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Early History of the PDV

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and

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Outline

Ted's background
Tony's background

Fabry-Perot Velocimetry
Desire for alternative method

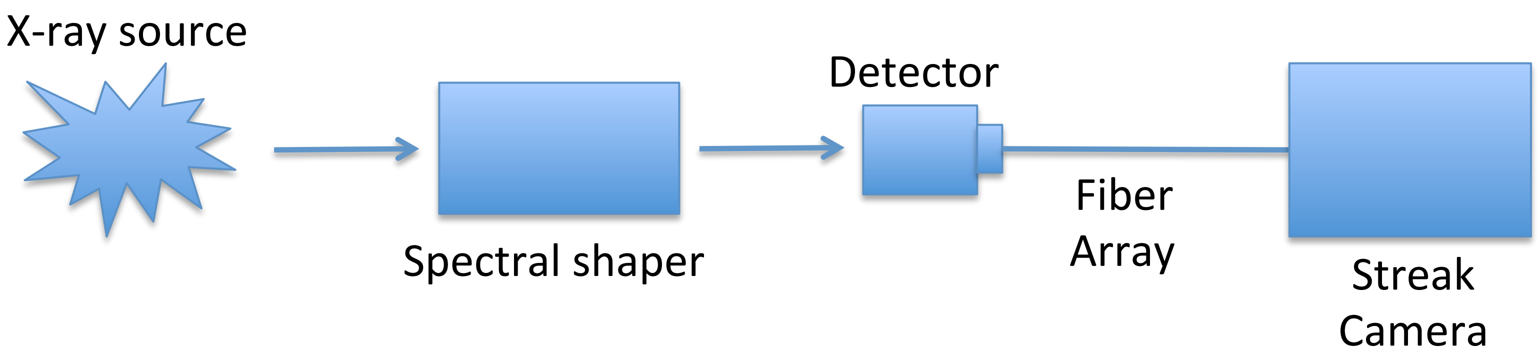
Tony discovers the circulator
Making PDV work

