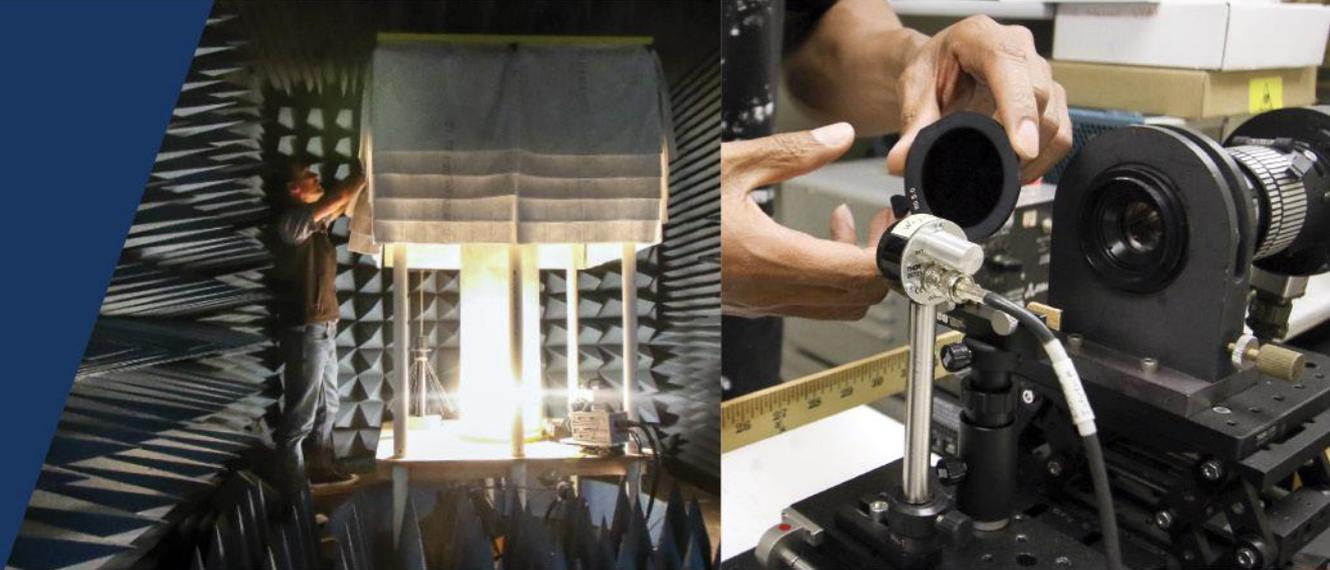




Brief History and Summary of the PDV

2023 Photonic Doppler Velocimetry Workshop
February 6–9, 2023



Oliver T. Strand
Senior Principal Scientist

The Nevada National Security Site is managed and operated by MSTS under contract number DE-NA0003624.

This work is done by Mission Support and Test Services, LLC, under contract No. DE-NA0003624 with the U.S. Department of Energy. DOE/NV/03624--1555.

Early history (from PDV Workshop 2014)

Evolution of PDV architecture

Homodyne
Heterodyne
Multiplexing

↓ Increasing
channel count

Motivation for very high channel count—optical pin dome
(scattered throughout)

Conclusion

Caution! Much of this is based on memory!
Some things are probably out of order.
Let me know if I fail to give credit where credit is due.

A few comments up front

I retired from LLNL in 2012 and was hired part-time by MSTS in 2013. (Thanks, Dave Esquibel!)

MSTS has changed names over the years:
Bechtel Nevada, NSTec, MSTS.

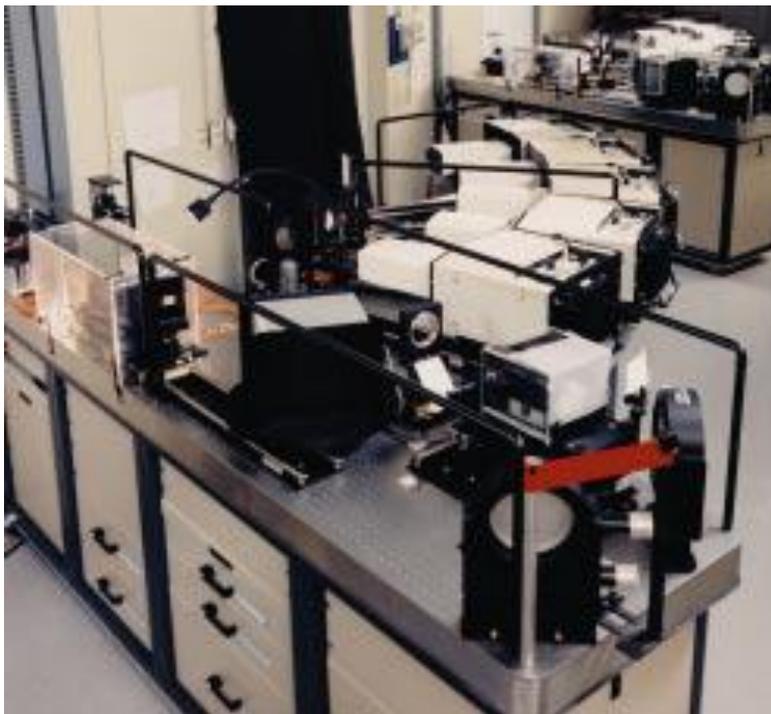
The Nevada Test Site (NTS) is now called NNSS.

The acronym SCE stands for Sub-Critical Experiments (sub-crits). These were performed in the U1a complex at NTS—1000' underground.

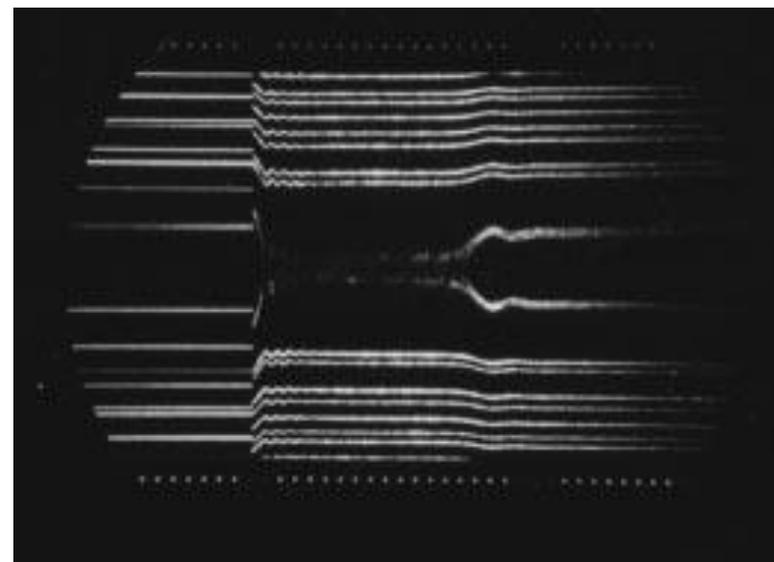
Fabry-Perot velocimetry at LLNL in 1996

The Manybeam velocimeter was designed by David Goosman

Analyzer table at Site 300, Bunker 851



Streak camera record.
 This is for one probe, but
 may be duplexed for 2 probes.



Images from: The Multibeam Fabry-Perot Velocimeter: Efficient Measurement of High Velocities, David Goosman, Science & Technology Review, July 1996

I was hired to field FP on Sub-Critical Experiments

I worked closely with Ed Daykin (MSTS) and his team.

15 Channels of Fabry-Perot Velocimetry at NTS/U1a (circa 2003)



Photo from Daykin et al., PDV Workshop, 2011.

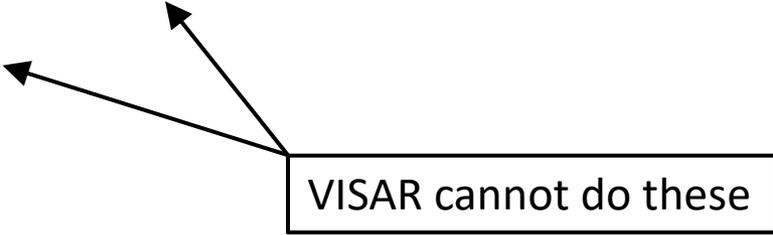
Advantages

- Carefully designed diffraction-limited optical system
- “Unlimited” maximum velocity
- Able to record multiple discrete velocities
- Able to record dispersion

Disadvantages

- Very expensive
- Many custom-built optics
- Labor intensive
- Large physical size

VISAR cannot do these

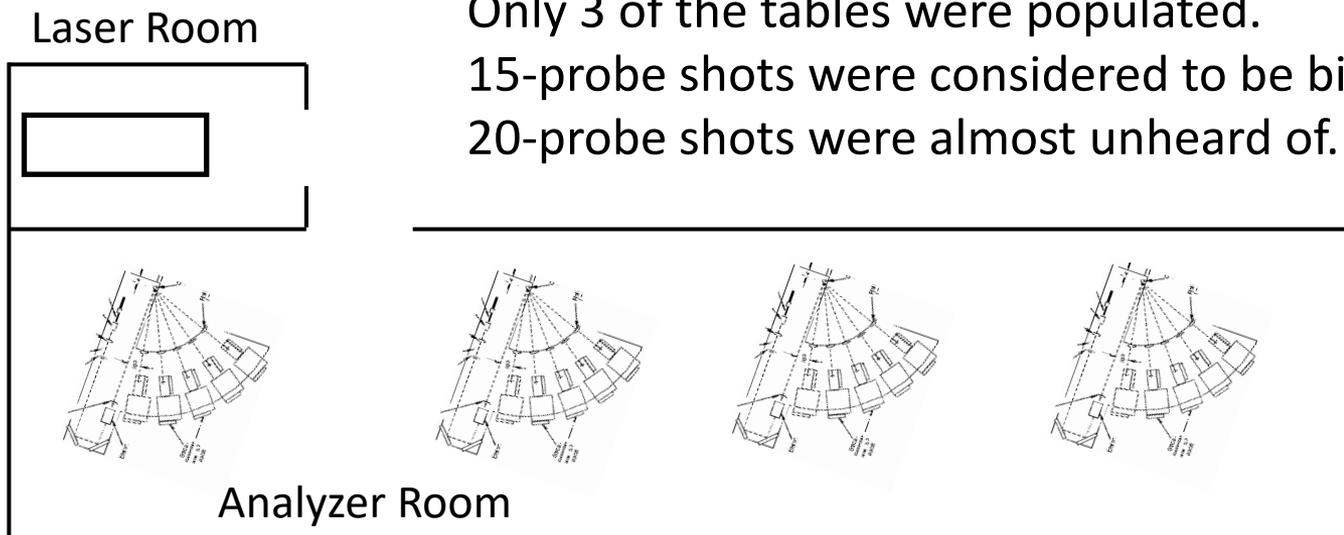


Ed Daykin and I spent many hours discussing how to make F-P smaller, easier, cheaper: “Fabry in a Box”

Manybeam Velocimeter at Site 300, Bunker 851

Let me digress for a few minutes...

There were 4 analyzer tables at Bunker 851.
 Only 3 of the tables were populated.
 15-probe shots were considered to be big shots.
 20-probe shots were almost unheard of.



Somehow Goosman convinced management to buy 4 analyzer tables at 851.
 This would have provided a 40-probe capacity, if we duplexed.
 Why in the world did David Goosman want to have
 a 40-probe capacity for this Fabry-Perot system?

An introduction to pin domes

The pin dome is an important diagnostic for LANL and LLNL used to evaluate the implosion of a device.

As the sphere implodes, signals from the pins track the imploded material moving toward the center.

This provides data about the temporal and spatial uniformity of the implosion.

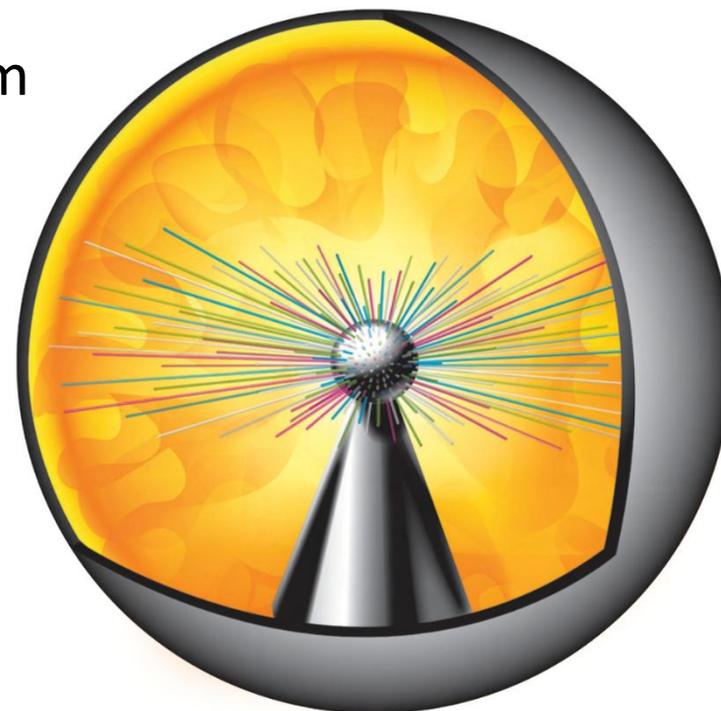


Image and text from Science & Technology Review, LLNL, September 2007.

Pin dome experiments are very expensive

Pin domes may have as many as 400 pins at 10 different levels.

The location of the tip of each pin must be accurately measured.

The entire pin assembly must be accurately positioned within the experiment.

The electrical signals are multiplexed onto many digitizers, which is a bookkeeping nightmare.

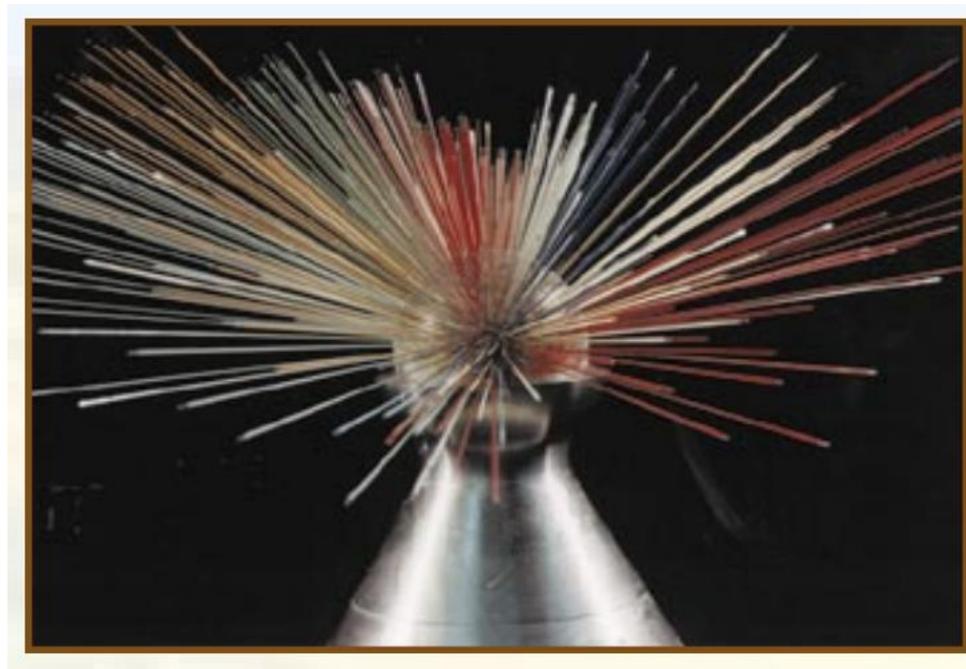


Image from S&TR, LLNL, March 1999.

Could anyone build an optical pin dome?

Goosman noted that there could be as many as 400 pins with 10 different lengths.

Might that somehow correspond to 40 optical probes to get equivalent spatial coverage? Plus continuous temporal data.

And just like that, Goosman convinced management to spend money on a 40-probe capacity at Bunker 851.

I have no idea if Goosman actively thought about how to build an optical pin dome...but he had the 40 Fabry channels at Bunker 851 to take the data if anyone figured it out!

I thought about the notion of an optical pin dome, but filed it away.

Accordion is added to the SCE schedule

Back to our story...

Accordion was to be a big expensive test with 15 FP probes. Fabry-Perot was to be the primary diagnostic, which was unusual. The designer wanted a fully independent backup velocimeter. It was much too expensive to build a 2nd Fabry system.

VISAR was an option, but...

Cannot handle multiple velocities or dispersion

We set out to see if we could build a “Fabry in a box” or something equivalent that might measure a beat frequency. Accordion was to be several years out, so we had time.

Measure a beat frequency?

How did we get the idea of measuring a beat frequency?

Prior to working for David Goosman, I spent 4 years working for a guy by the name of Mark Lowry at LLNL.

Mark's group specialized in photonics technology when it was still quite new. High-bandwidth optoelectronics, in particular.

I knew that generating a beat signal at 532 nm would involve multi-GHz frequencies, which was standard practice for his group.

I asked Mark if he was interested in working with me on this idea.

What technology existed in 1997?

At 1 km/s and 532 nm, the beat frequency is 3.76 GHz.

Status in 1997:

High bandwidth detectors (10's GHz) existed.

No digitizers existed to record multi-GHz for 10s of μ s.

SMF core at 532 nm is 5 μ m. Very difficult to launch high power lasers into such small cores.

Fiber lasers did not exist.

Update to 2014 talk: Fiber lasers were invented in the 1960s. IPG Photonics introduced a 1 W model (1550 nm) in 1990. We didn't know that at the time.

We applied for some research funding (LDRD)

Our proposal was funded for 2 years.

LDRD-ER Proposal
Photonic Doppler Velocimetry
 May 14, 1997



<p>Principal Investigator</p> <p>Ted Strand - DNT</p>	<p>Co-Investigators</p> <p>Mark Lowry - P&ST Ron Haigh - DSED Rick Ratowsky - DSED Paul Sargis - DSED</p>
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These pages are from our original proposal. (FY98 and FY99)

Goal

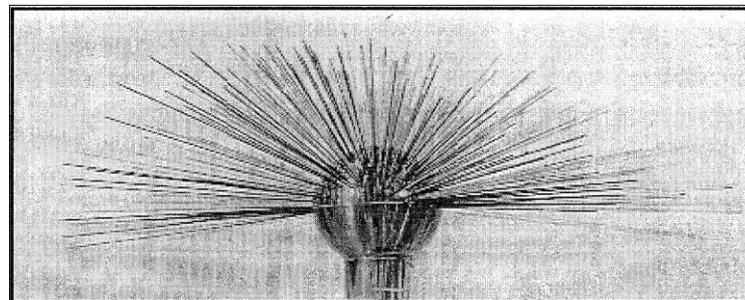
Long term (3-5 years):

- Develop 100+ channel, compact 3-D velocimetry diagnostic for time-resolved, full 3-D HE experiments.

