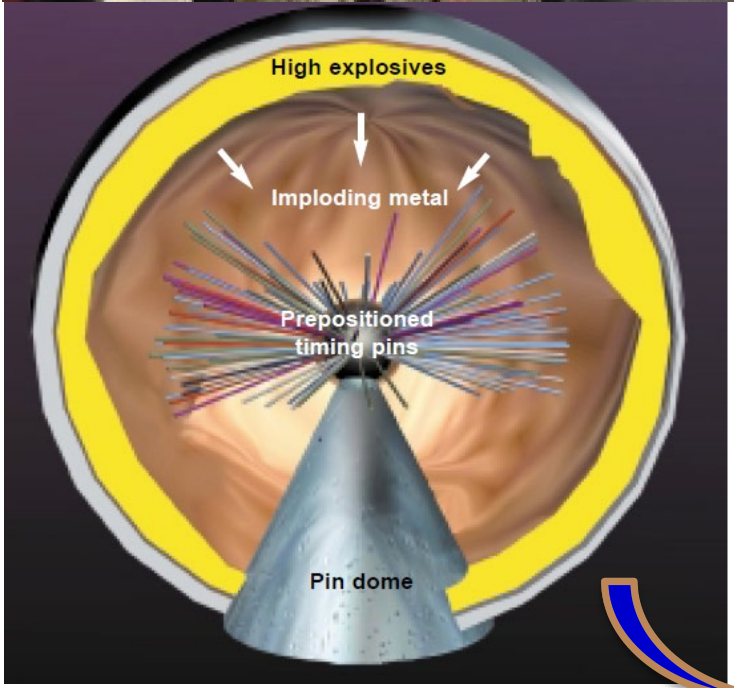


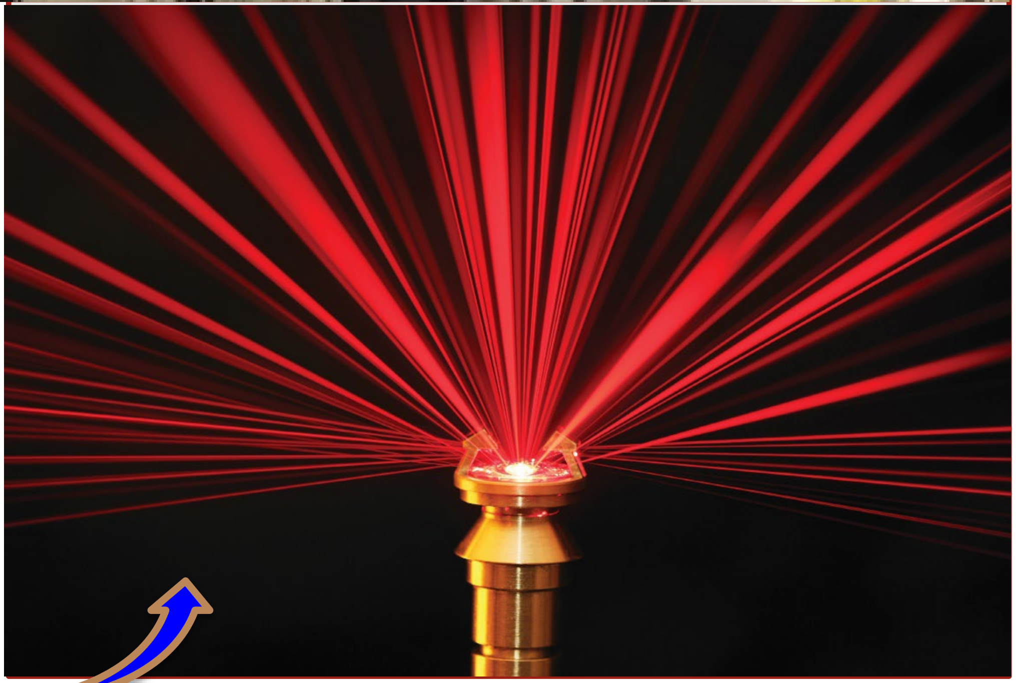
VISAR and Fabry-Perot: diagnostic break-throughs informed decades of shock physics work, but …

- Very (or very, very) expensive
- Limited measurement count ~ 5 to 20 data channels.
- Custom designed optics requiring extensive expertise
- Labor intensive
- Large physical size
- Required two-fiber probes
- Only Fabry-Perot able to measure multiple discrete velocities/dispersion
- Herculean effort to field at U1a with remote controls/monitors

… how are we going to effectively and economically field experiments requiring hundreds of data channels?

The enabling capability of PDV and MPDV stands on the shoulders of decades of dedicated effort





… and has transformed the way we conduct many experiments

This concludes our survey of VISAR and Fabry-Perot Velocimetry, now on to …

Bonus Backup Material

Bonus material: 'Asay foiled' – the measurement of lots and lots of ejecta

- What if we were asked to use PDV (or back in the day Fabry-Perot) to measure lots and lots of tiny little 'bullets' traveling faster than a speeding bullet …

- Millions and billions of 'bullets'
- Traveling many km/s
- Differing calibers
- Weighing ~ picograms

… we'll call this ejecta

Imagery and insights courtesy of Paul Steele

Jim Asay (Sandia National Labs) developed a diagnostic technique in the 1970s

Ejection of material from shocked surfaces*

J. R. Asay, L. P. Mix, and F. C. Perry

Sandia Laboratories, Albuquerque, New Mexico 87115

(Received 12 May 1976)

Velocity interferometry and double-pulse holography have been used to study material ejected from surfaces which are impulsively loaded with plane shock waves. Experiments performed on aluminum shocked to 25 GPa (250 kbar) provide the average mass and velocity distribution as well as the spatial distribution of material ejected from the surface. A total mass of about 3 $\mu g/cm^2$ was ejected when the shock arrived at the surface in the present experiments, and a substantial part of this material resulted from jetting at small pits on the surface.