First real data for a paying customer

Conclusions

Ted's Background

1982 – 1992 X-ray measurements using
multi-mode fibers and streak cameras



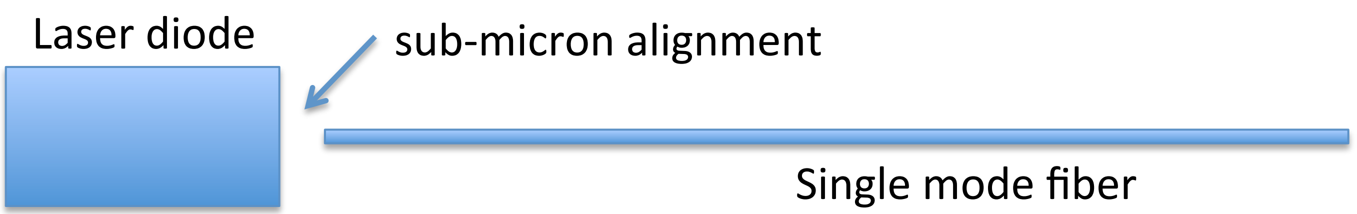
Absolutely-calibrated systems

Correlate counts per pixel to x-ray output at source

Pulsed systems required accurate timing

Ted's Background

1992 – 1996 High-bandwidth opto-electronic devices coupled to single mode fibers



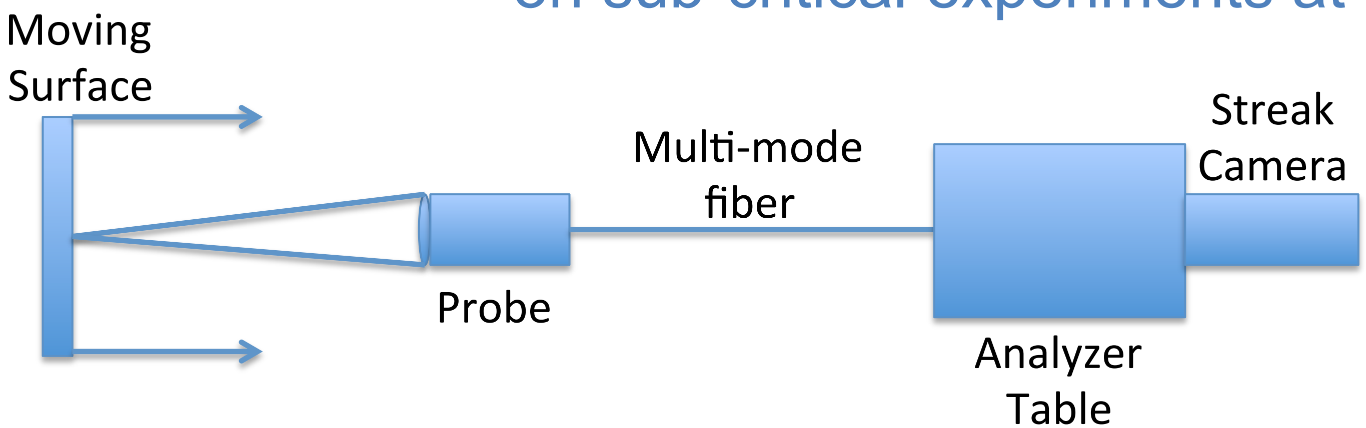
Collaborated with outside industry
- Learned about commercially-available products

Team members worked with electronic components
- at many 10's of GHz

Learned about single mode fibers and components

Ted's Background

1996 - 2003 Fabry-Perot Velocimetry on sub-critical experiments at NTS



Learned that some people actually care about velocities
Learned how to measure km/s velocities
Programmatic requirement for independent measurement

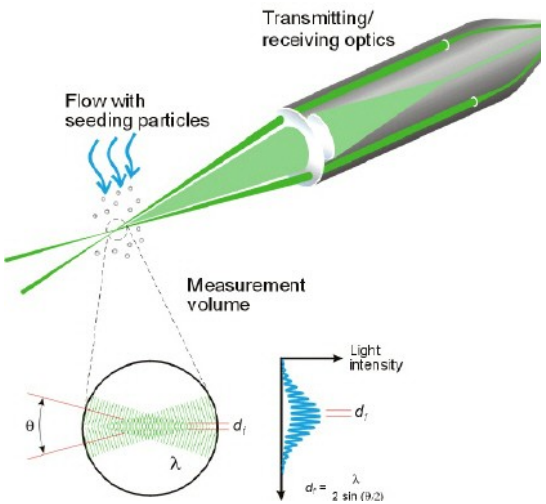
Tony's Background

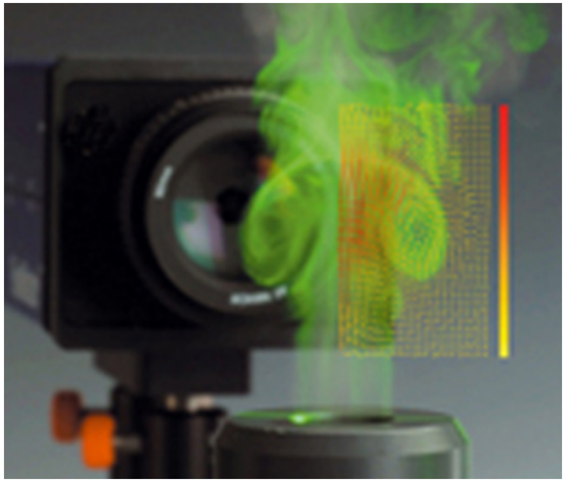
1989-1994 Lawrence Livermore National Lab
AVLIS Program working with
Copper Vapor Lasers

1994-1995 Hobart Laser Systems, service engineer
multi-kilowatt CW Yag laser systems

Tony's Background

1995-2000 Sandia National Lab / CA
Combustion Research Facility
Particle Image Velocimetry, Laser Induced Fluorescence, Laser Doppler Anemometry