Vision:

- A pin dome diagnostic with time resolved velocity profiles on every data channel

Paul Sargis worked most closely with us.



We proposed a 2-fold effort

Our approach to measure a beat frequency at 532 nm (LDRD):

Challenge #1: Determine the limits of maintaining some level of coherence in multimode fibers. (50–100 W/probe)

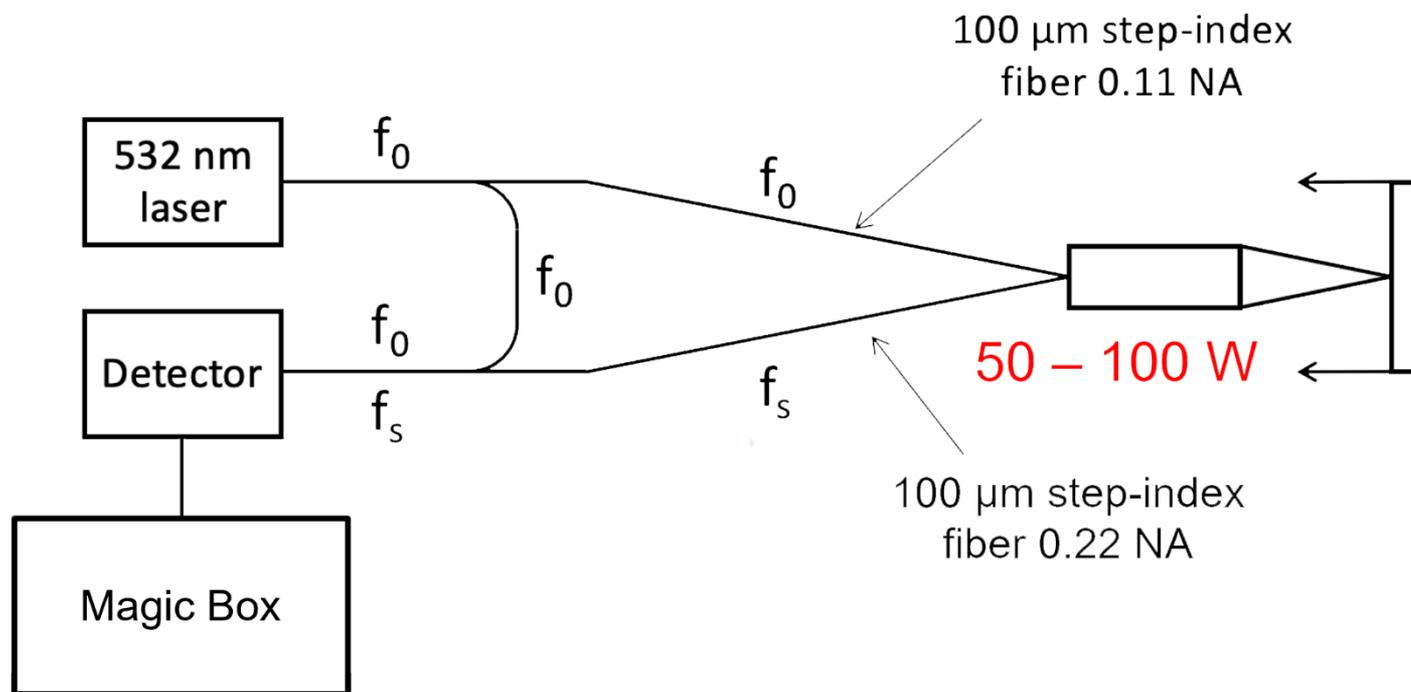
Challenge #2: Convert multi-GHz frequencies to some other parameter that is more easily measured with standard digitizers.

(500 MS/s = 2 ns per point → Nyquist velocity = 67 m/s at 532 nm.)

Challenge #1: coherence in multimode fibers

We were convinced that we needed multimode fibers because we needed such large laser powers.

How far could we propagate a coherent signal?



Challenge #1: coherence in multimode fibers

There were some published results on maintaining coherence in multimode fiber (LDRD)

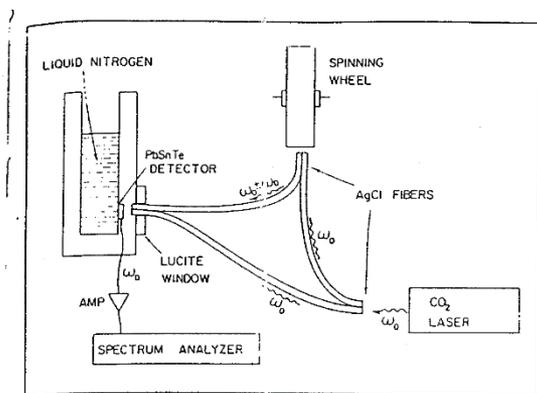


Fig. 1. Laser Doppler velocimetry experiment for measuring the speed of a rotating wheel.

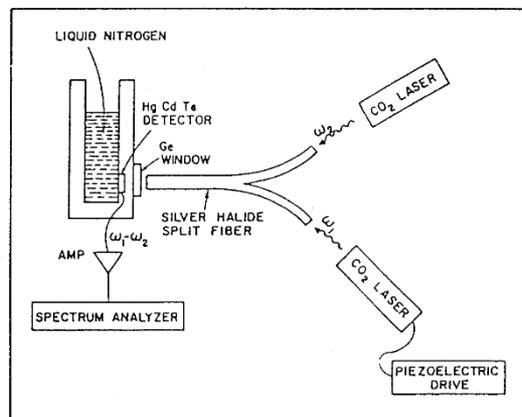


Fig. 4. Heterodyne measurement between two CO₂ laser beams, through a split silver halide fiber.

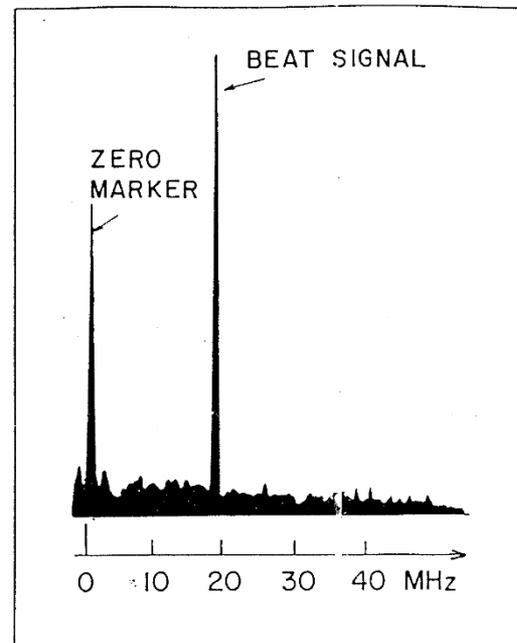


Fig. 3. Heterodyne signal, as measured in the spectrum analyzer.

CO₂ lasers at 10.6 μm
 Katzir et al., Opt Eng 23(4), 1984

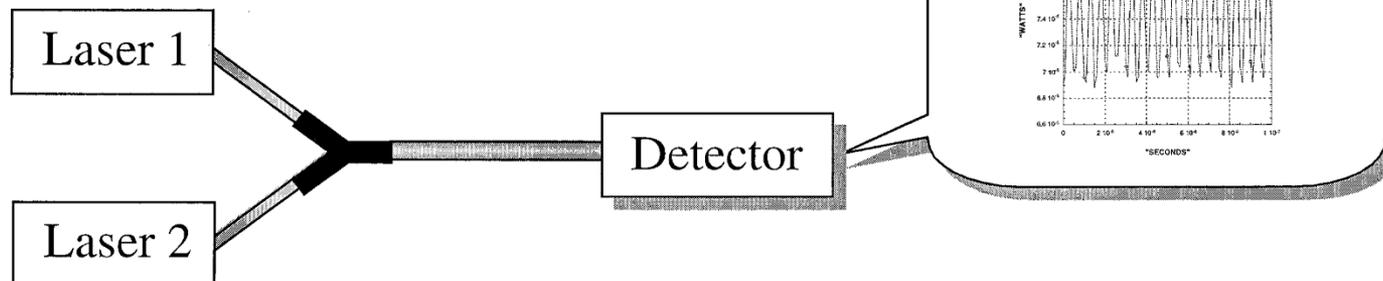
Challenge #1: coherence in multimode fibers

Our group did some work to reproduce those results (LDRD). This looked good enough to satisfy our first challenge.

Recent experiments verified heterodyne detection using multimode waveguides



Modulation depths of over 10% (using a kilometer of 50 μ m diameter multimode fiber with a multimode fiber coupler) have been achieved when beating two lasers.

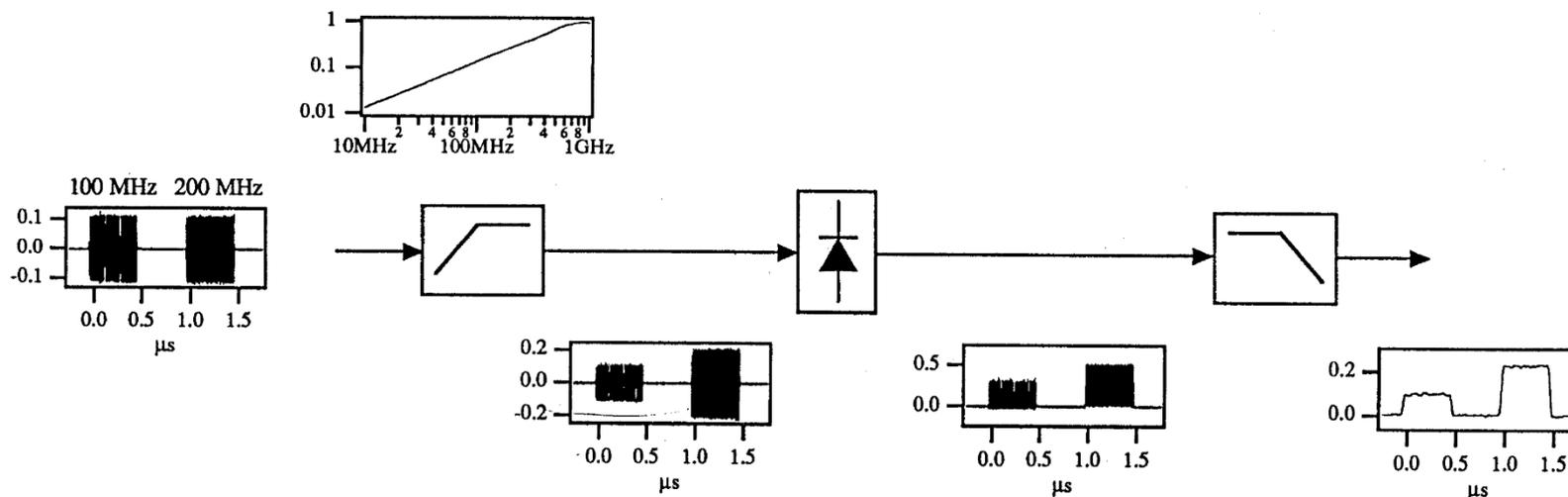


Very little theoretical and experimental background to validate concept and governing physics; some results at 10 μ m in the literature.

Heterodyne detection using multimode waveguide Y-couplers,
J. Salzman, U. Sivan, E. Kapon, and A. Katzir, *Applied Optics* 22(24),
3931-3934 (1983)

Challenge #2: convert RF to something measurable

Consider converting RF to amplitude (LDRD):



Can measure resulting waveforms at slower digitizing rates,

But--

Hard to characterize for, say, 1% measurements.

Need multiple high/low pass filters for large velocity range.

Multiple detectors per probe.

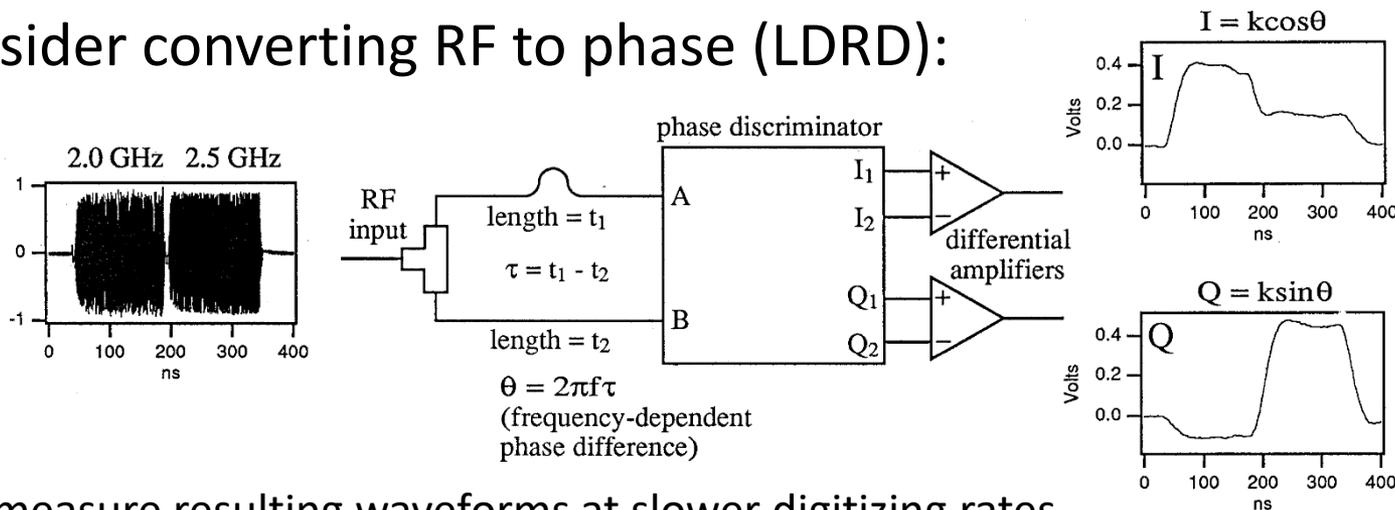
Can make only single-frequency measurements.

Requires homodyne with constant beat amplitude.

Hard to implement above 1 GHz.

Challenge #2: convert RF to something measurable

Consider converting RF to phase (LDRD):



Can measure resulting waveforms at slower digitizing rates,

But--

Need to characterize for, say, 1% measurements.

Need multiple delay circuits for large velocity range.

Multiple detectors per probe.

Can make only single-frequency measurements.

Frequencies <500 MHz require up-conversion.

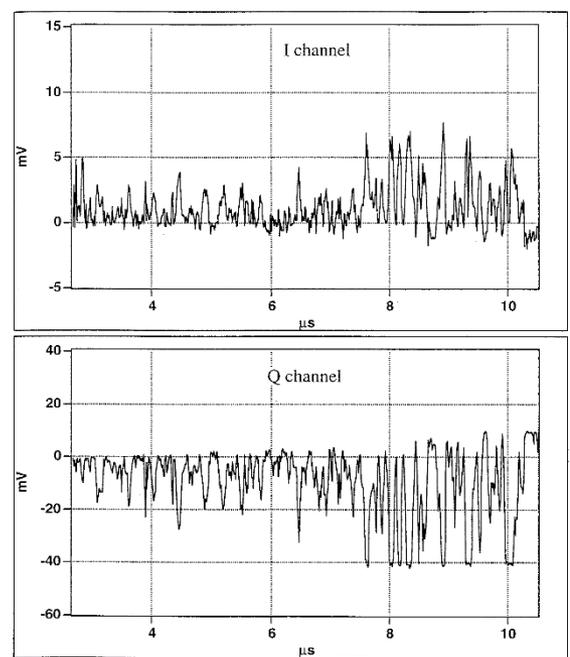
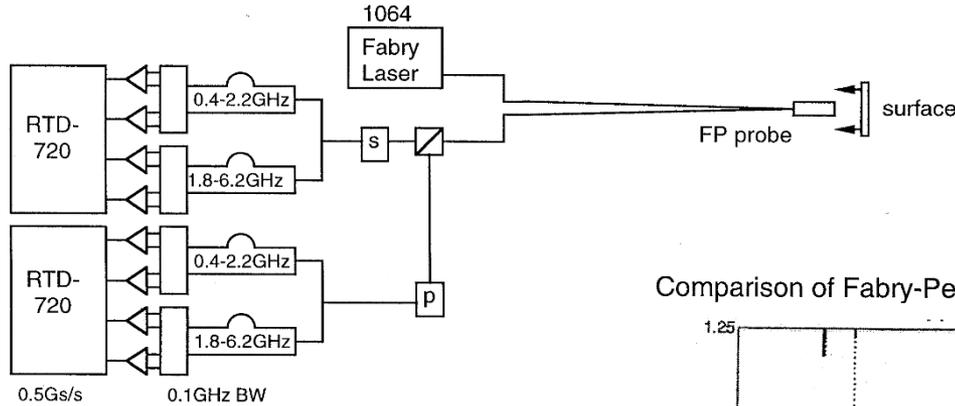
Similar to VISAR but compact and easy to use

We built this box and tested with mixed results—

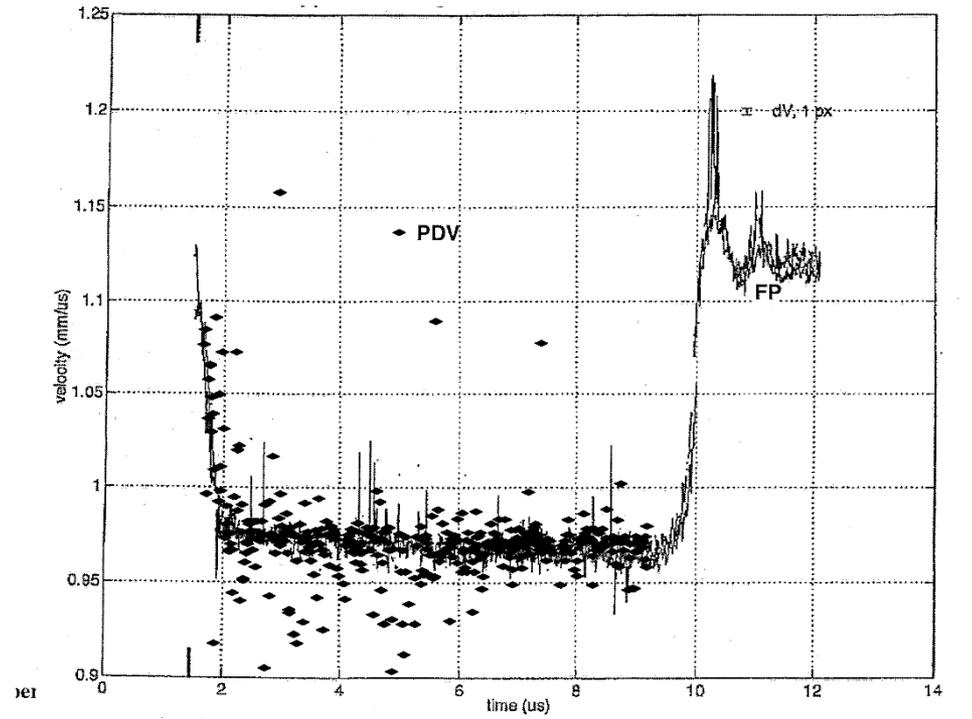
good in the lab but not so good on tests.