PACS numbers: 62.50.+p, 79.90.+b, 42.40.Kw

It is well known that the reflection of strong shock waves from surfaces can cause either the development of Rayleigh-Taylor instabilities at material interfaces[1,2] or jetting of material from surfaces.[3-6] However, very little is known about physical mechanisms which are important in the degradation of surfaces during shock loading. In this paper, we present a technique which should prove to be useful for evaluating the ejection of material from shocked surfaces. The technique allows quantitative measurements of the mass-velocity distribution of ejecta and also a measure of its spatial distribution. The latter information is especially useful for studying physical mechanisms which influence the ejection of mass.

It has been observed in previous investigations that when a shock arrives at a free surface, material can be ejected in the form of a fine spray.[3,4] A common technique previously employed to study the motion of this spray has been fast streak and framing photography.[4] With these methods, it is difficult, if not impossible, to deduce information about the mass or velocity distribution of ejected material. In addition, the spatial resolution obtained previously has generally been inadequate to reveal structure of ejecta on the scale of a few microns. Both of these features can now be investigated with the technique described here, and the method has been used to obtain the first measurements of the spatial and velocity distribution of material ejected from aluminum surfaces during shock loading.

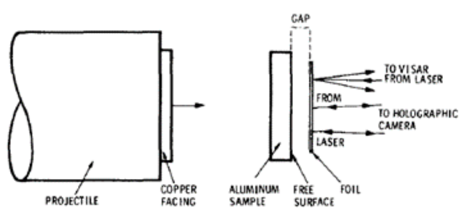


FIG. 1. Schematic illustration of the technique used to produce plane shock waves in a specimen. The copper facing and aluminum specimen thicknesses in the present experiments were on the order of 0.3 and 0.4 cm, respectively. Either aluminum or cellulose acetate was used as foils. For the cellulose acetate foils, a 120-nm-thick spectral aluminum reflector was vapor deposited on the rear surface.

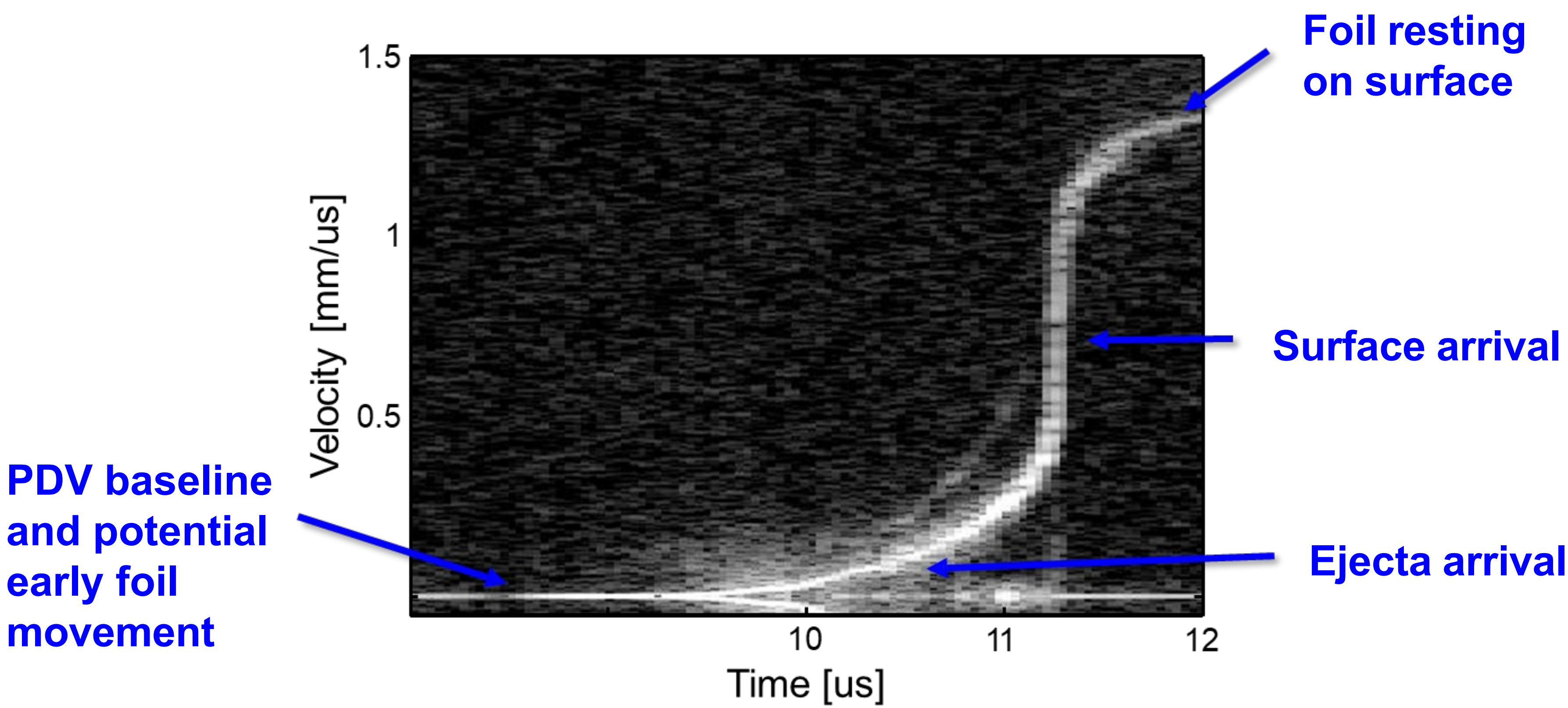
Jim Asay's technique became known as 'Asay foils'

Conservation of momentum: bullet hits thin foil, foil moves, measure ejecta and foil velocity and back out ejecta mass = f(t)

Requires:

1. Inelastic collision
2. Uniform ejecta across foil
3. Negligible effects from foil mechanical support
4. Incident ejecta have single velocity at a given instant