Tony's Background

2000-2001 Continuum Lasers

Scientific and custom laser testing

2001-Current Lawrence Livermore National Lab

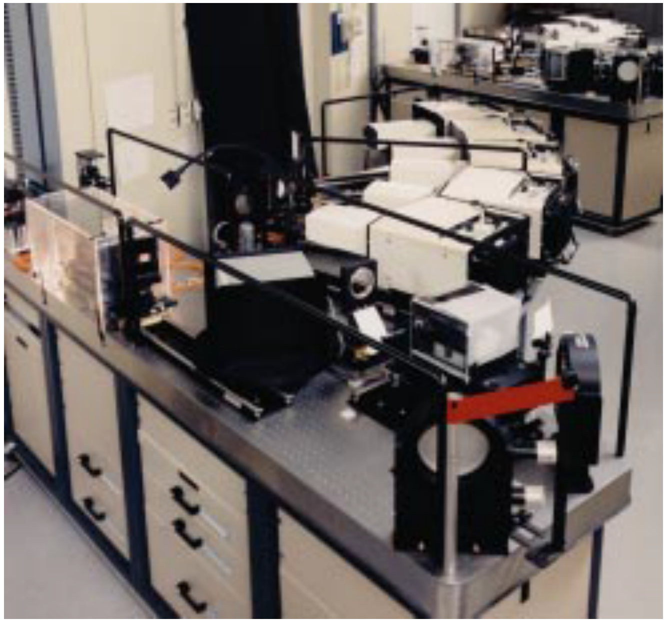
Photonic Doppler Velocimetry

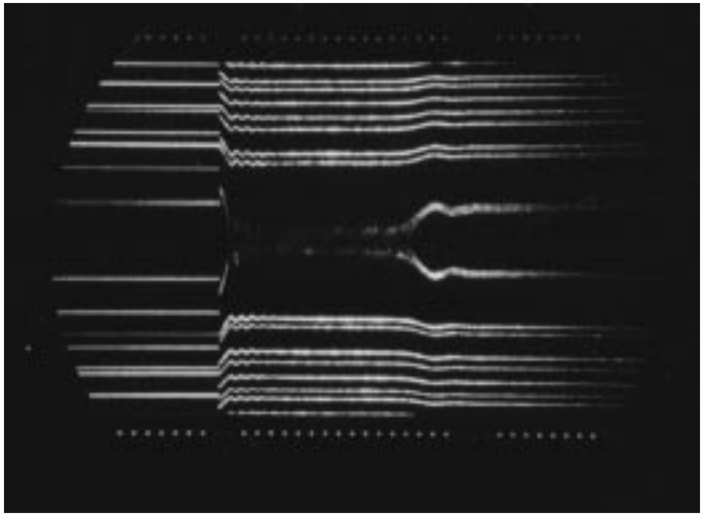
Doppler Shock Arrival diagnostic

VISAR