Challenge #2: convert RF to something measurable

The phase discriminator method was noisy on shots (1064 nm)



Comparison of Fabry-Perot and Photonic Velocimetry Data on Site 300 Shot



Our LDRD project was only partially successful

By the end of the LDRD funding, we had only partially achieved our goals:

Found evidence that some level of coherence may be achieved in multimode fibers, but the SNR is not good enough for our purposes.

Built the phase discriminator box, which worked very well. It was built into a rack-mountable chassis. Easy to transport and set up. No optics to align.

With no funding, the LDRD team disbanded, but a few of us continued to work the issue in our “spare” time. We continued to take data on SCEs, but low quality.

We shifted our attention to low velocities

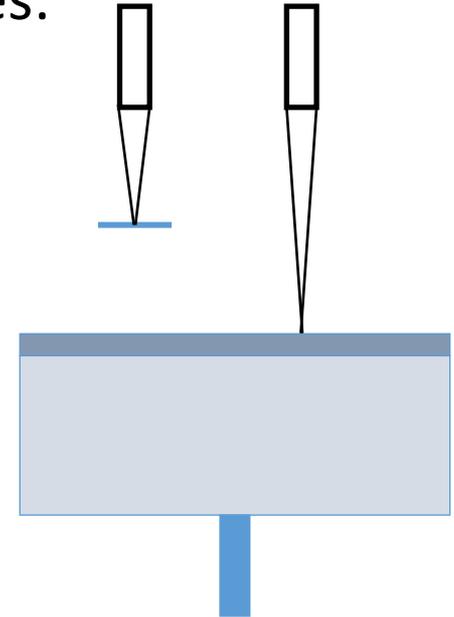
By 2000, Accordion was still off into the future, but our current set of SCEs required 2 frequency regimes:

High frequencies: use phase discriminator method

Measure surface velocities
HE-driven experiments

Low frequencies: use direct record method

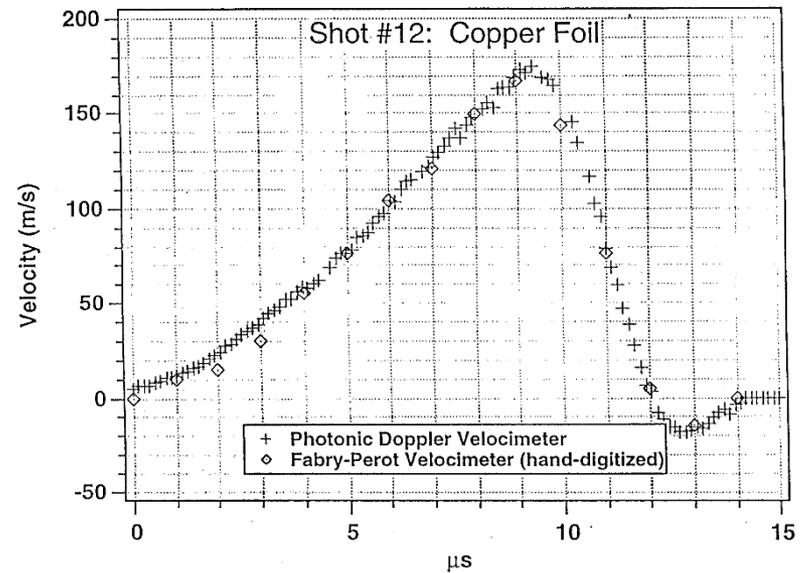
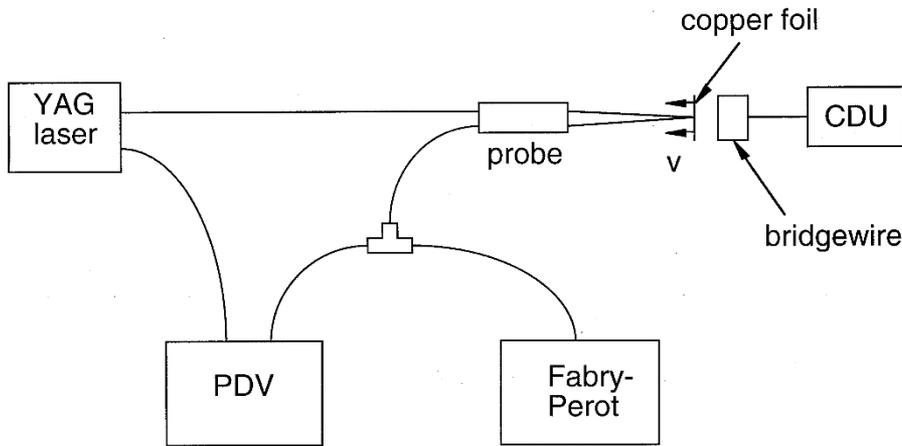
Asay foil velocities were almost too low for the Fabry system.
Beat frequency is low enough to record directly with standard digitizers.



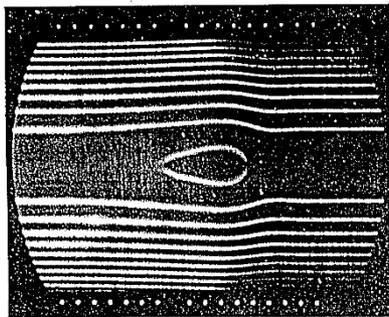
For more info on Asay foils: <https://doi.org/10.2172/1726147>, Tregillis and Harrison, LANL, 2020

We investigated the direct record method

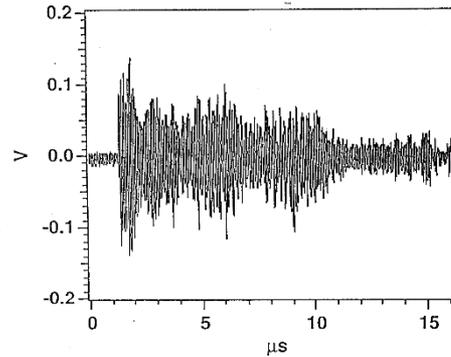
We compared direct record PDV with Fabry-Perot (532 nm)



Fabry-Perot Velocimetry



Photonic Doppler Velocimetry



We investigated the direct record method

We observed polarization effects with direct record method

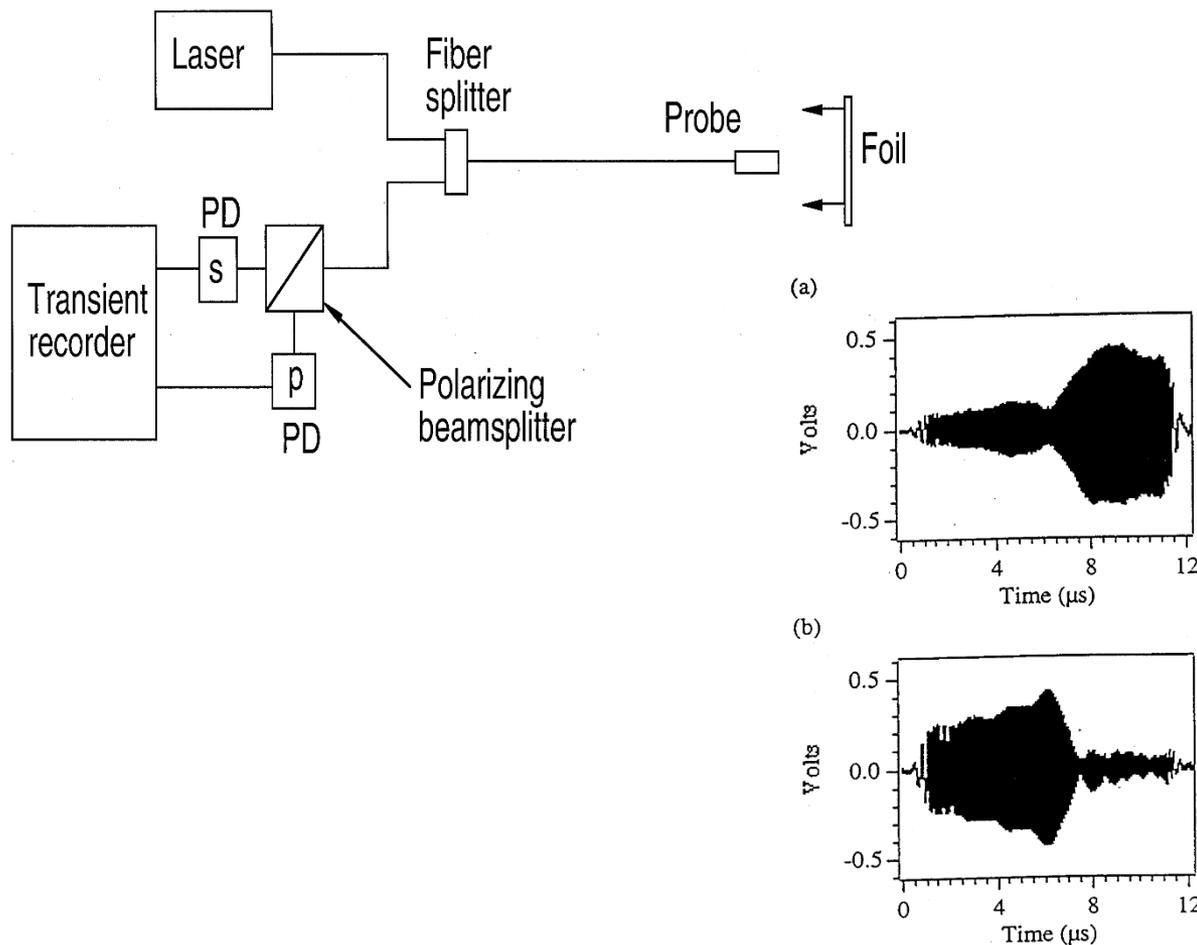


Figure 4. Raw data from niobium foil experiment: (a) S polarization, (b) P polarization.

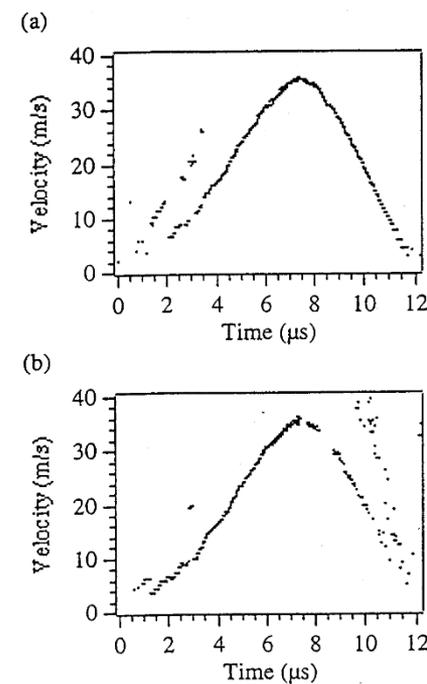


Figure 5. Processed data from niobium foil experiment: (a) S polarization, (b) P polarization.

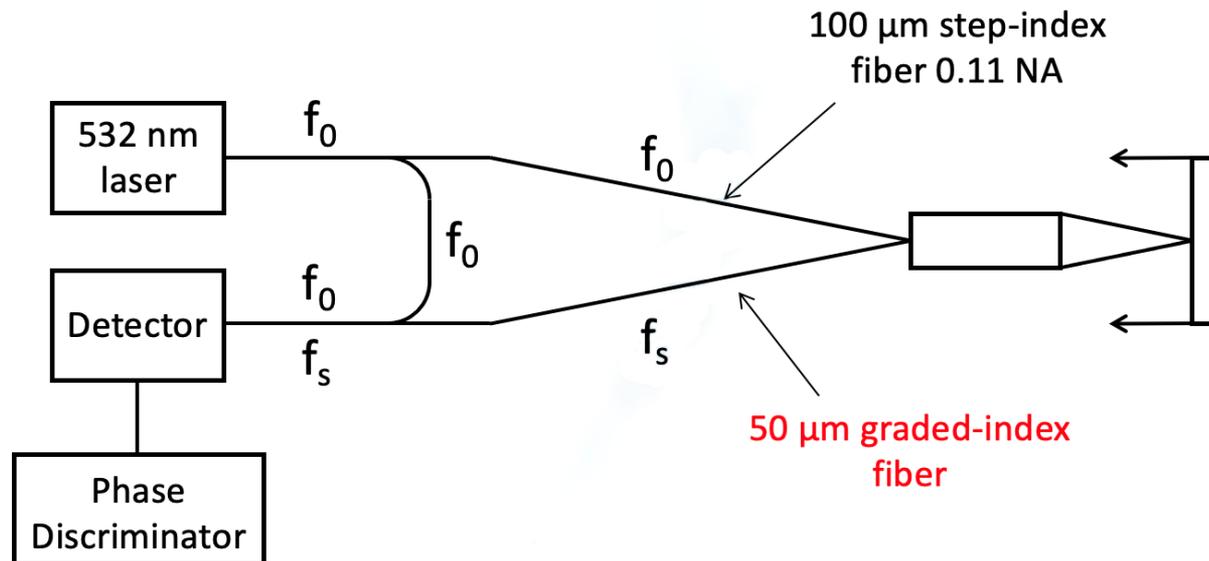
Modal dispersion is longer than the beat period

At U1a for the SCEs, the fiber runs were 80 m long
 → modal dispersion = 2.2 ns (multimode step index).

At 1 km/s and 532 nm, the beat period is 0.26 ns.

But, for graded index fiber, the modal dispersion is 2 ps.

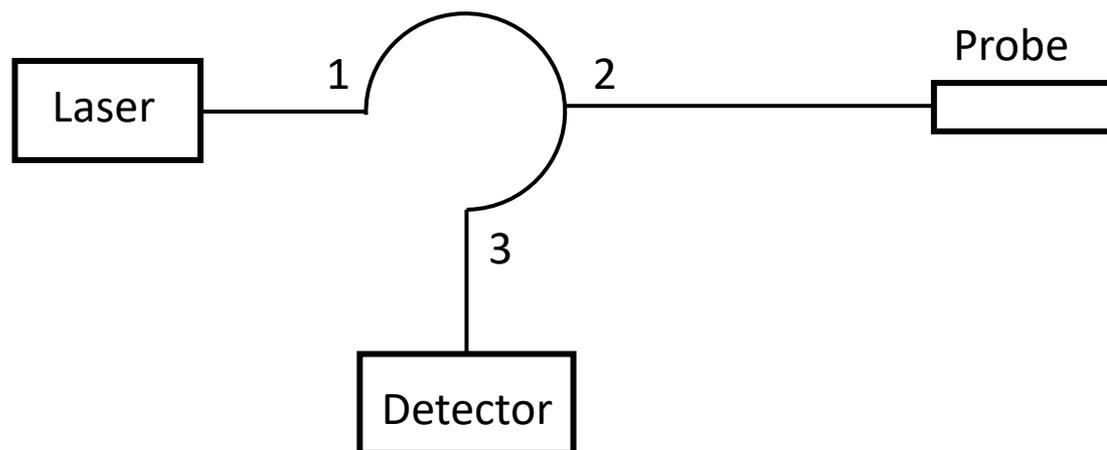
I decided to build
 a probe with
 graded index
 multimode
 return fiber...



Tony discovers the circulator

Tony Whitworth walked into my office with some literature on a device called a “circulator.” He had to explain it to me.

He said “Suppose we hook up a laser here, and put a probe here, and a detector here...will that work?”



“And, by the way, we would need to use single mode fiber and switch from 532 nm to 1550 nm.”

Consequences of going from 532 to 1550 nm

1550 nm is not visible—need some type of visible alignment laser.

Parts for 1550 nm are commercially available.

(No high speed digitizers, but Asay foils are low velocity.)

Final configuration will be much smaller and cheaper.

Multimode fiber (100 μm core) to single mode fiber (9 μm core).

(We are still thinking 50–100 W per probe.)

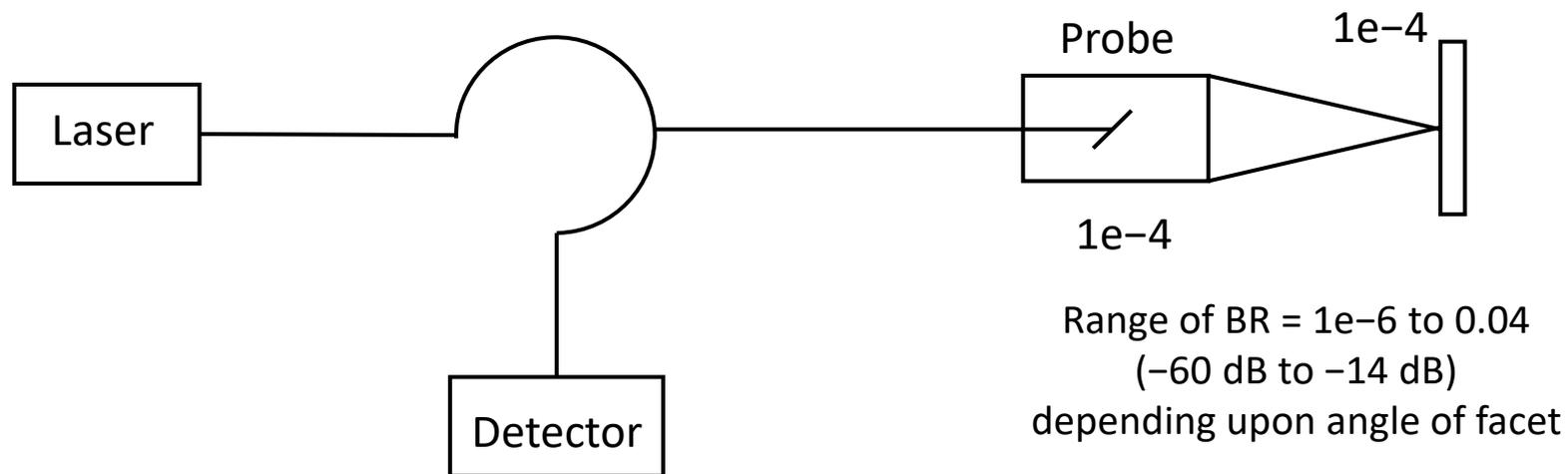
Spot size goes from 1 mm dia to 100 μm with standard probe.

Higher spatial and temporal resolution, surface roughness?