Asay foils have been used successfully for decades

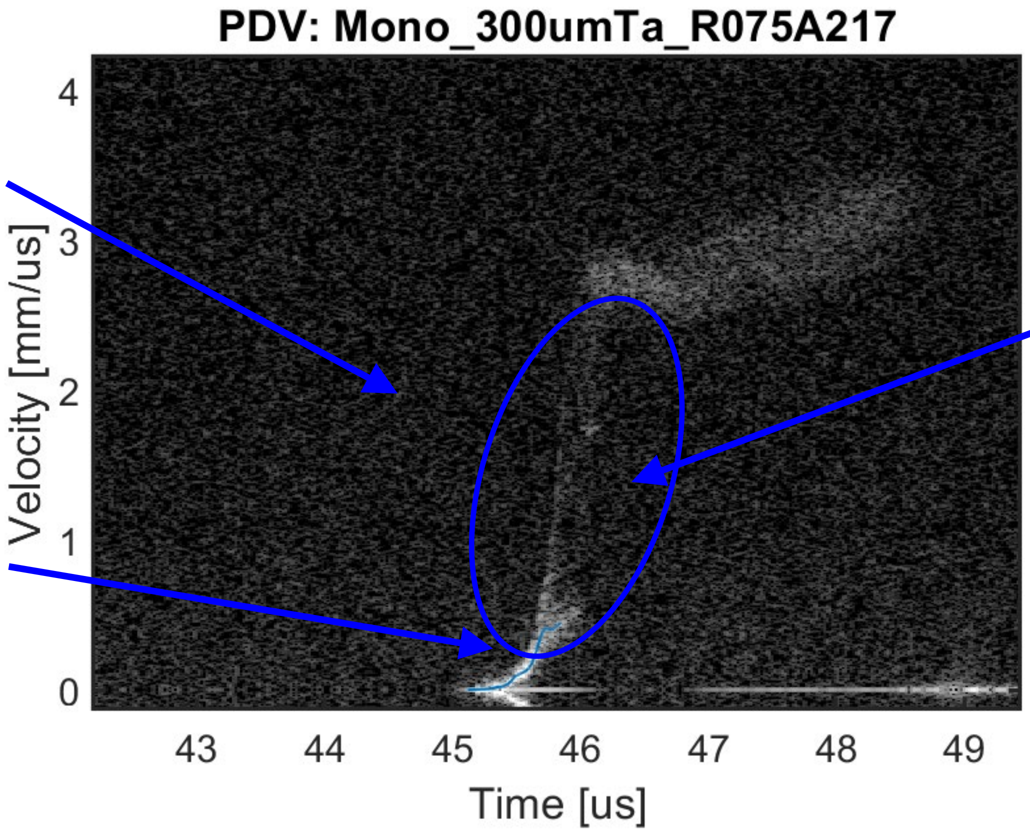


Asay foiled: however recent experiments & modeling demonstrate potential failure modes

- Asay foil failure modes have not been previously explored.
- PDV spectrograms may be evaluated for indications of foils being driven beyond their measurement capabilities

Signatures of foil 'punch-through' evident

Asay foil 'plateaus' and no longer responding to momentum transfer from mass deposition.