Fabry-Perot Velocimetry at LLNL

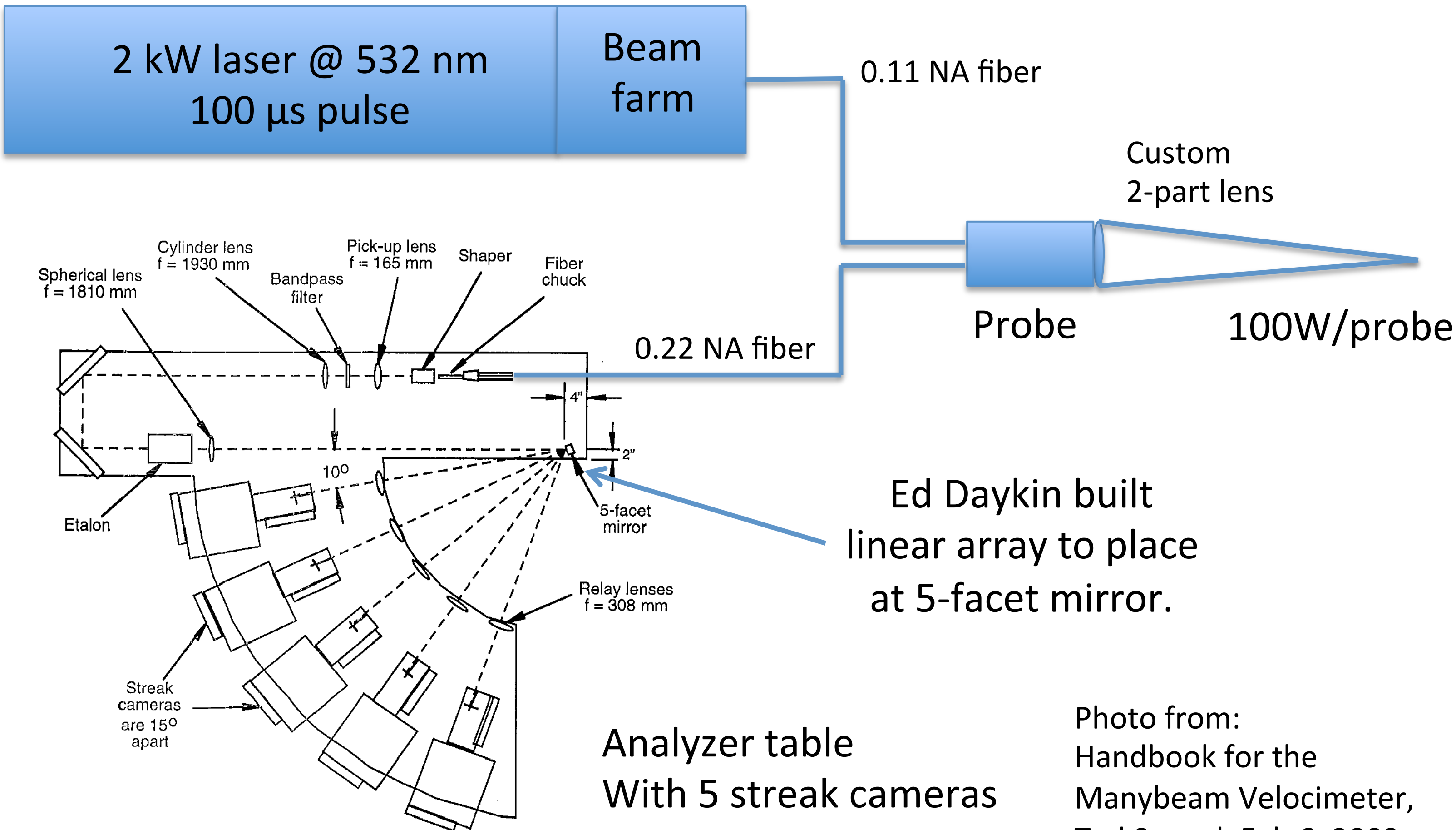
Manybeam Velocimeter developed by David Goosman





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

Manybeam Velocimeter at LLNL: beautiful but expensive



Ed Daykin built linear array to place at 5-facet mirror.