Single-fiber probe allows much more flexibility—optical pin dome?

Commercially available probes are much cheaper.

Where should we put the reference source?



We decided to put the reference source at the fiber endface inside the probe:

Simple system—very few knobs

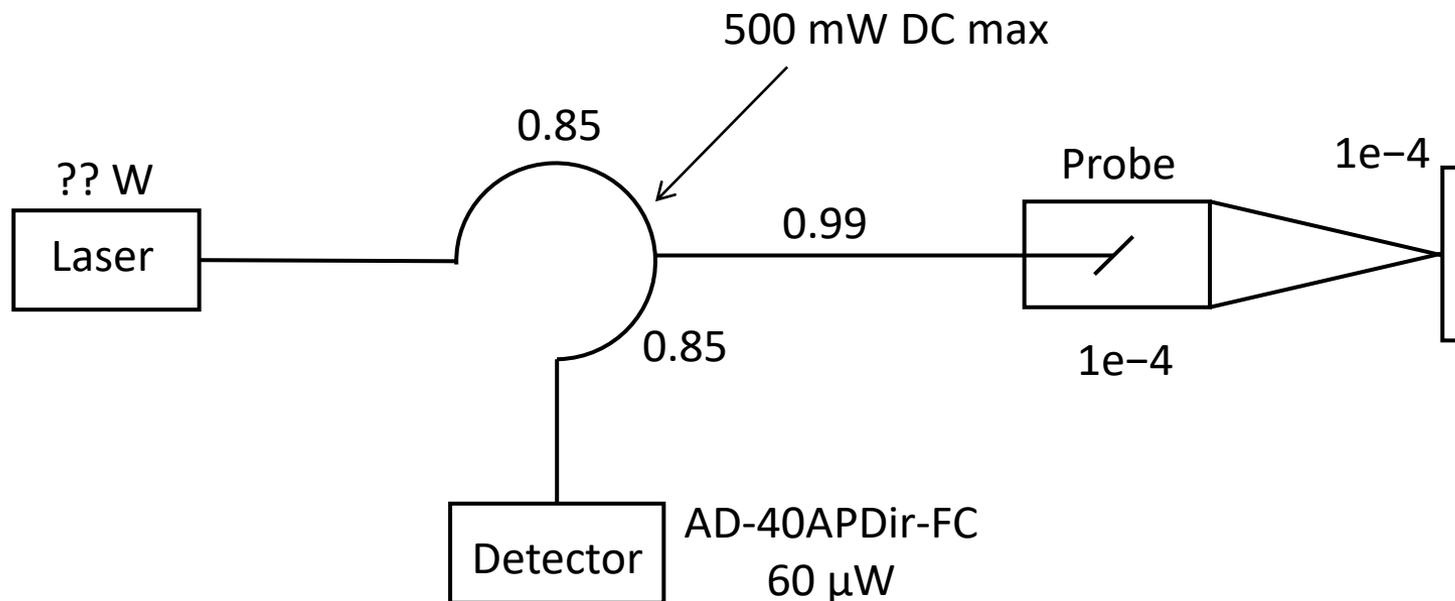
Doppler-shifted and reference follow essentially the same path

But

Need to calculate what the surface return might be before ordering probes

Could not adjust reference level prior to the experiment

Power Budget for 1550 nm PDV with circulator

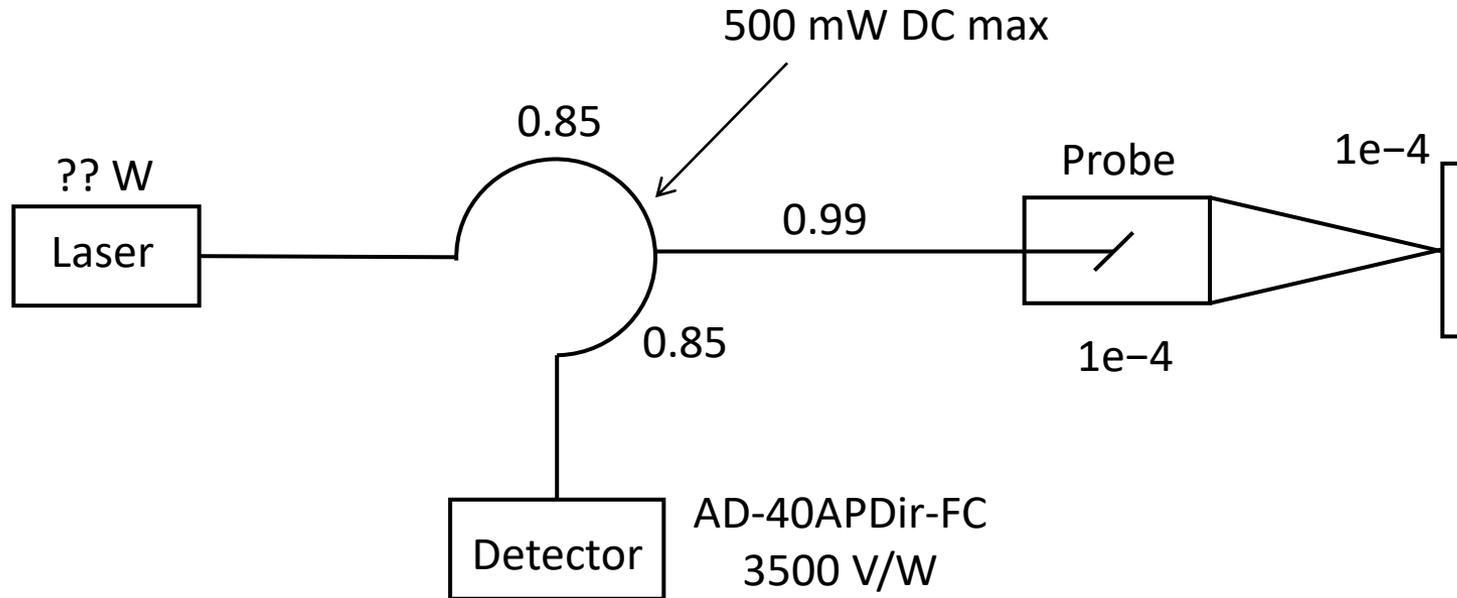


$$?? \text{ W} \times 0.85 \times 0.99 \times (1e-4 + 1e-4) \times 0.99 \times 0.85 = 60 \mu\text{W}$$

$$?? = 424 \text{ mW} !!$$

(Compared to 50–100 W per probe for Fabry-Perot)

Calculate Signal from Probe



$$60 \mu\text{W} \times 3500 \text{ V/W} = 210 \text{ mV total}$$

Half = 105 mV from surface

Half = 105 mV from reference

Tony started gathering up parts

30 mW linearly polarized fiber-coupled laser diode

1550 nm single mode fiber

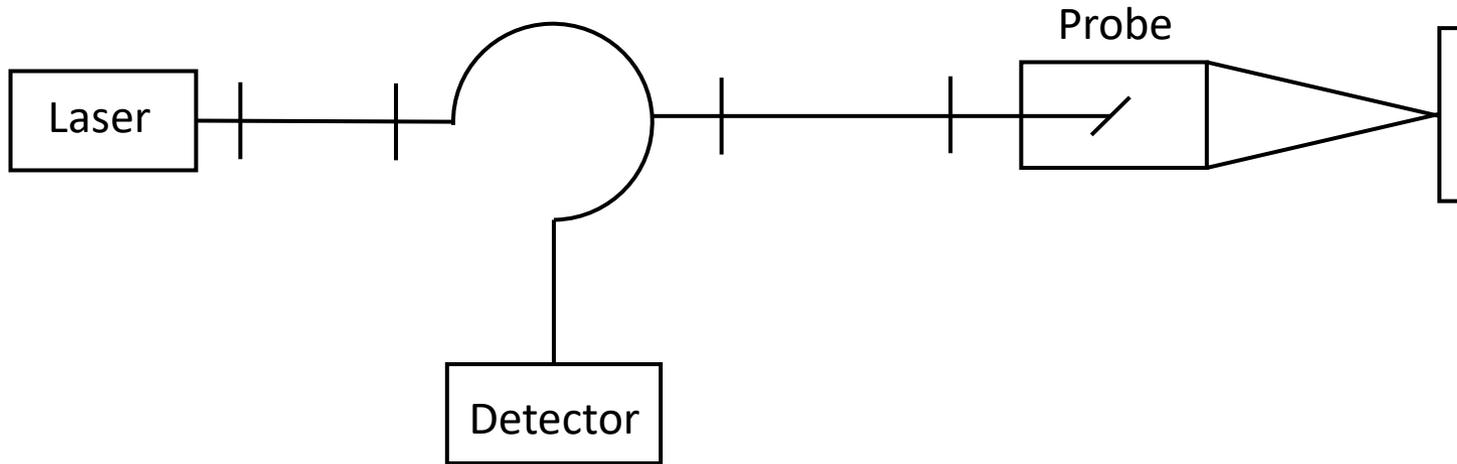
Polarized circulator

Focuser and collimator probes

Thorlabs detector

Woofers speaker

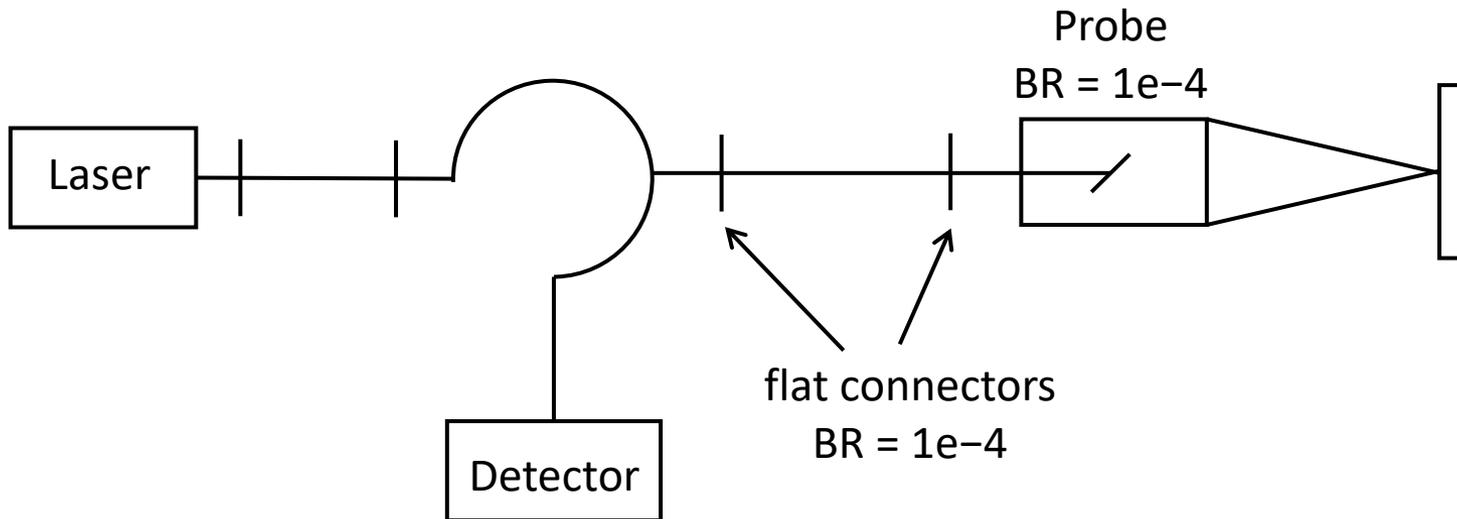
Tony set a basic system up in the lab



We had a very difficult time maintaining good beat amplitude.

The slightest touch would make the signal change wildly.

We realized we had more than one reference source

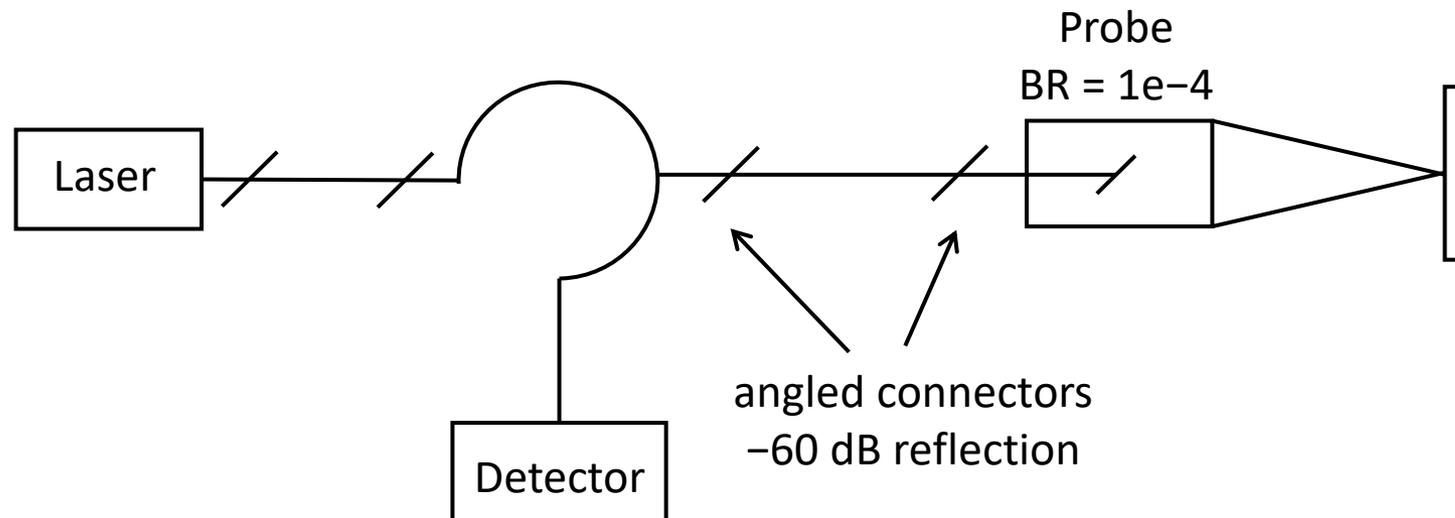


The reflections from the various flat connectors were competing with the reference from inside the probe.

Different sources easily go in and out of phase as the fibers move.

Changed to angled connectors

This is particularly important between circulator and probe



This helped enough that we could maintain fairly good beat amplitudes → Keep investigating this method.

Put together a real system...

We realized from our previous work that we needed to go to a polarization-insensitive system.

By this time, we discovered the fiber laser.

We bought a 1-watt unpolarized model.

We bought polarization insensitive circulators.

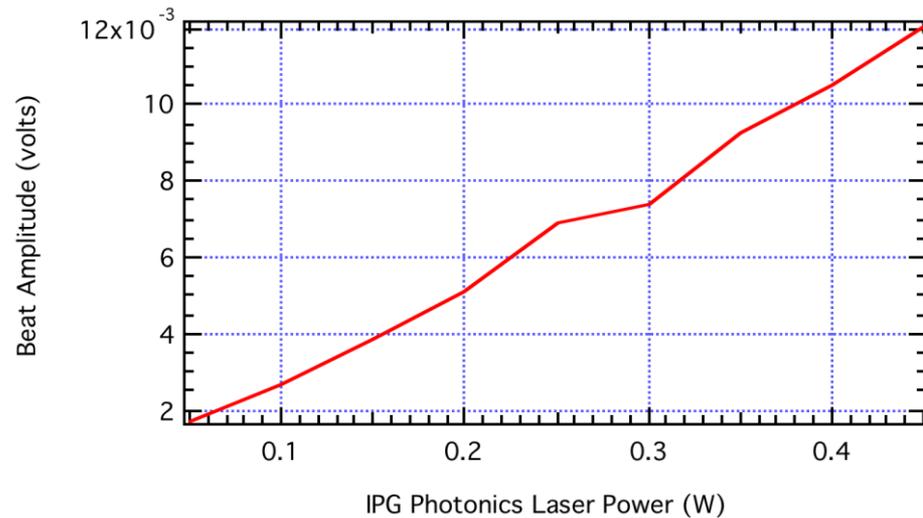
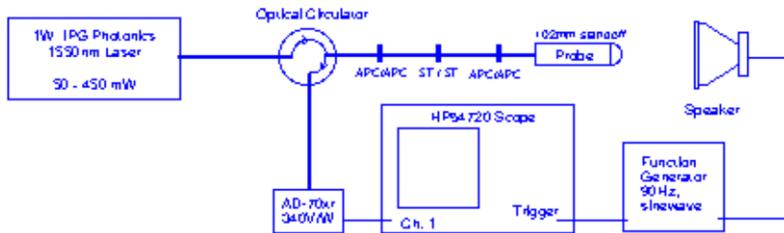
We used angle polished connectors everywhere.

Things started working well enough to start making performance measurements in the lab.

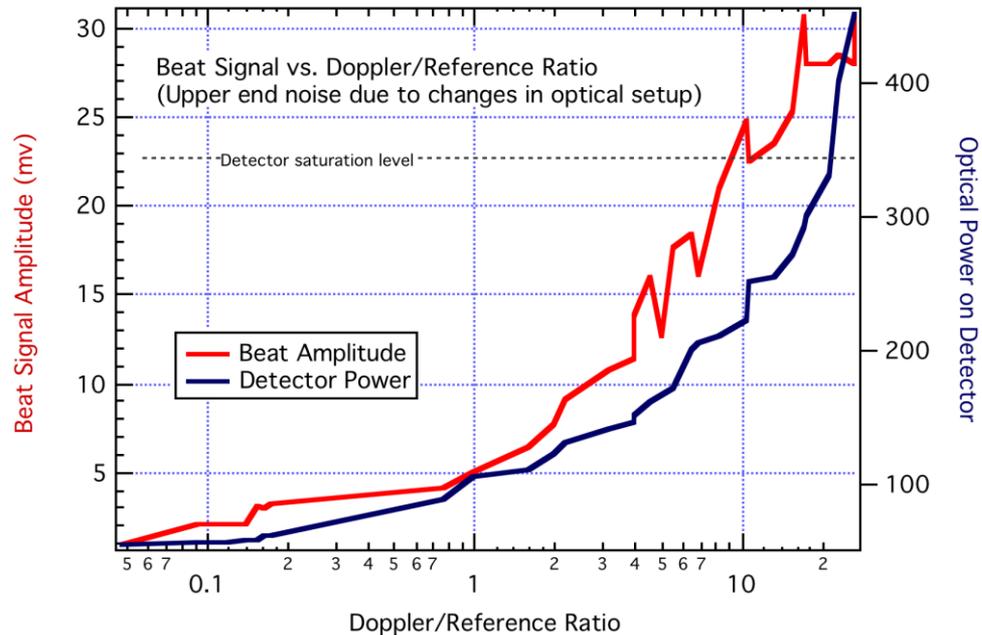
Tony got busy...