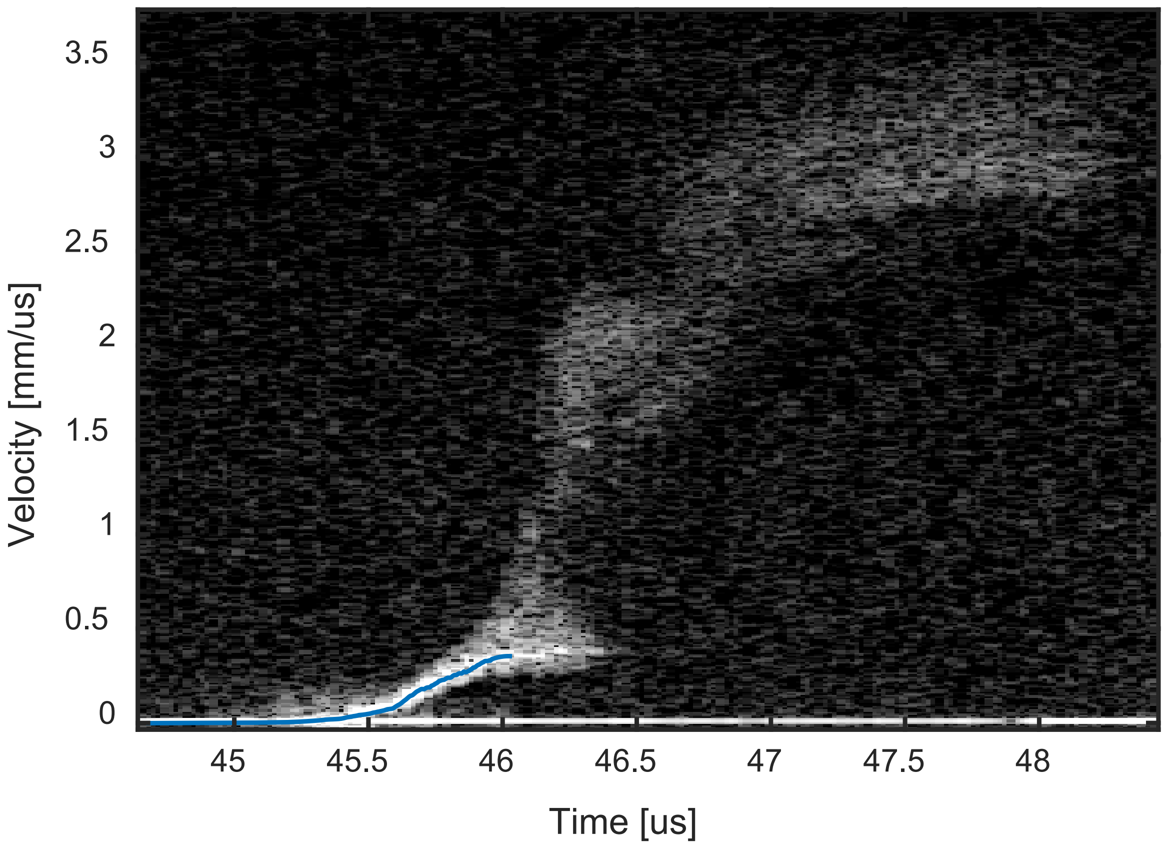
Dispersive signal resolved by PDV

Could have been seen using Fabry-Perot

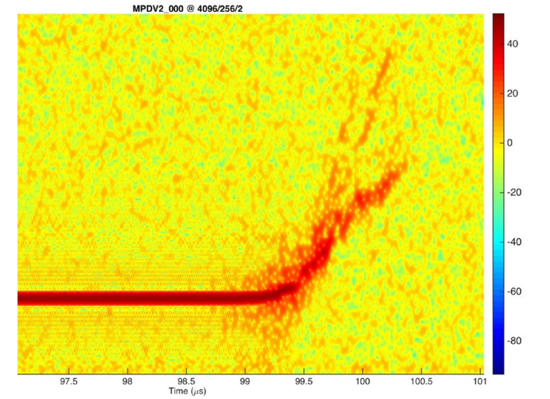
*Would **not** be resolvable using VISAR*

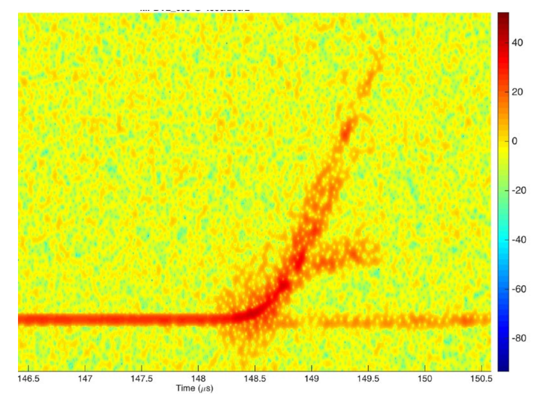
Asay foiled: example spectrogram signatures of foil failure (and a Rorschach test)

PDV: Mono_300umTa_R050A155



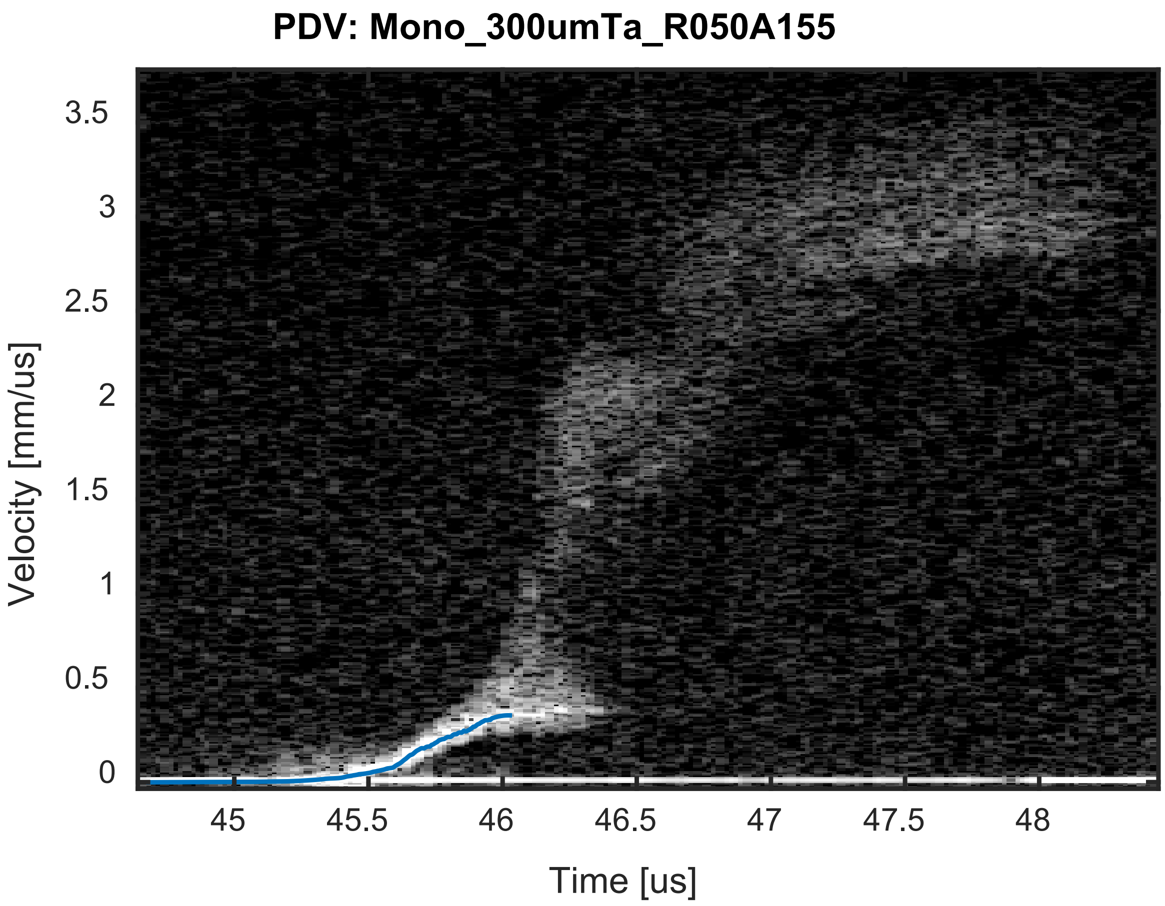
STL experiment J2 (Aug 8, 2020). Typical PDV spectrogram of Asay foil failure (300 um Ta Asay foil)