Analyzer table
With 5 streak cameras

Photo from:
Handbook for the Manybeam Velocimeter,
Ted Strand, Feb 6, 2002

Manybeam Velocimeter

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

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

SCE requirement: a backup to FP for Accordion

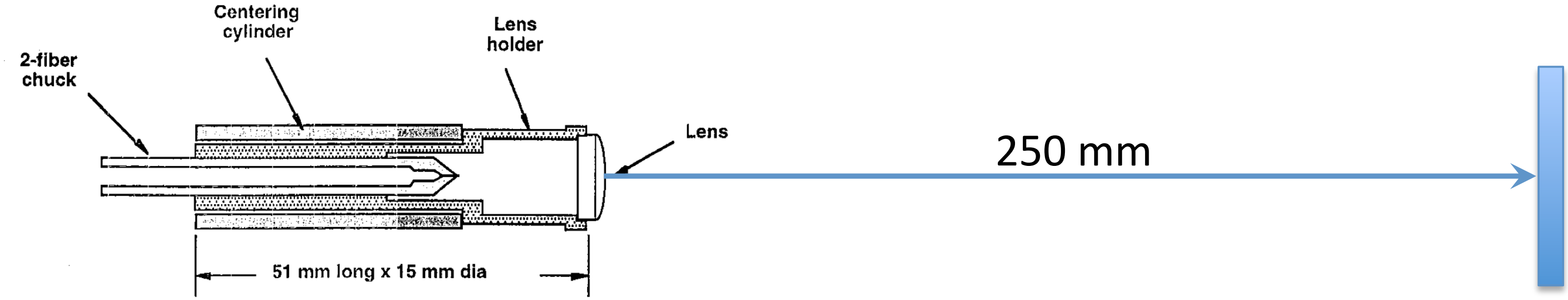
Accordion was to be a big expensive test.
Fabry-Perot was to be the primary diagnostic.
The test designer wanted a fully independent velocity measurement.
Too expensive to build a 2nd FP system

VISAR was an option, but…
Cannot handle multiple frequencies.

We set out to see what we could do by generating and measuring a beat frequency.

Manybeam Velocimeter

Standard probe geometry



Any alternative velocimeter needed to accommodate a probe of this size and collection efficiency = 1e-4.

Our goal was to complement the number of F-P probes with additional probes, plus provide backup.

In 1996, we were heavily invested
in the Fabry-Perot Manybeam system

We had systems at several locations

Site 300:	4 systems
HEAF:	1 system
U1a:	3 systems
BEEF:	1 system

Each analyzer table had 5 streak cameras ($100K each)
Each laser was custom long pulse doubled YAG ($250K each)
Etalons were $50K to $75K each.

It was a given that we would try to capitalize on that inventory.

What if we tried to measure the beat frequency?

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

Status in 1996:

High bandwidth detectors (many 10's GHz) existed.

No technology existed to record multi-GHz for 10s of μs.

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

Fiber lasers did not exist.

We applied for some research funding (LDRD) in 1997

LDRD-ER Proposal

Photonic Doppler Velocimetry

May 14, 1997

Principal Investigator

Ted Strand - DNT

Co-Investigators

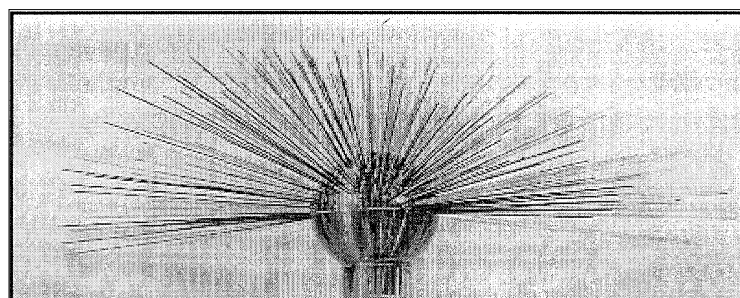
Mark Lowry - P&ST
Ron Haigh - DSED
Rick Ratowsky - DSED
Paul Sargis - DSED

FY98 and FY99

Goal

Long term (3-5 years):
- Develop 100+ channel, compact 3-D velicometery diagnostic for time-resolved, full 3-D HE experiments.