Performance measurements

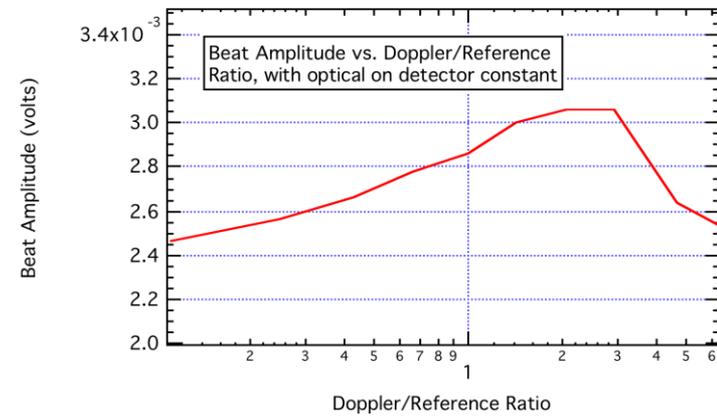
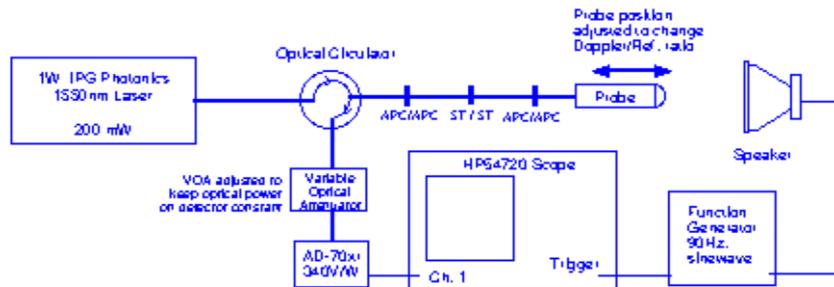
Beat amplitude vs laser power is linear as expected.
(Doppler-shifted signal equal to reference signal)



Beat Signal Amplitude and Optical Power on Detector vs. Doppler/Ref Ratio



Beat signal vs ratio of reference to Doppler-shifted light.
Should peak at 1:1, but these are difficult measurements when the probes have large back reflection.



Time to get serious...

It was time to start looking for shots to field our new system on.

People were very reluctant to give us any useful real estate—edges of flanges, etc.

Poor geometry = poor data

Could not impact shot schedule

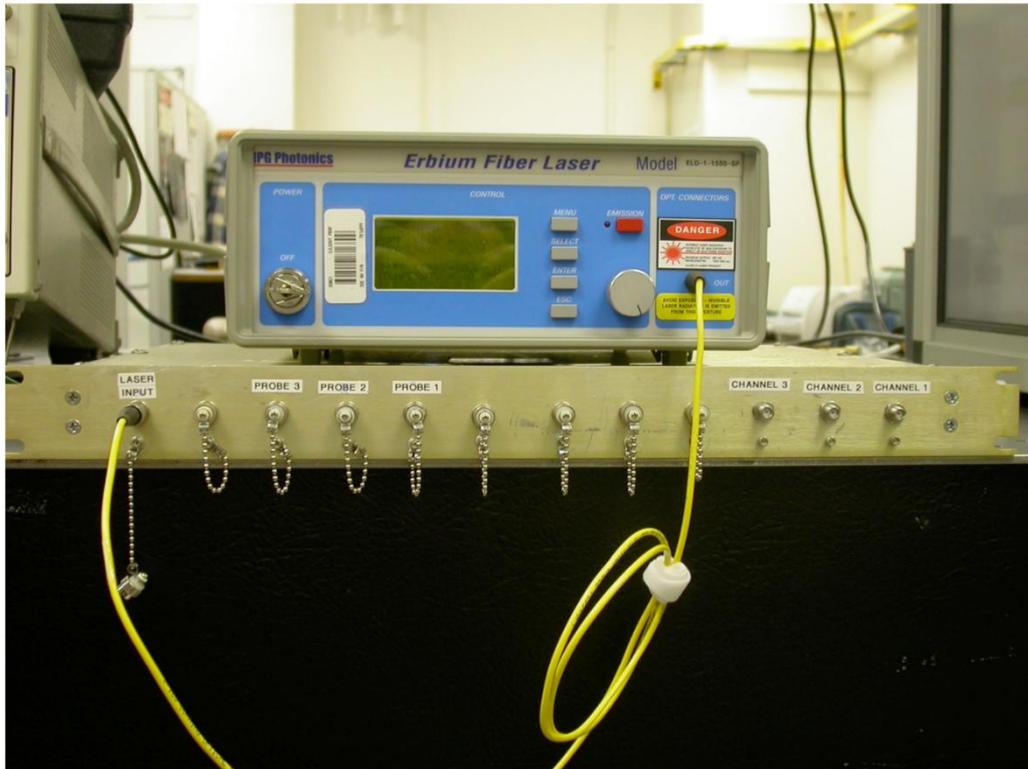
This went on for quite a while

Finally, Leon Berzins arranged with Vlad Georgevich of LLNL to let us field our PDV on one of his shot series. Fortunately, these were deflagration shots = low velocities.

Our first PDV system

Tony cobbled together a 3-channel system with a mixed bag of probes and we went to NTS

Our 1st shot with the PDV was at the BEEF bunker (NTS) on March 10, 2003.



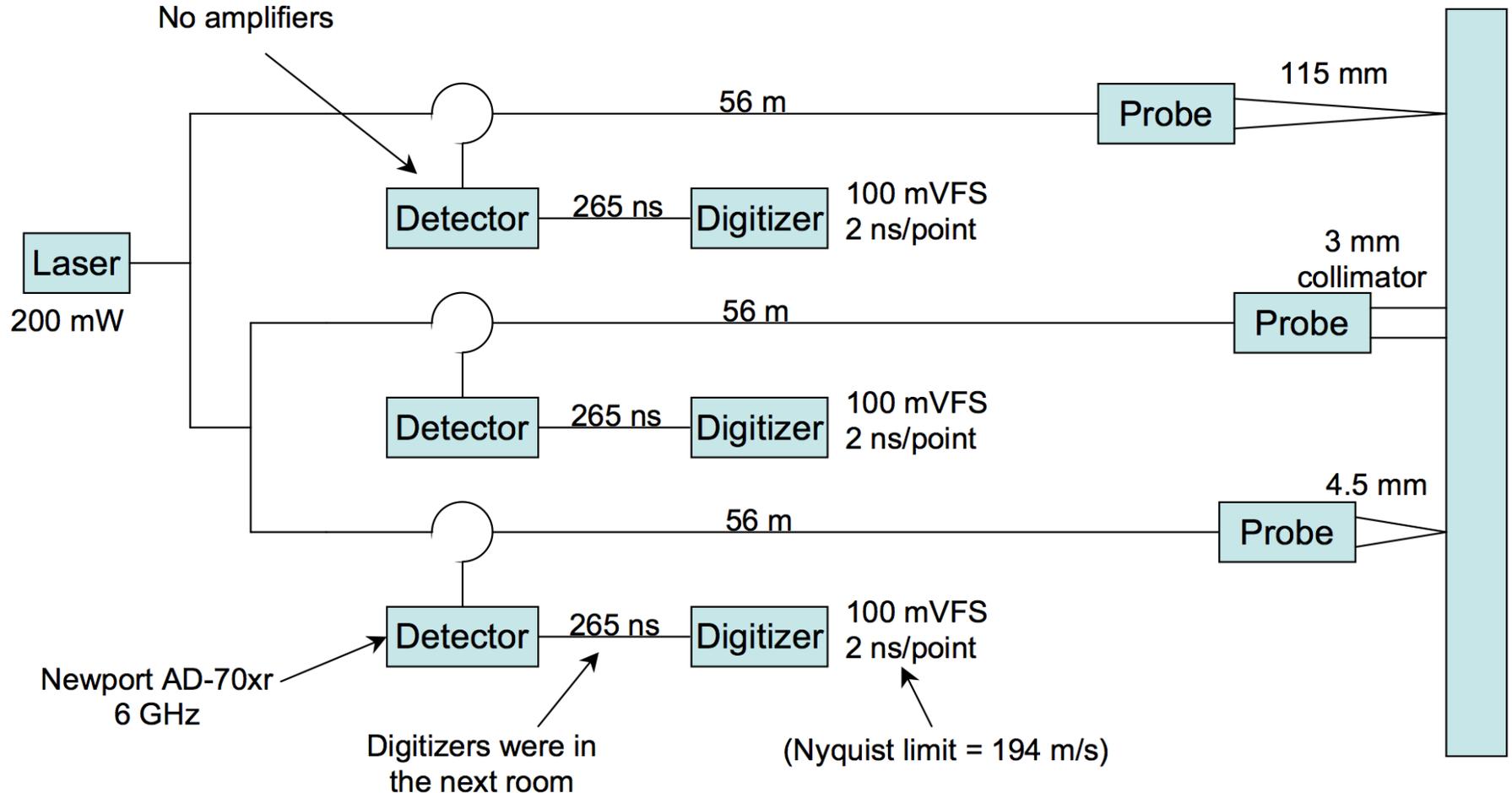
1 W laser

3 channels
(no knobs!)

We borrowed
digitizer channels
from the bunker

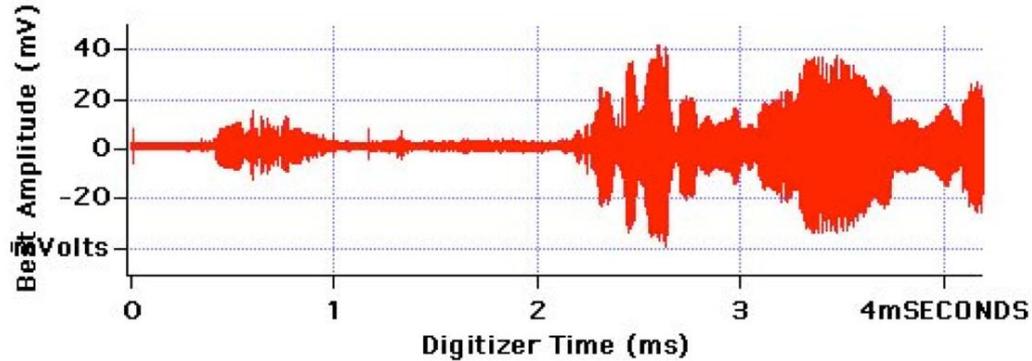
Our first PDV system

We barely had enough parts for 3 channels and borrowed digitizers from the bunker.



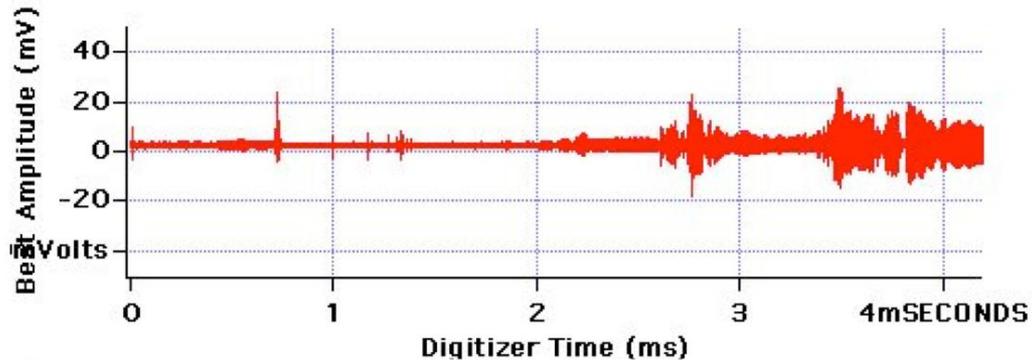
The data were less than perfect...

Probe 1
115 mm



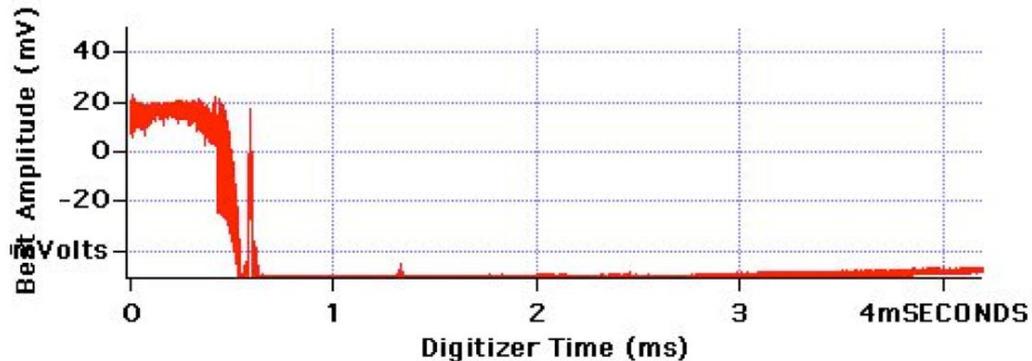
Looks good!

Probe 2
3 mm
collimator



Anything here??

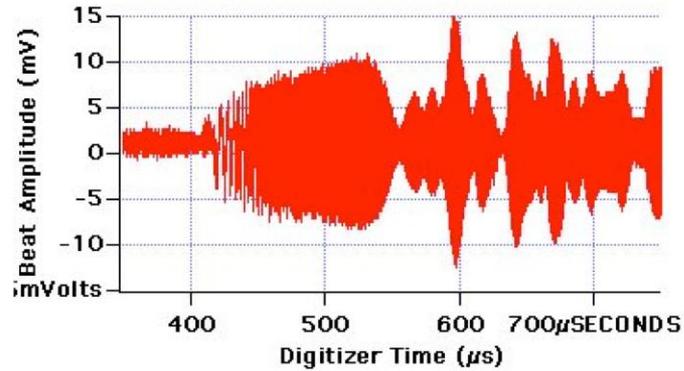
Probe 3
4.5 mm



Electrical noise here

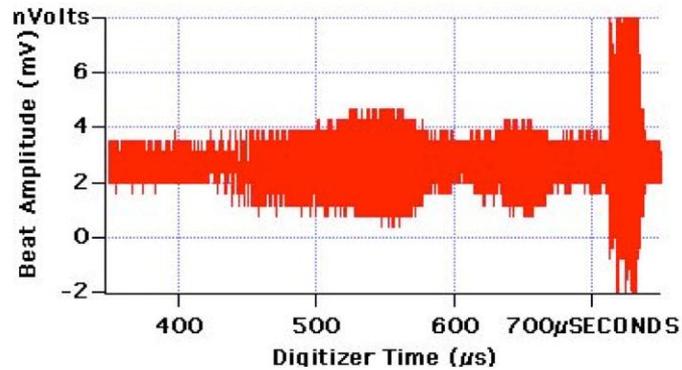
But at least we got something!

Probe 1
115 mm



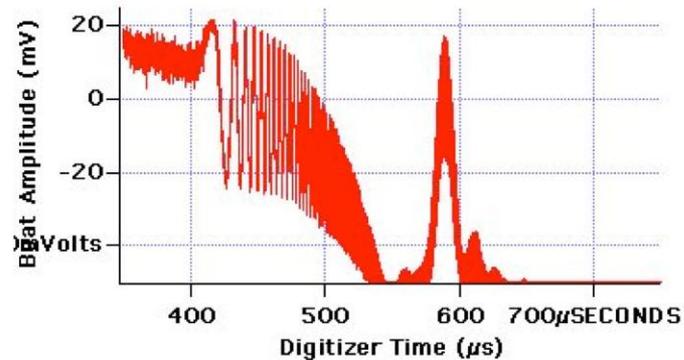
Still looks good!

Probe 2
3 mm
collimator



Still not sure

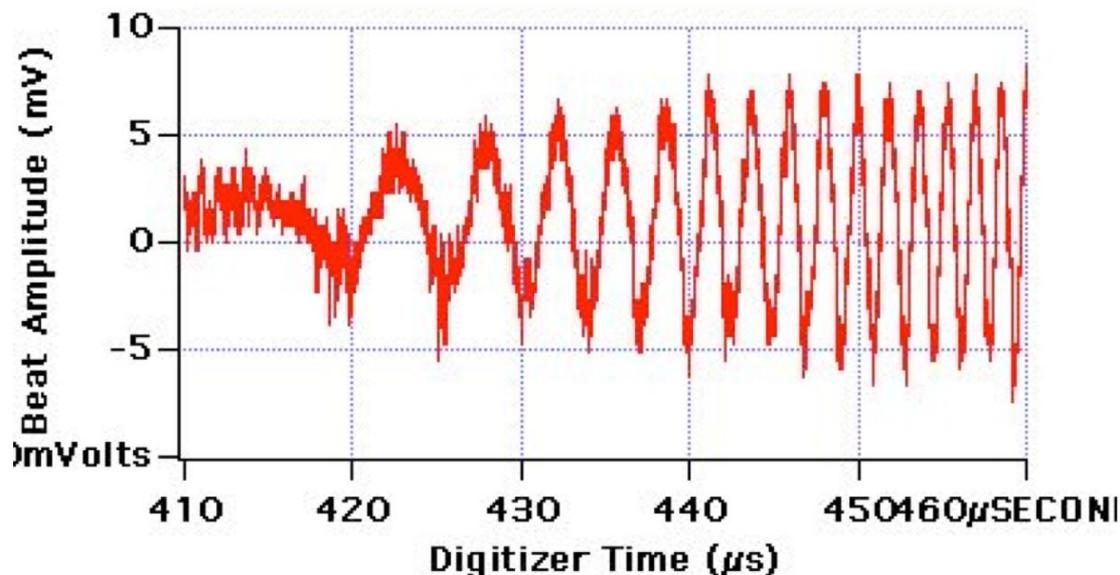
Probe 3
4.5 mm



Definitely have some data!