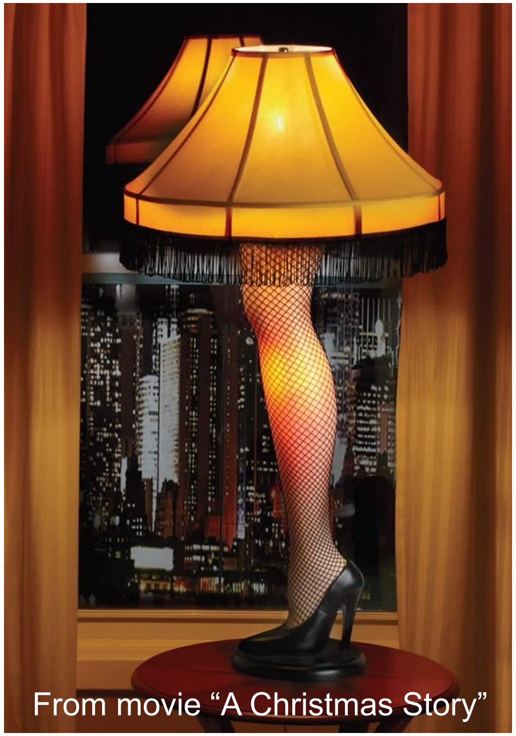




STL experiment J1 (Aug 6, 2020). Typical PDV spectrograms of Ti and Ta foils failing

Asay foiled: if you look carefully …





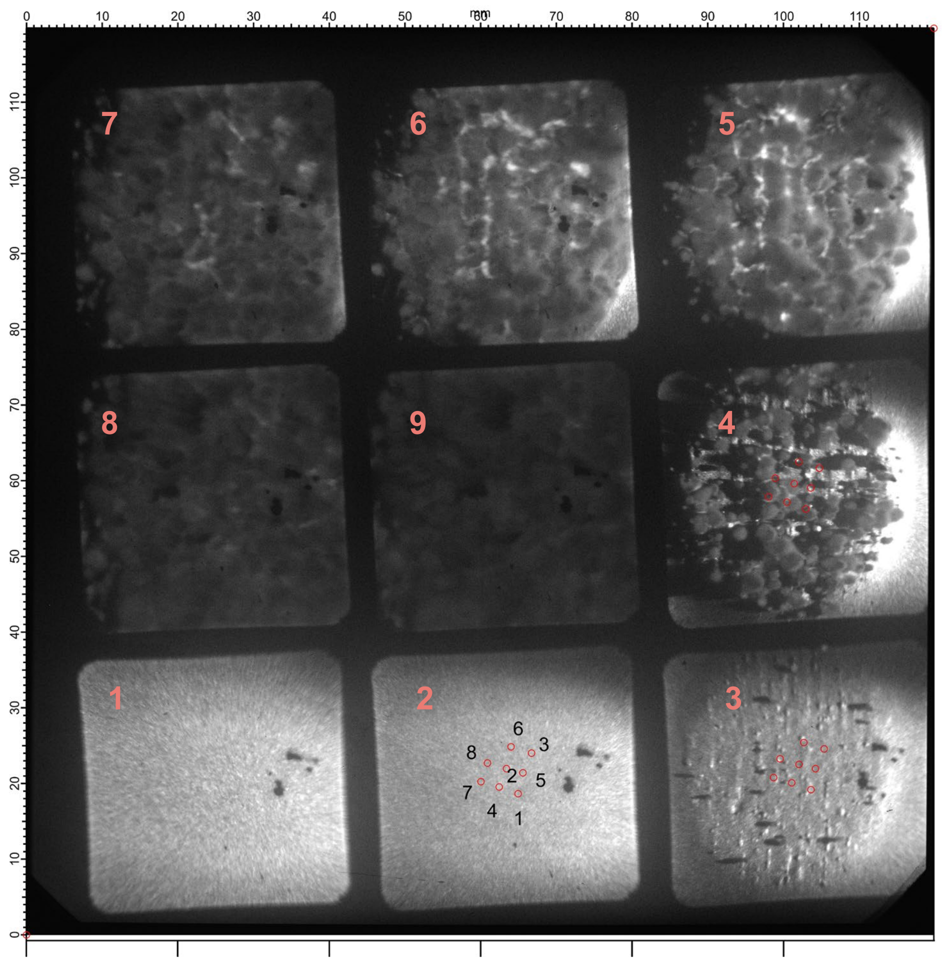
Asay foiled: punch-through is one failure mode for foils subject to highly energetic ejecta

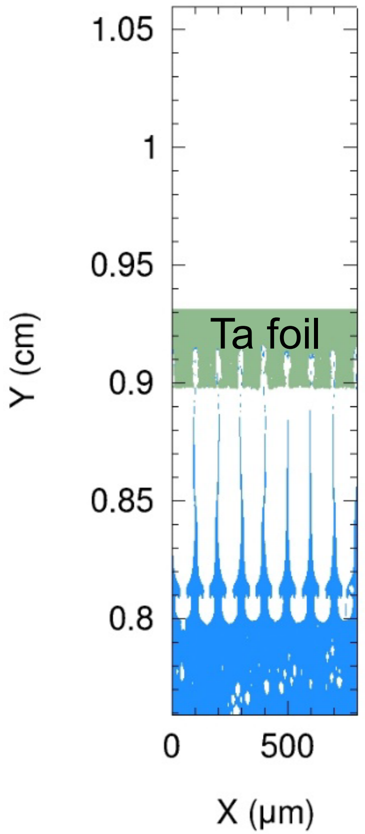
Initial CTH modeling (G. Stevens, STL) suggested punch-through was an explanation and additional experiments (STL, March 2021) provided further evidence of material response

High speed video looking down onto 520 um Ti64 foil. Ejecta impacting foil from below.