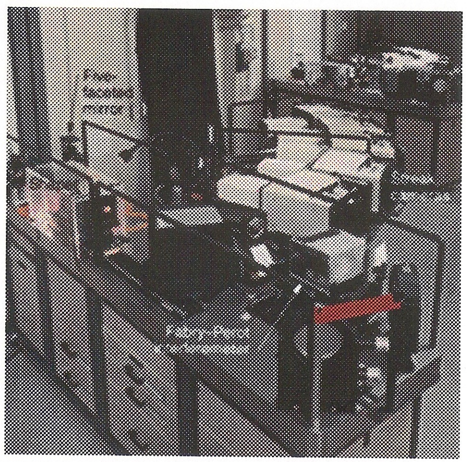
Vision:
- A pin dome diagnostic with time resolved velocity profiles on every data channel



We emphasized the advantages of alternative methods

Motivation
Velocimetry Using High-Bandwidth Techniques

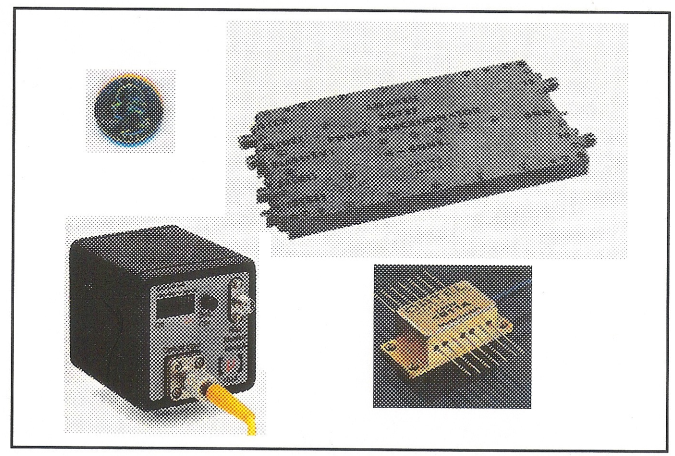
Fabry-Perot



This is the best way we know
- High-quality data
- Robust against multiple velocities

But....
- Large physical size
- Labor intensive
- Expensive

Photonics Technology



This has many advantages
- Small physical size
- Inexpensive components
- Large number of channels
- Low manpower

But....
- Always unambiguous data?

HighBandVel-08

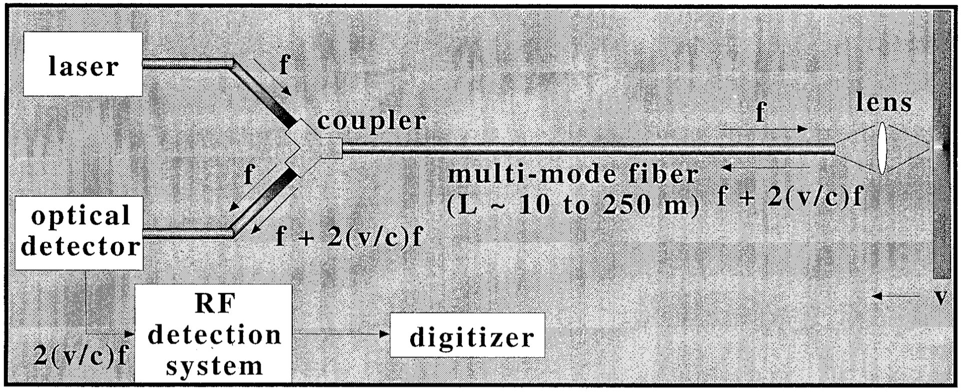
Our approach to measure beat frequency at 532 nm: (LDRD)

Determine the limits of maintaining some level of coherence in multi-mode fibers.

Convert frequency to some other parameter that is more easily measured with standard digitizers.

Our big unknown was whether multi-mode fibers would work (LDRD)

Velocimeters require multimode fibers for sufficient light collection from an illuminated target



Challenges:

- Understand fundamental physics through modeling and experiments
  -- fiber lengths, index profiles, dispersion effects, launch conditions
- Develop algorithms for data reduction and noise suppression
- Develop RF detection schemes to record the "envelope" of the RF beat signal

There were some published results on maintaining coherence in multi-mode fiber (LDRD)

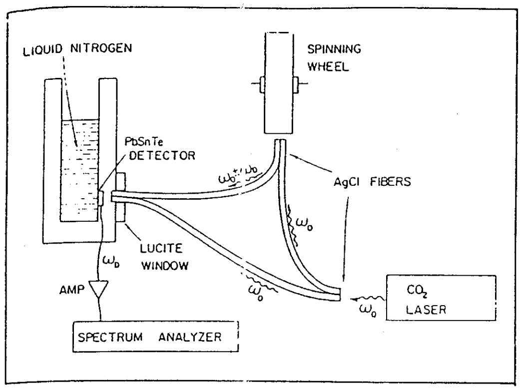


Fig. 1. Laser Doppler velocimetry experiment for measuring the speed of a rotating wheel.