Data analysis was tedious

I did the 1st analysis via a peak-finding method using Excel spreadsheets



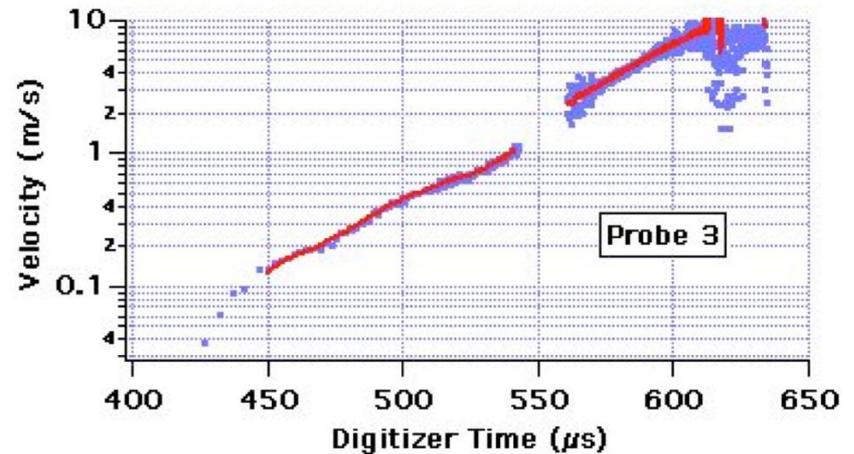
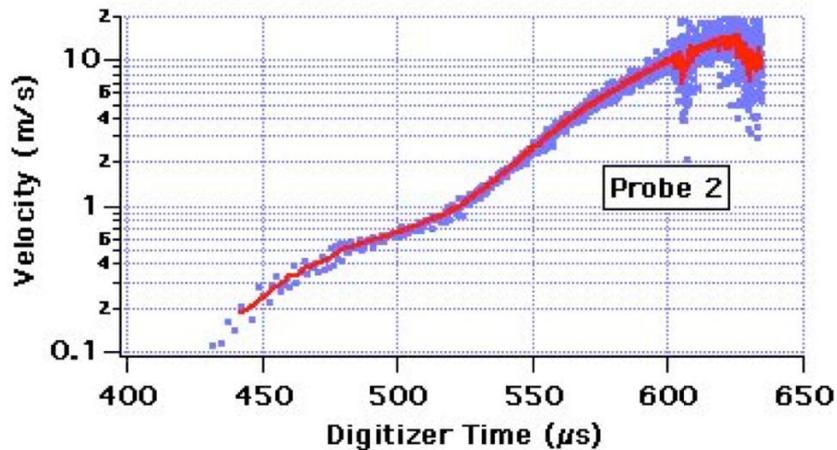
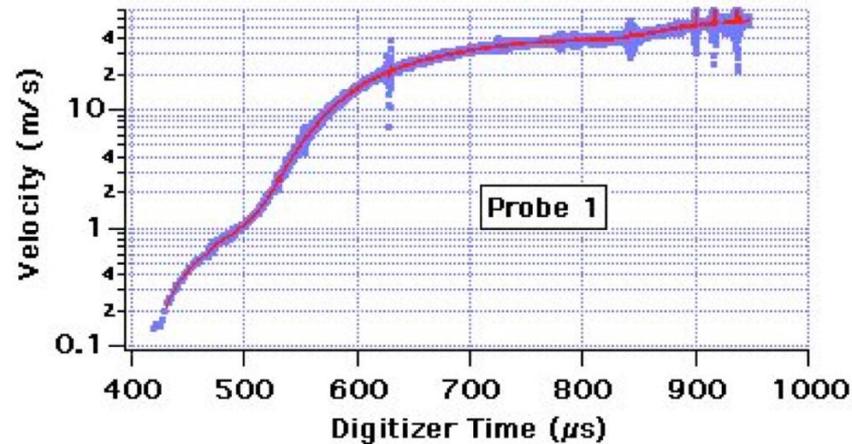
Excel can handle only 50,000 rows of data, so I needed to split the data file among 10 spreadsheets.

I applied different amounts of smoothing until I found only 1 peak per half cycle.

Then I gathered up all the times at which the peaks occurred, and calculated the velocity averaged over the half cycles.

This took about 2 days per probe.

Not too bad for our 1st try on a real shot



We needed a better way to process the data

Bill Kuhlow of Bechtel Nevada (now MSTs) modified his Fabry analysis code for PDV:

Used MatLab

Two parts:

- Batch mode to calculate spectrograms

- Interactive mode to define regions of interest and extract

Sliding Fourier transform with fixed 50% overlap

User-friendly for defining regions of interest

This was a lifesaver!

Better components quickly became available

By mid-2003, fiber lasers were getting more powerful:
2W models were available.

Agilent came out with the first digitizers that could record
at 20 GS/s (7.8 km/s) and 6 GHz (4.7 km/s) for 50 μ s !!

Bechtel Nevada (MSTS) bought first two Agilents for the SCEs.

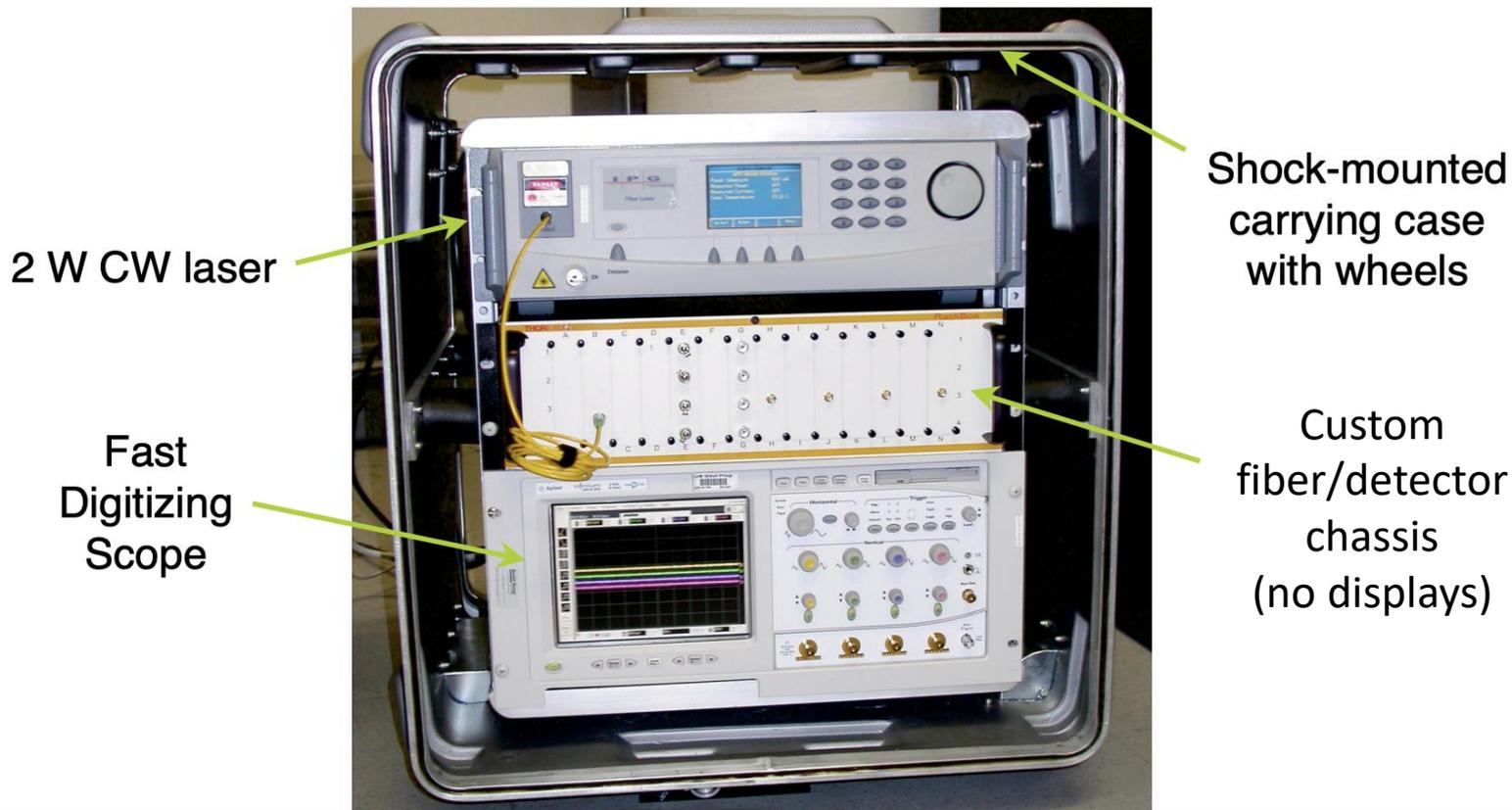
We had shown that the direct record method worked well.
Abandoned the phase discriminator method.

We now had a good backup for the Fabry-Perot (7 years).

(Accordion was eventually cancelled.)

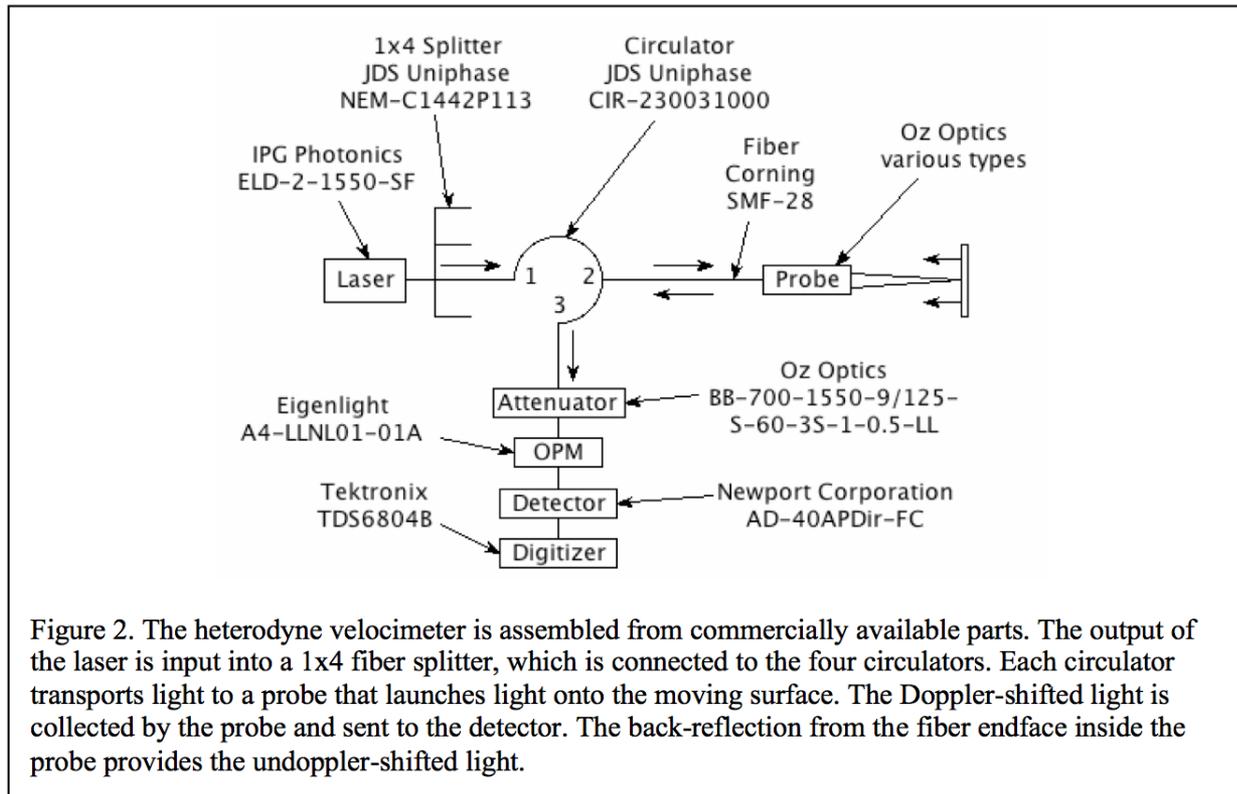
Tony built two 4-channel systems in portable boxes

We hauled these 2 systems to many different labs in many different locations. Velocimetry was now cheap and easy. "Have PDV, Will Travel!"



Notes: Still only 1 knob per channel—optical attenuator.
 No built-in OPM display—used handheld DVMs.

We designed the modern PDV system with 4 channels to match the number of inputs on the digitizers.

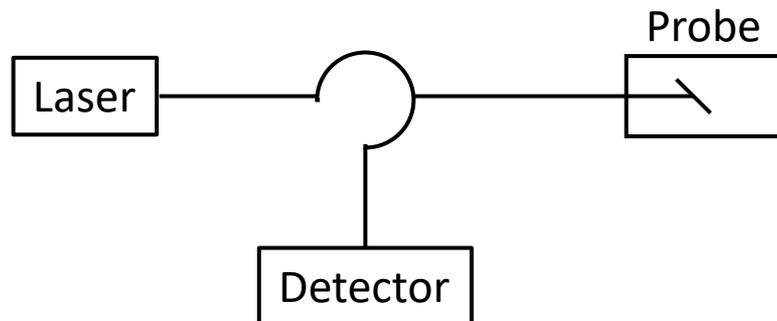


Rev. Sci. Instrum. **77**, 083108 (2006)

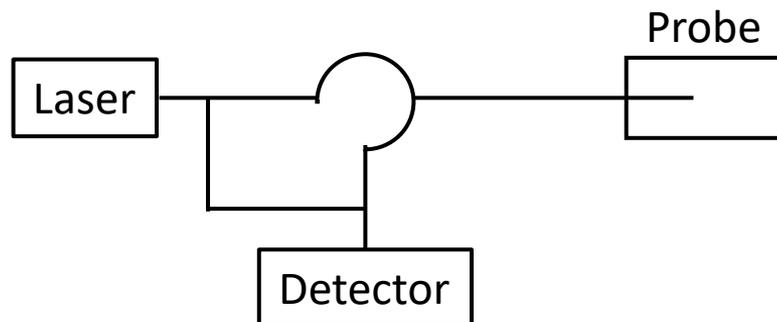
First step in the evolution of the PDV

David Holtkamp (LANL) wanted to build some PDV systems but did not like having to order probes with calculated back reflections. He wanted probes with essentially no BR and instead split light directly from the laser to provide the reference signal.

Original Version
 Homodyne
 Reference at probe



1st Evolution
 Homodyne
 Reference split from laser



There are other ways to do this. See PDV Handbook and also
 D. H. Dolan, Rev. Sci. Instrum. 91, 051501 (2020).

Evolution of the PDV

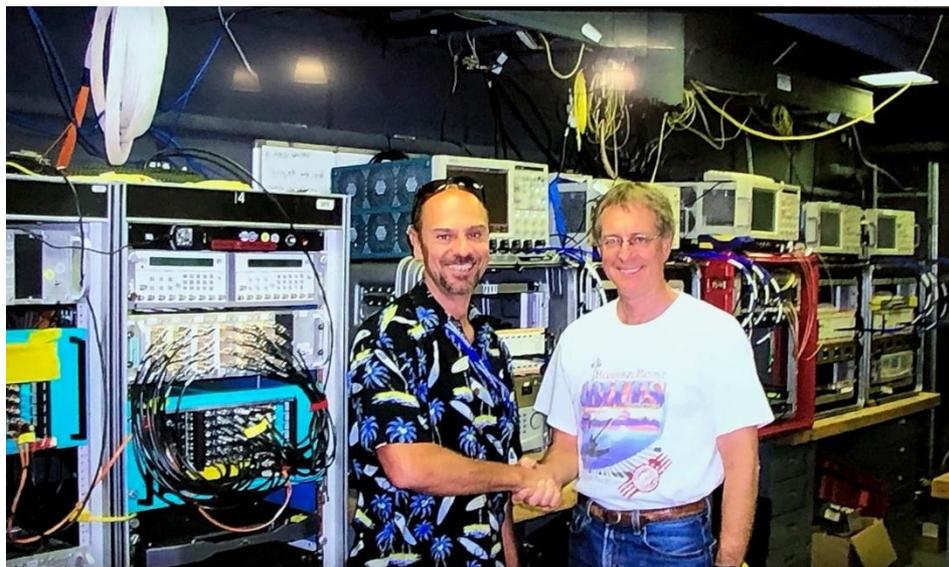
This is what I would consider to be a logical progression of the evolution.
Reality was actually fairly close to this.

<u>System Design</u>	<u>Probes per digitizer</u>
Homodyne, reference at the probe	4
Homodyne, reference split from the laser	4

Other labs started building 4-channel systems, too

20-probe shot
at the BEEF bunker
at NTS.

4-channel
systems from both
LLNL and MSTs.

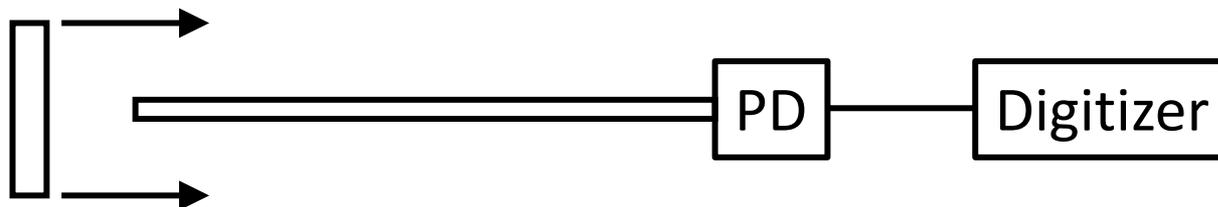


Early evolution of the optical pin dome

In the 1990s, Frank Roeske of LLNL developed an optical time of arrival diagnostic.

It consisted of a multimode fiber with a thin layer of aluminum coated onto the fiber endface.

When the Al was impacted by the surface, it emitted a flash of light. The fiber transported the light to a PD and a digitizer recorded the signal.

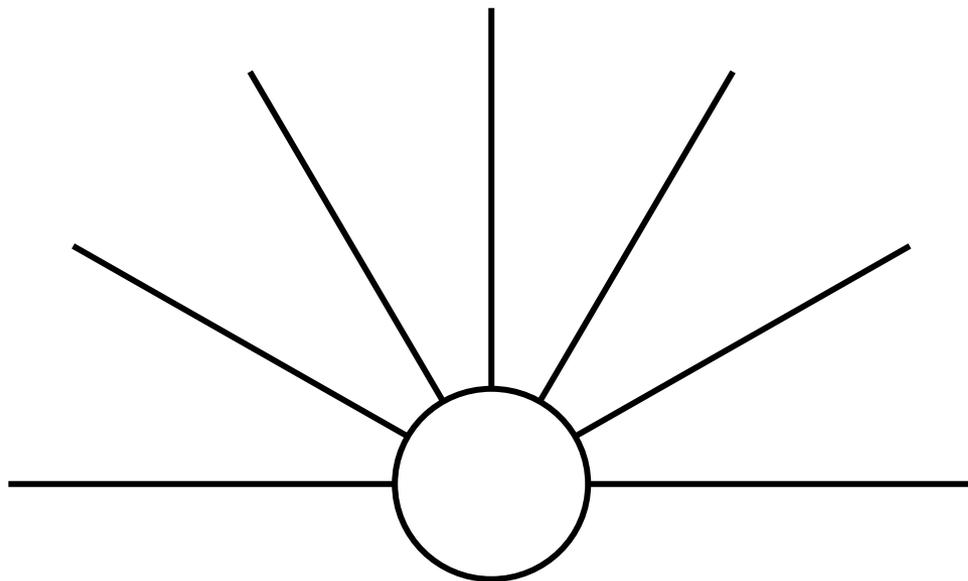


Early evolution of the optical pin dome

Somebody got the idea that maybe we could use Roeske's optical pins in a pin dome instead of wires.