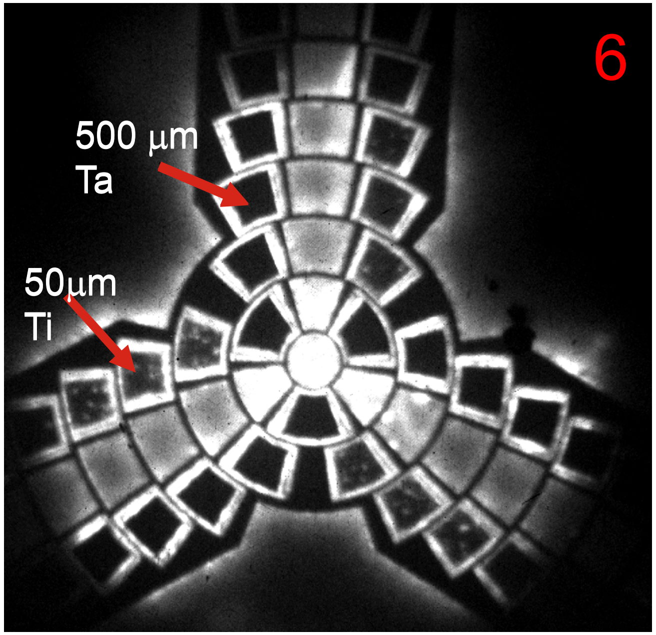
HSV rate=1us/frame

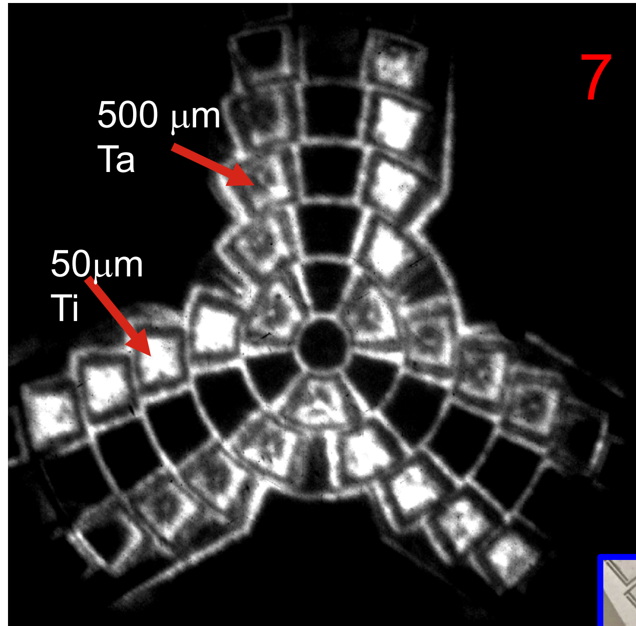
Small red circles indicate locations of PDV measurements.



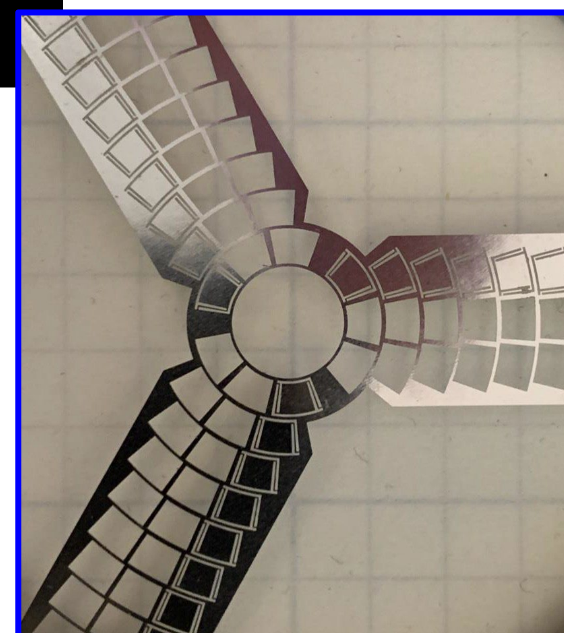


Asay foiled – high speed video of Asay foil array being impacted by ejecta





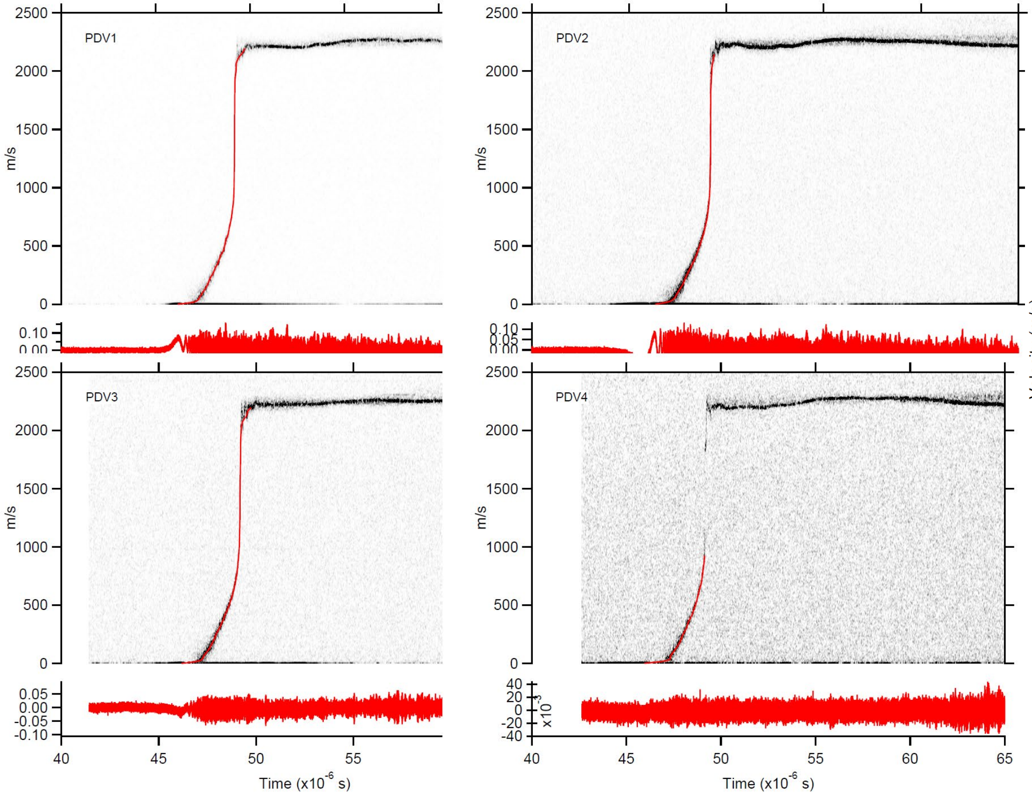
‘WOMBAT’ Asay foil array invented by Paul Steele (LLNL)