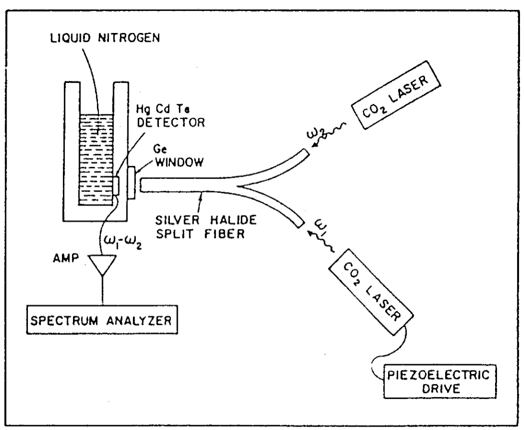


Fig. 4. Heterodyne measurement between two CO_2 laser beams, through a split silver halide fiber.

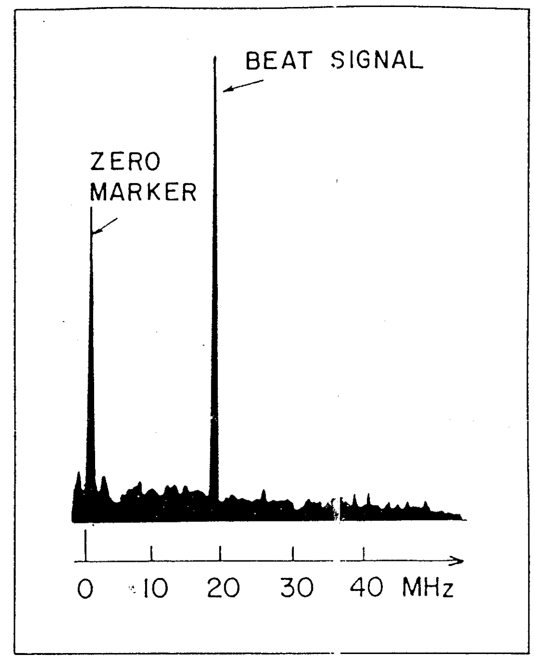


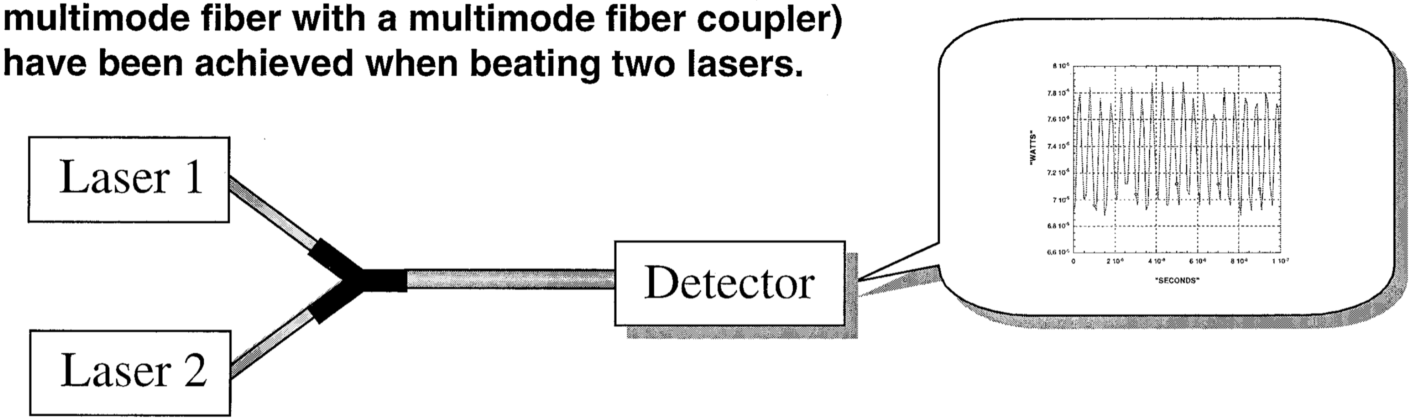
Fig. 3. Heterodyne signal, as measured in the spectrum analyzer.