The fibers would be supported by glass capillaries with the fibers inserted into the capillaries.

This idea never went very far. It would have provided no more information than the wire pin domes and would have required developing a new infrastructure for building, metrology, and recording.

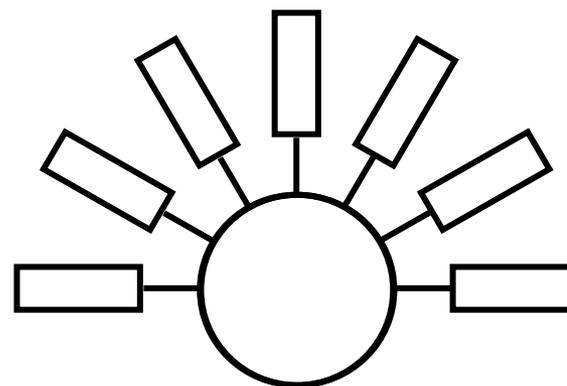


Early evolution of the optical pin dome

Somebody else got the idea that we could install small optical probes onto the ends of the capillaries.

This was a great idea. It could be built with almost no changes to the dome geometry.

Unfortunately, the overall size was too big. The designer would not be able to follow the surface to small radius.



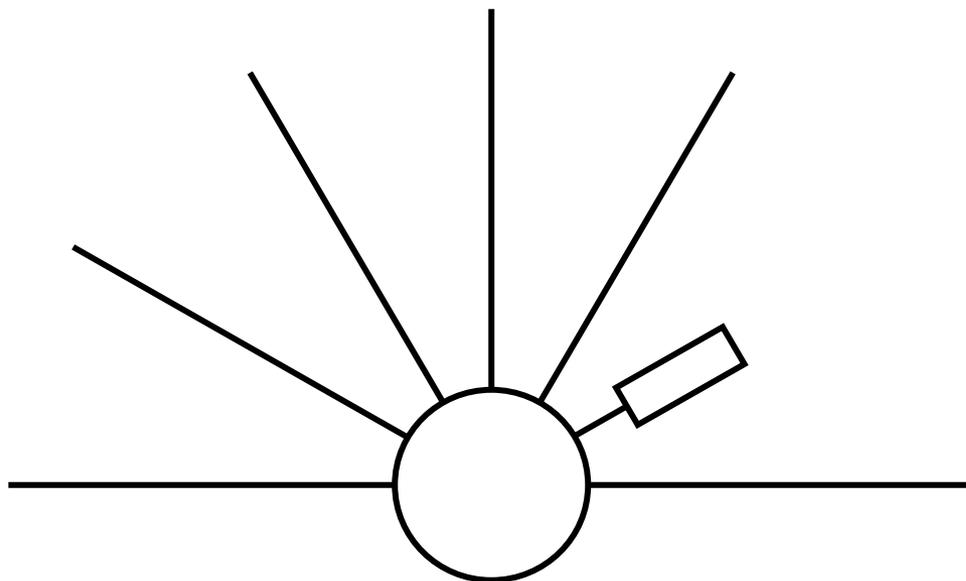
Early evolution of the optical pin dome

However, it did raise the possibility that we could try to field a single optical probe in a wire pin dome.

We were allowed to displace only one wire. The probe needed to be in an area where all the neighboring pins were longer than the probe.

We could not impact the shot schedule.

We were very happy to have this opportunity.

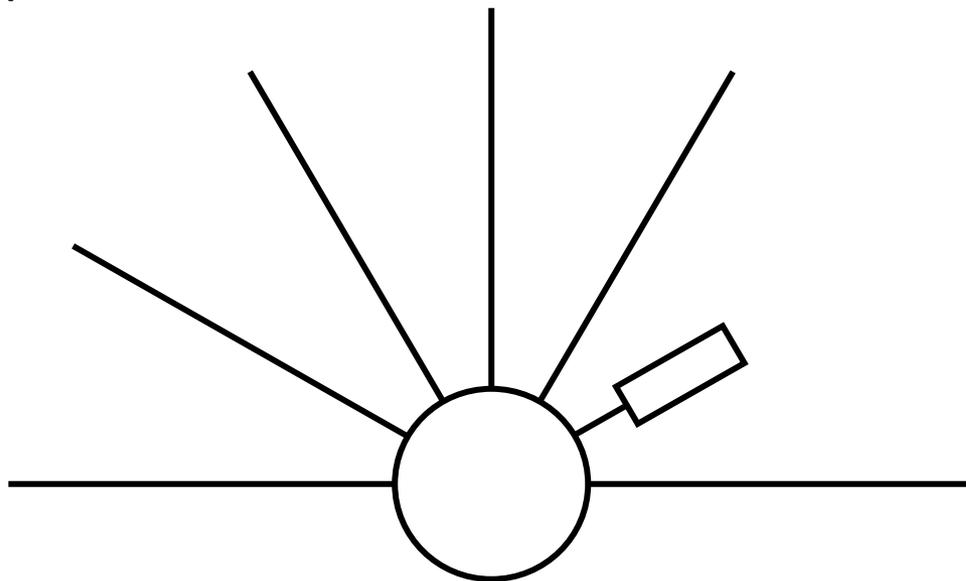


Early evolution of the optical pin dome

The data turned out great.

This showed that an optical probe could survive in the hostile environment of the pin dome geometry.

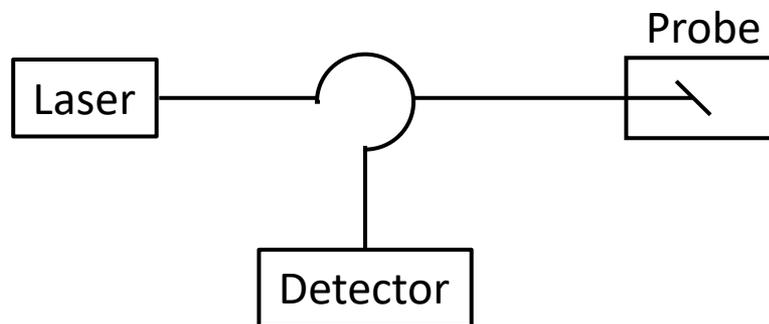
Now it was just a matter of finding an experiment designer who was willing to take the risk of an all-optical dome.



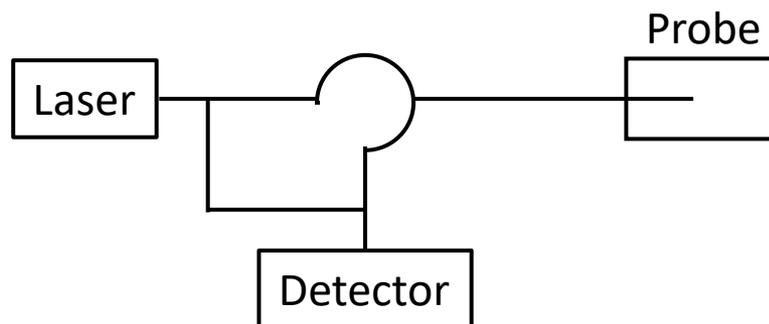
Evolution of the PDV—people want more probes

These two versions of the PDV allowed for the possibility of temporal multiplexing.

Original Version
 Homodyne
 Reference at probe



1st Evolution
 Homodyne
 Reference split from laser



The digitizers have 4 inputs, which limits the number of PDV channels per digitizer.

Having 4 probes is nice but it is not unreasonable to want a few more channels.

The digitizers are the most expensive part of the PDV system.

It was only a matter of time before people started looking at multiplexing.

Looking at the titles of the PDV workshop talks, I note that multiplexing really took off in 2010.

Multiplexing came next

Temporal multiplexing is the easier and cheaper way to multiplex, compared to frequency multiplexing.

This works with a homodyne system.

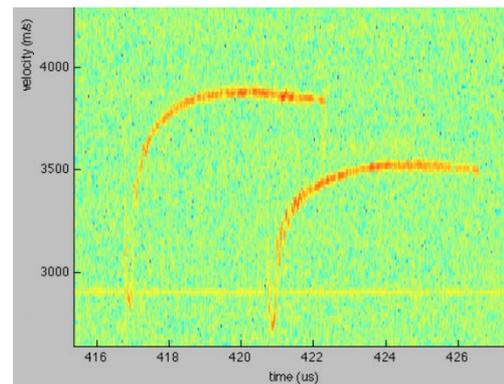
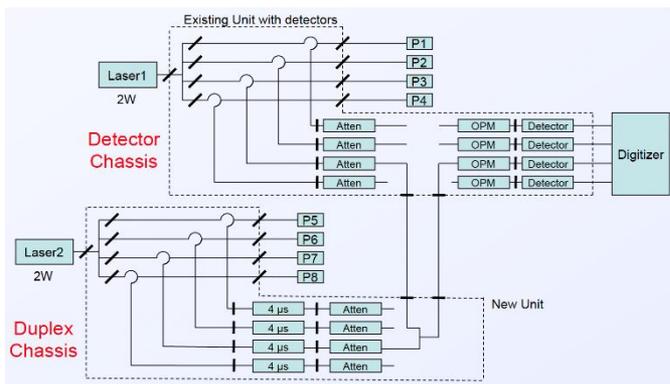
You mainly need inexpensive passive components and lots of fiber for delays. (1 km of fiber = 5 μ s delay)

It is important to keep the power budget in mind as you design and build your system.

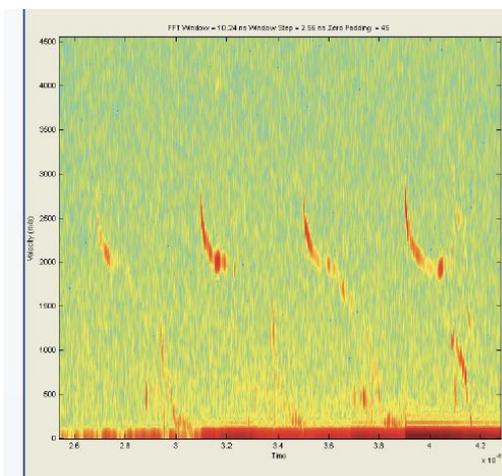
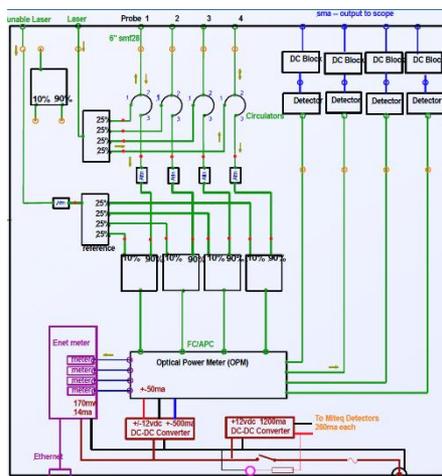
The laser will need to provide more power for more probes.

Homodyne with Temporal Multiplexing

2-way temporal multiplexing, Strand et al., PDV Workshop, 2011



4-way temporal multiplexing, Hodgin et al., PDV Workshop, 2010



Evolution of the PDV

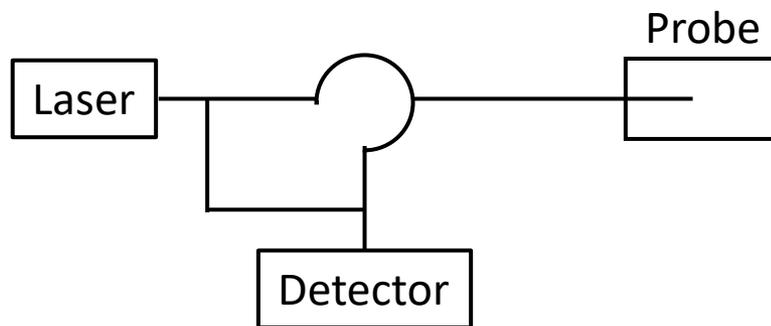
This is what I would consider to be a logical progression of the evolution.
Reality was actually fairly close to this.

System Design	Probes per digitizer
Homodyne, reference at the probe	4
Homodyne, reference split from the laser	4
Homodyne, temporal multiplexing	8, 16

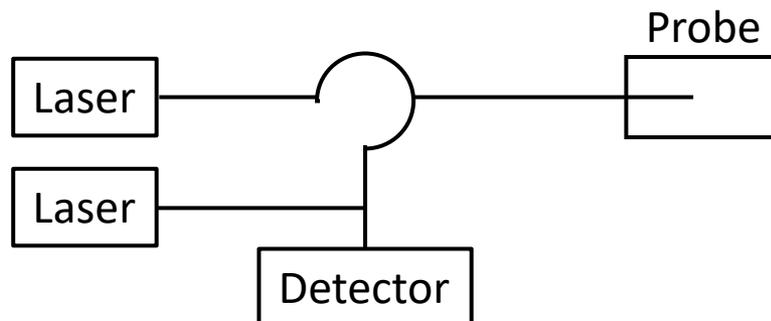
Evolution of the PDV

A parallel evolutionary step involved the heterodyne geometry. This opened up the possibility of frequency multiplexing.

1st Evolution
 Homodyne
 Reference split from laser

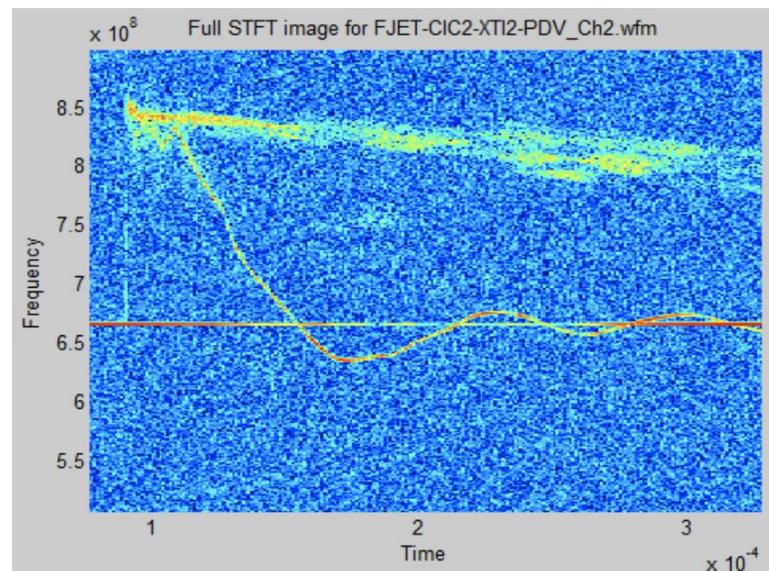
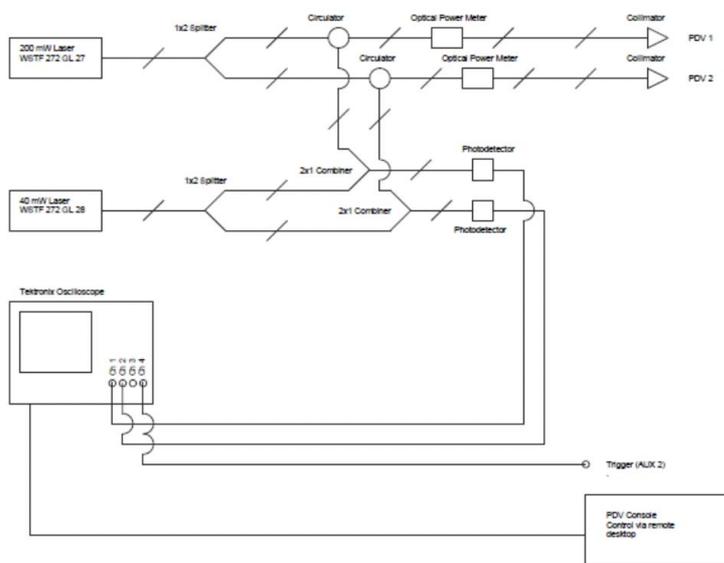


2nd Evolution
 Heterodyne
 Reference from second laser



Heterodyne with 2 channels and no multiplexing

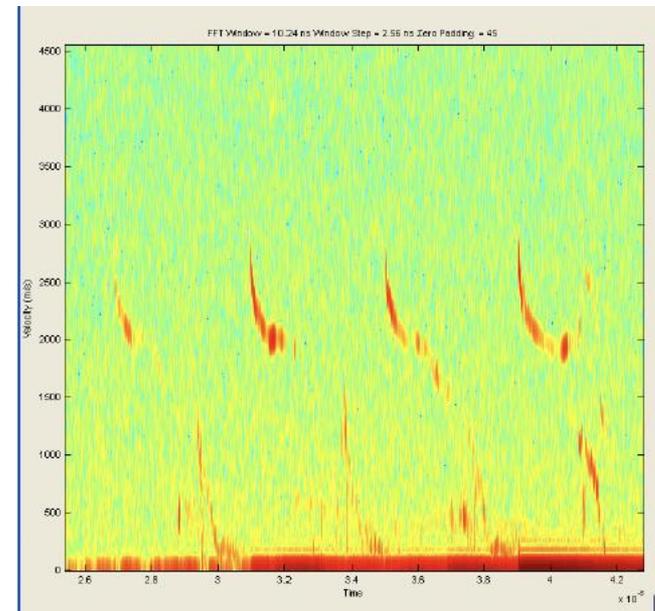
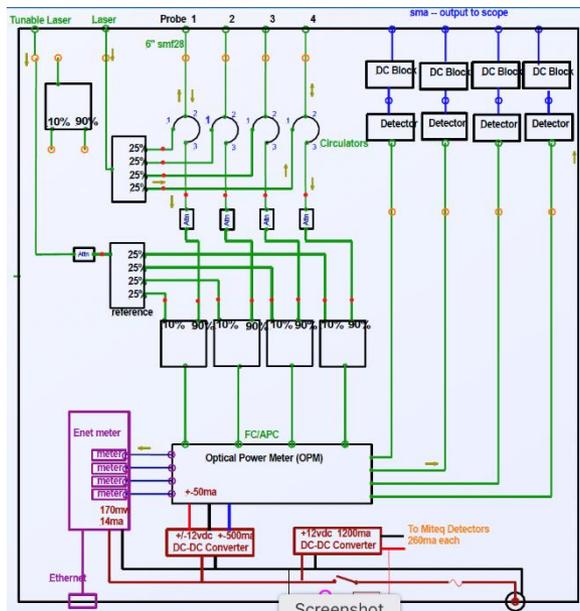
Dan Wentzel (NASA) uses a 2-channel heterodyne system to look at frangible joints.



Illustrations from Wentzel, PDV Workshop, 2014

Heterodyne with Temporal Multiplexing

Ralph Hodgkin et al. of LLNL continued developing their homodyne 4-way temporal multiplexing system. They modified their system to become a heterodyne 4-way temporal multiplexing system. This allowed increased temporal resolution for short pulse signals.