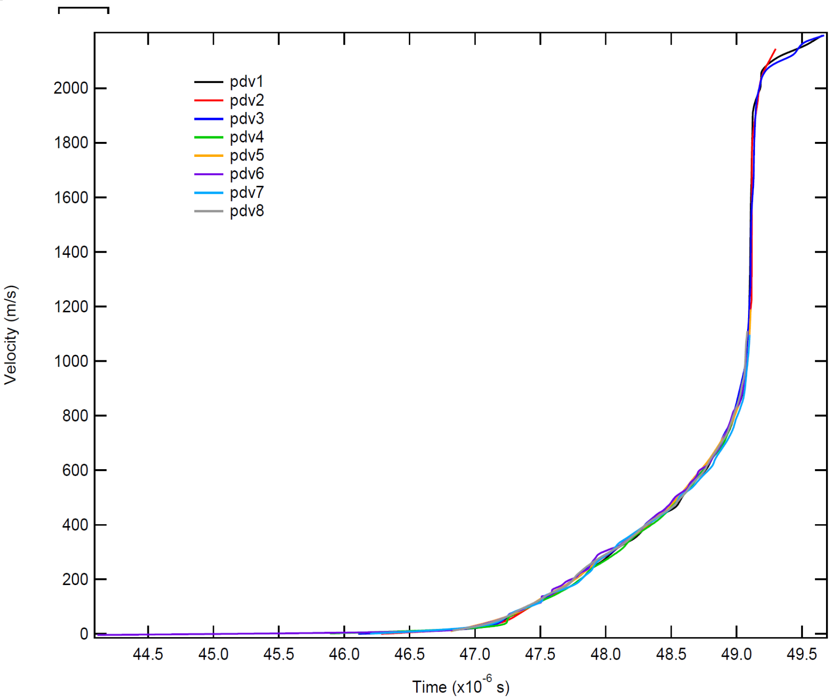


STL experiment J5 (Aug 26, 2020). High speed video of integrated Asay foil self illumination from ejecta impact. Frame rate = 1us/frame.

Asay foiled: thicker foils may fare better but …

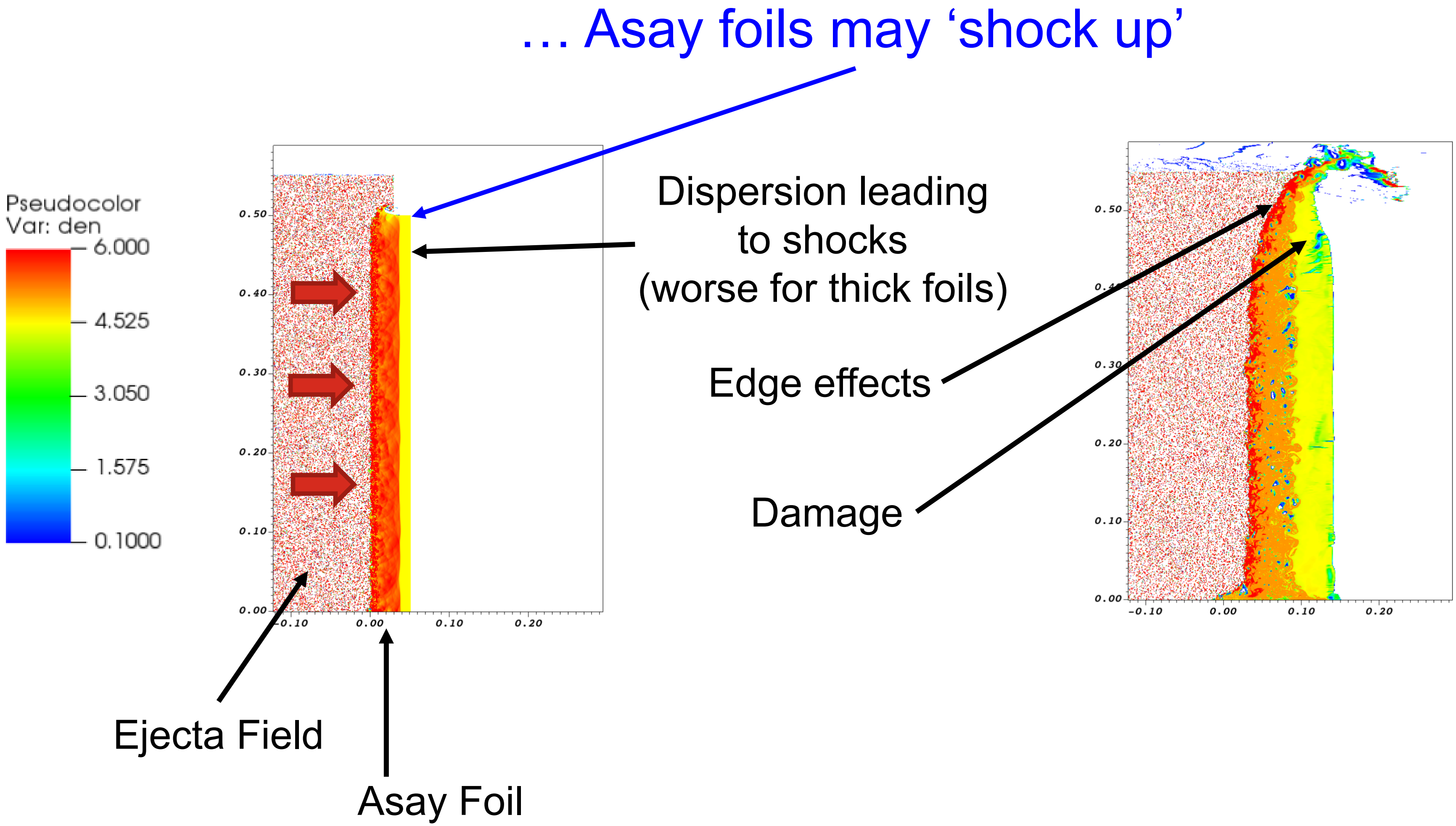
… are other Asay foil assumptions being violated?