Illustrations from Hodgkin et al., PDV Workshop, 2011.

This is what I would consider to be a logical progression of the evolution.
Reality was actually fairly close to this.

System Design	Probes per digitizer
Homodyne, reference at the probe	4
Homodyne, reference split from the laser	4
Homodyne, temporal multiplexing	8, 16
Heterodyne, reference is separate laser	2
Heterodyne, temporal multiplexing	16

Heterodyne with Frequency Multiplexing

As time went on, the digitizers had higher sample rates.

20 GS/s to 50 GS/s -> Nyquist velocity = 19.4 km/s !

Ed Daykin noticed that there was a lot of room at the top of the spectrograms that was not being used.

Frequency multiplexing could take advantage of that unused real estate.

He applied for some SDRD money to investigate frequency multiplexing.

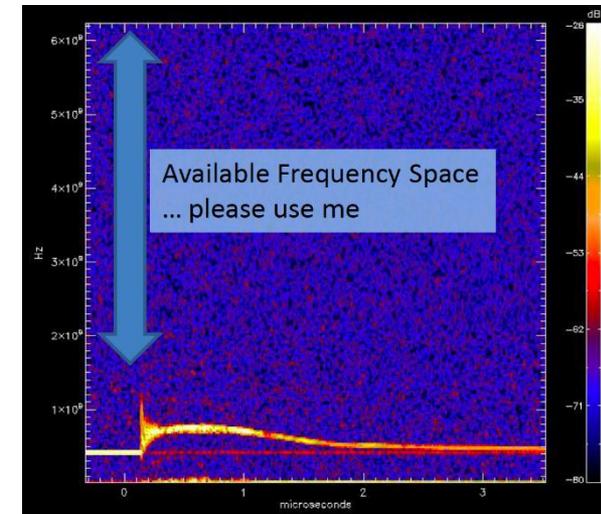


Illustration from Daykin et al., PDV Workshop, 2010.

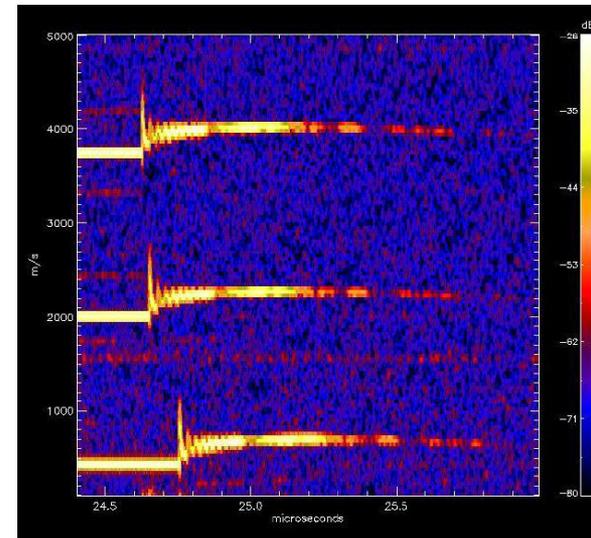
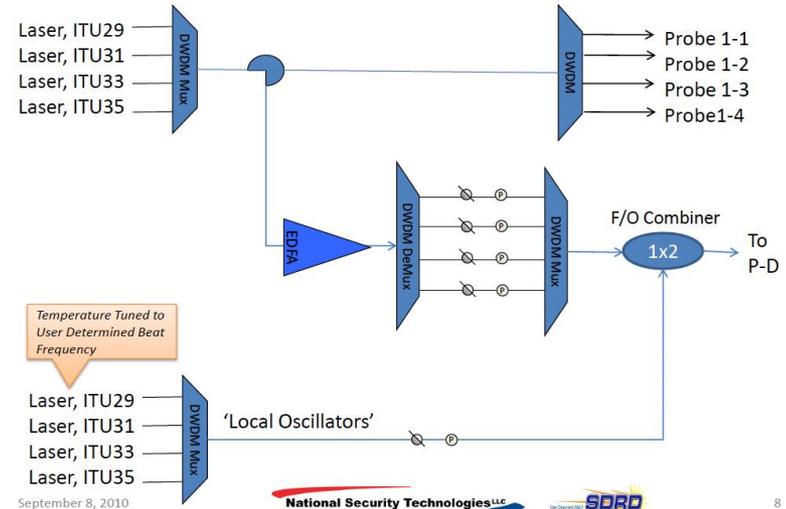
Use telecom components for 4X frequency mux

Modular lasers on the ITU grid

Optical amplifier after port 3 compensates for smaller lasers and allows for very long delays.

DWDM components provide high efficiency and suppress ASE from the amplifier.

Slight delay between channels to avoid overwriting traces at shock arrival.



Images from Daykin et al.,
PDV Workshop, 2010.

Heterodyne with Temporal and Frequency Mux

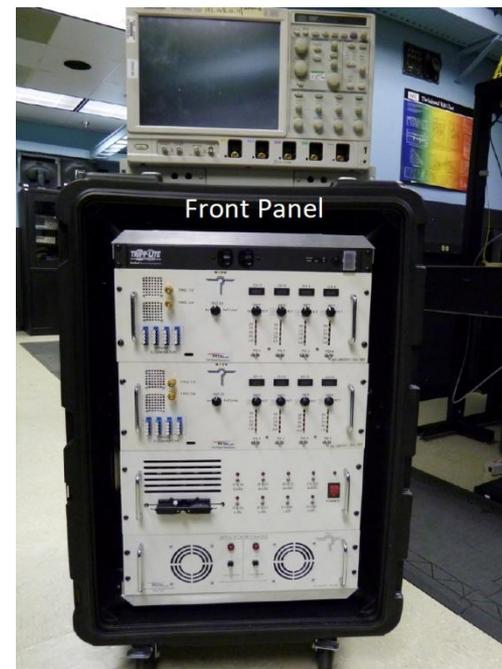
High-bandwidth, high-sample-rate digitizers now have 50 GS/s and 100 μ s sweeps.

MPDV allows for 4X frequency multiplexing and 2X temporal multiplexing = 32 probes/digitizer.

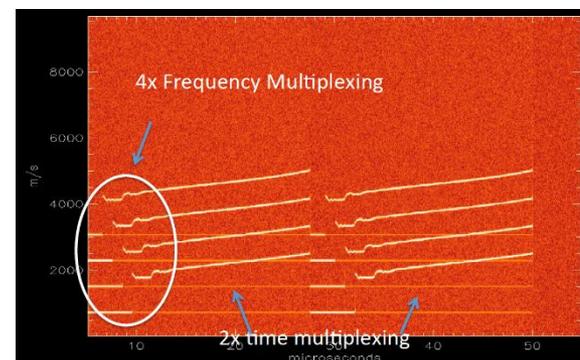
Also included polarization adjustments.

R&D 100 awarded to Daykin et al., 2012.

Images from Daykin et al., PDV Workshop, 2011.



(and kudos to Carlos Perez!)



PDV Evolution

This is what I would consider to be a logical progression of the evolution.
Reality was actually fairly close to this.

System Design	Probes per digitizer
Homodyne, reference at the probe	4
Homodyne, reference split from the laser	4
Homodyne, temporal multiplexing	8, 16
Heterodyne, reference is separate laser	2
Heterodyne, temporal multiplexing	16
Heterodyne, frequency and temporal multiplexing (MPDV)	32

missing a step?
(heterodyne with
only freq. mux)?



LLNL fields an all-optical pin dome

Don Roberts of LLNL agrees to try an all-optical pin dome.

Tony Whitworth carries the ball on this project:

- Evaluated small probe designs.

- Worked with engineers to incorporate the probes into a dome.

- Assisted with the metrology.

- Processed the data.

60 discrete probes in the pin dome
(12 more probes elsewhere)

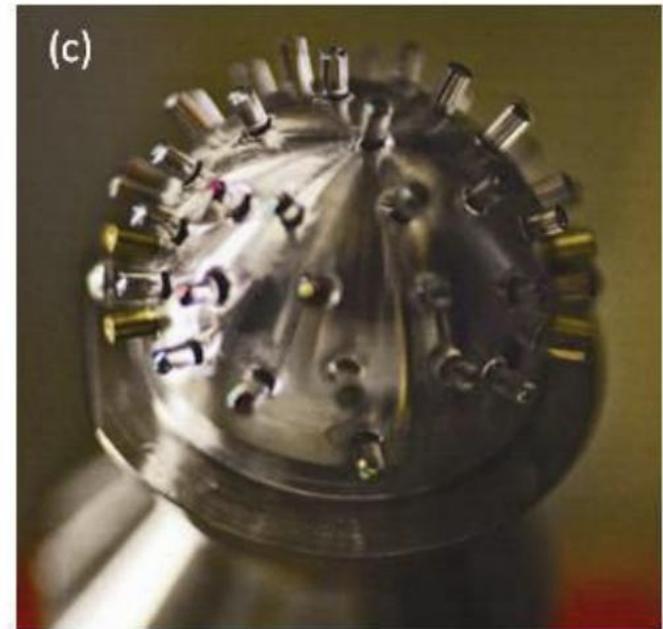


Photo from S&TR LLNL,
October 2011

We used every PDV channel we could find

We fired the shot in October 2011.

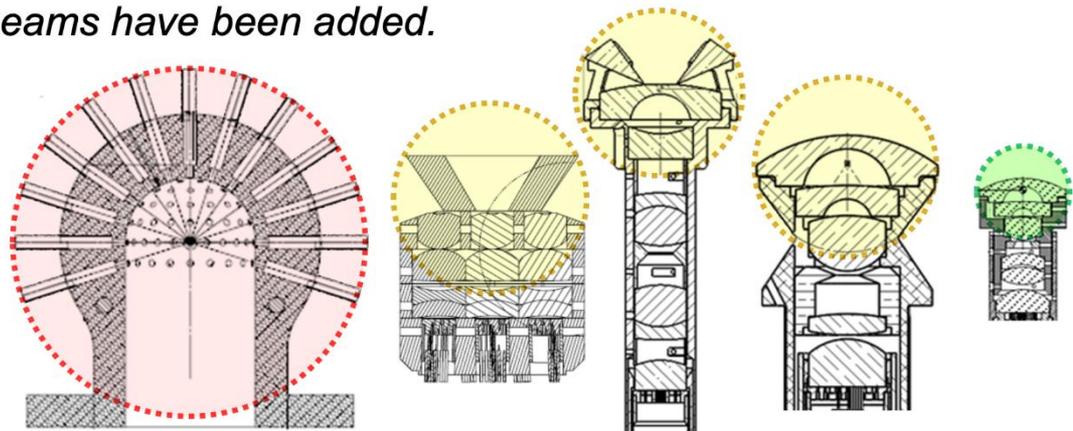
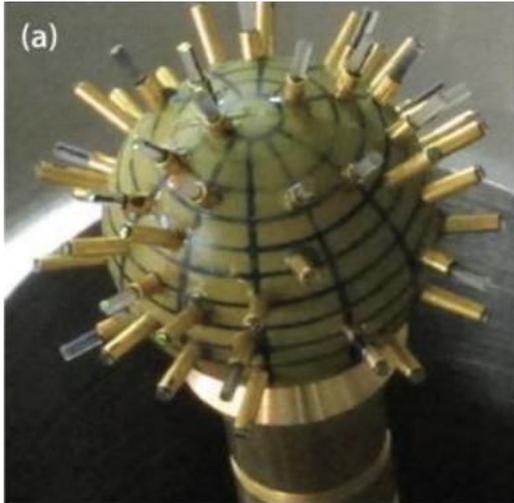


We obtained 100% data return. Excellent!
(I retired 8 months later.)

MSTS worked closely with LANL to build optical domes

David Holtkamp (LANL) continues to promote the idea of a 100+ probe dome. The design progressed from discrete probes on a dome to imaging fiber arrays onto a fish eye lens.

Since 2010, probe designs have gotten smaller and more beams have been added.



<i>Probe</i>	LANL H4227	Bugeye	Argus NX1	Argus NX2	Argus NX3b
<i>Radius of closest approach</i>	17 mm	9.3 mm	8.1 mm	8.8 mm	4.5 mm

Screenshot

Images from Advanced Optical Cavity Probes
<https://www.osti.gov/servlets/purl/1544776>
 LANL 2011

This is what a 128-probe optical dome looks like...

Bob Malone, Brian Cata, Brent Frogget, Morris Kaufman, Vince Romero,
MSTS, PDV Workshop, 2016.



These probes generally have efficiencies of only $1e-5$. This really pushes the limits of the PDV capabilities.

Photo from Stockpile Stewardship Quarterly,
volume 4, number 1, March 2014.
Article by Brent Frogget (MSTS)

And the 128 channels of PDV to record the data

Herculean effort by Ed Daykin and his team (MSTS) to build four 32-channels of MPDV for this optical dome.



This is a lot of data! Abel Diaz of MSTS was tasked with writing a code called QuickView that could do the job: PDV Workshop 2011, PDV Workshop 2014.

This is what I would consider to be a logical progression of the evolution.
Reality was actually fairly close to this.

System Design	Probes per digitizer
Homodyne, reference at the probe	4
Homodyne, reference split from the laser	4
Homodyne, temporal multiplexing	8, 16
Heterodyne, reference is separate laser	2
Heterodyne, temporal multiplexing	16
Heterodyne, frequency and temporal multiplexing (MPDV)	32

But wait, there's more!

Deep time multiplexing records 16 probes per channel

4-way frequency multiplexing lowers the SNR of the data.
 Holtkamp wants better SNR. Daykin gets back to work.
 Better to go with only temporal multiplexing.

This digitizer record is 800 μ s long with
 16 separate multiplexed records at 50 μ s each.

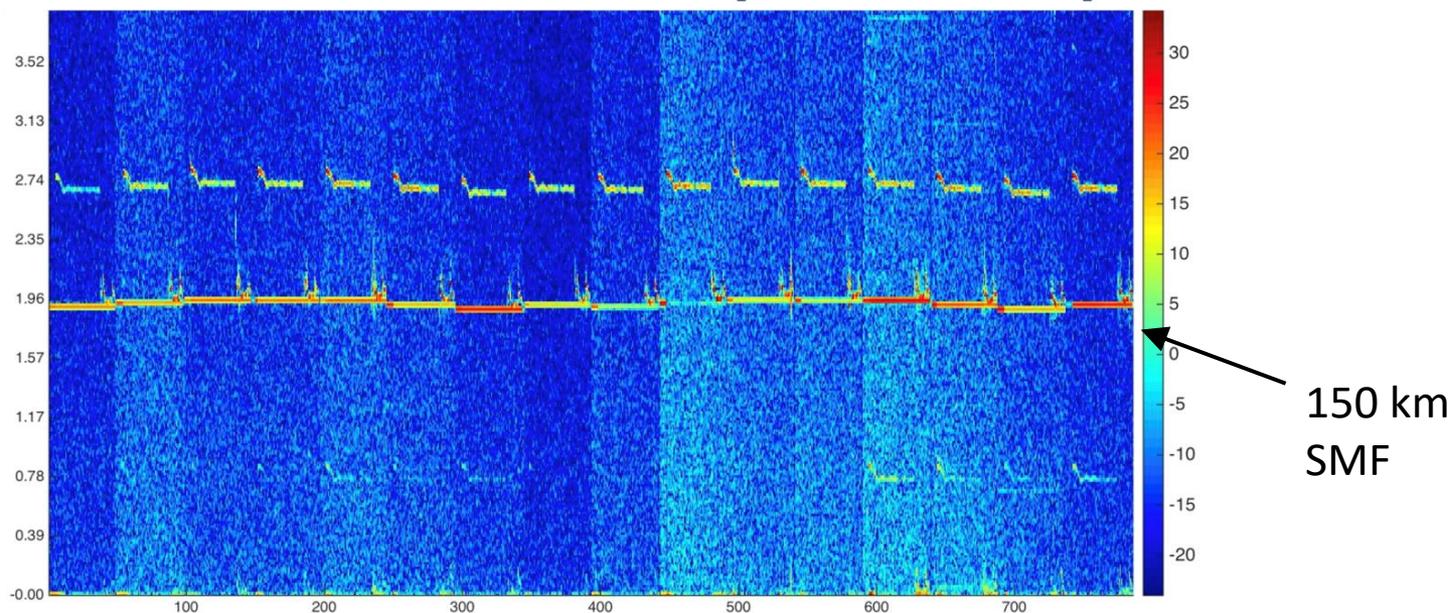


Image from: Pena, PDV Workshop, 2016.
 See also: Miller, PDV Workshop, 2016.

This is what I would consider to be a logical progression of the evolution.
Reality was actually fairly close to this.

System Design	Probes per digitizer
Homodyne, reference at the probe	4
Homodyne, reference split from the laser	4
Homodyne, temporal multiplexing	8, 16
Heterodyne, reference is separate laser	2
Heterodyne, temporal multiplexing	16
Heterodyne, frequency and temporal multiplexing (MPDV)	32
Heterodyne, deep time multiplexing	64

100+ channels took longer than we thought

Instead of 3–5 years to get 100+ channels, it took 17 years.

The evolution of the PDV and the pin dome are intricately woven together. It was the work of many people from different organizations working together to make it happen.

1997

2014

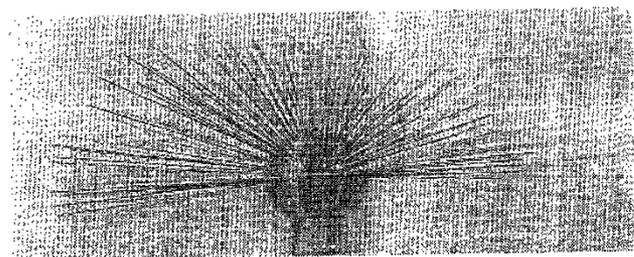
Goal

Long term (3-5 years):

- Develop 100+ channel, compact 3-D velocimetry diagnostic for time-resolved, full 3-D HE experiments.

Vision:

- A pin dome diagnostic with time resolved velocity profiles on every data channel



PDV Evolution

This is what I would consider to be a logical progression of the evolution.
Reality was actually fairly close to this.

System Design	Probes per digitizer	
Homodyne, reference at the probe	4	reasonable
Homodyne, reference split from the laser	4	
Homodyne, temporal multiplexing	8, 16	
Heterodyne, reference is separate laser	2	
Heterodyne, temporal multiplexing	16	
<hr/>		
Heterodyne, frequency and temporal multiplexing (MPDV)	32	radical
Heterodyne, deep time multiplexing	64	

Conclusion

The early development of the PDV was not a straightforward process.

There were many fortuitous events that occurred over several years to make it happen.

The drive toward more PDV channels per digitizer was initially driven by the high cost of the digitizer.

The optical pin dome diagnostic for the national labs was the driver for very large channel count.