Results from Jovial-2 experiments, STL, March 2021. Response of 1mm thick, Ti64 foils appear well behaved and repeatable.

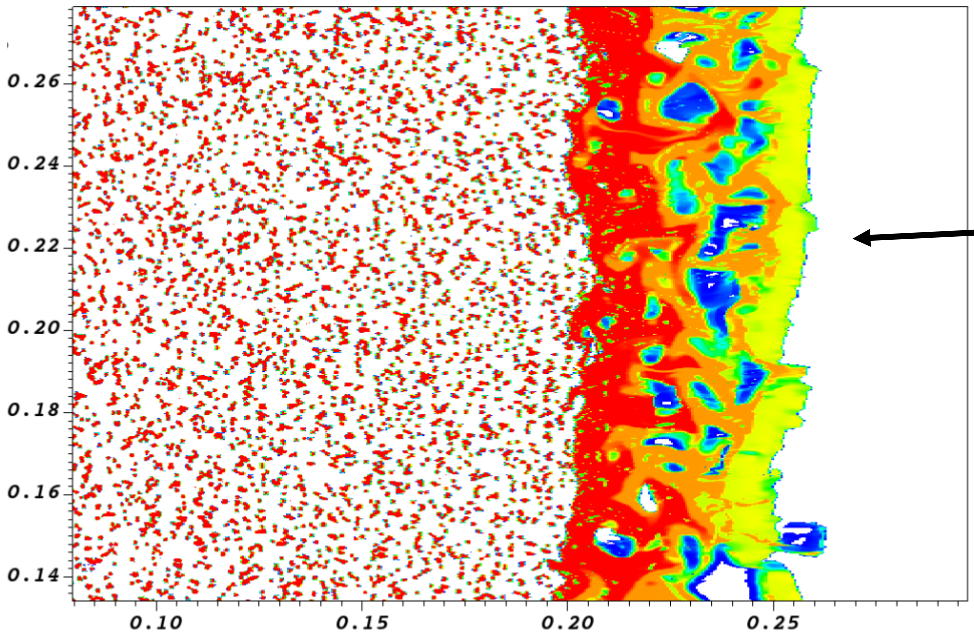
Asay foiled – however high resolution modeling of Asay foil response predicts several potential failure modes …



Modeling courtesy of Garry Maskaly

Asay foiled – Asay foils may also be highly disrupted and provide inaccurate and misleading data

Foil disruption: punch-through, voids, etc.

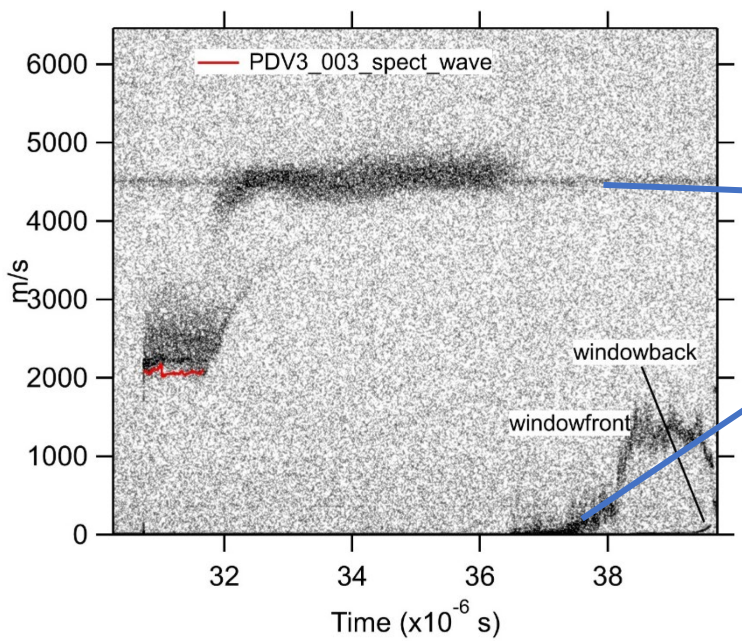


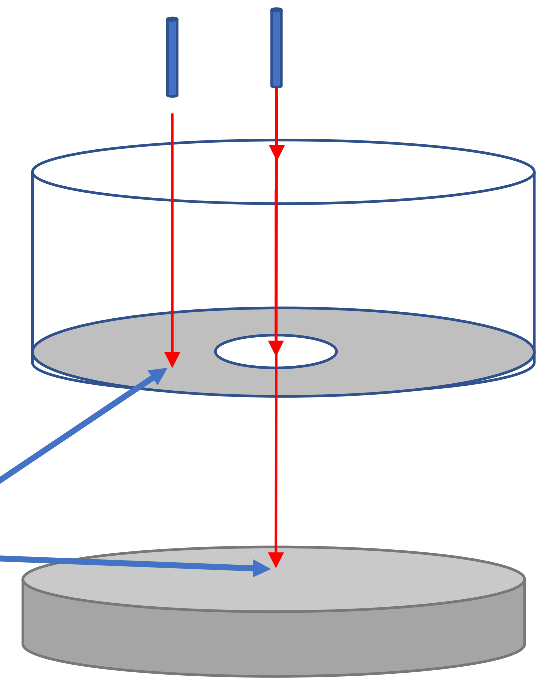
Large disruption from high mass jets (worse for thin foils)

Modeling courtesy of Garry Maskaly

The Asay window – an original Jim Asay concept + STL experiments = an alternative approach

Special Technologies Laboratory (STL) not only provided evidence of a potential problem with Asay foils, they also provided an alternative diagnostic approach as a solution – the Asay window





Shameless plug – See Dan Champion's analysis talk at this years PDV Workshop

Questions?