CO_2 lasers at 10.6 µm
Katzir, et al, Opt Eng 23(4), 1984

Our group did some work to reproduce those results (LDRD)

Recent experiments verified heterodyne detection using multimode waveguides

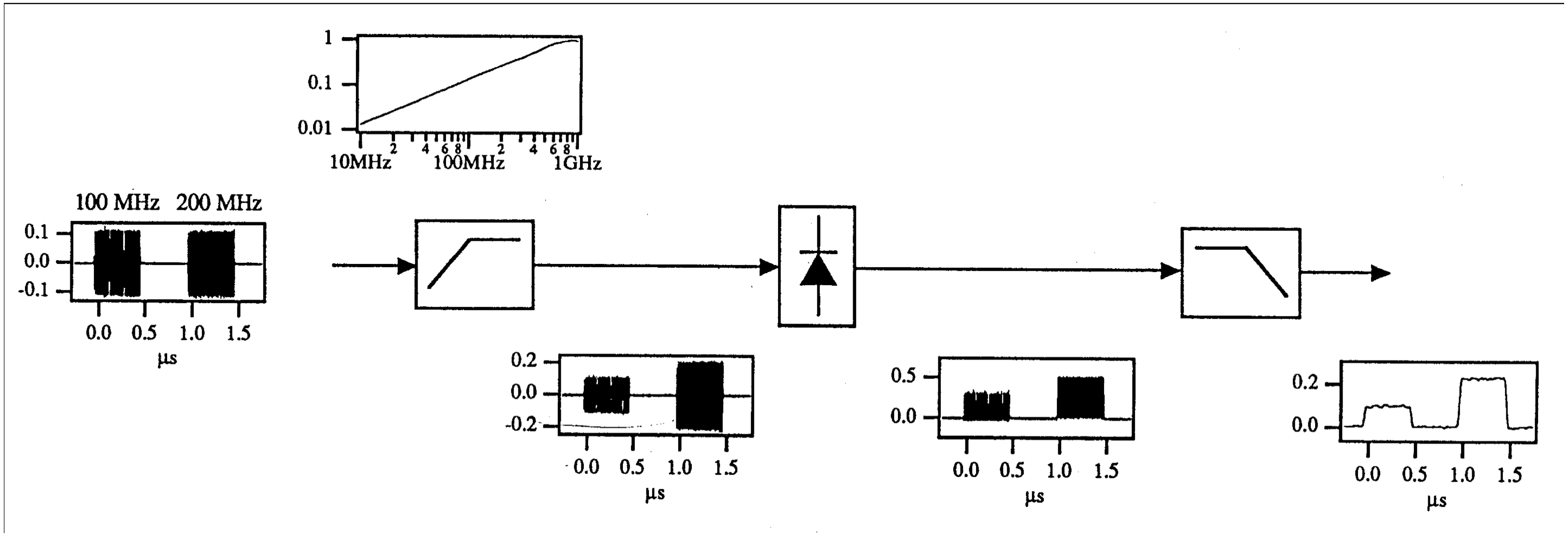
Modulation depths of over 10% (using a kilometer of 50μm diameter multimode fiber with a multimode fiber coupler) have been achieved when beating two lasers.



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

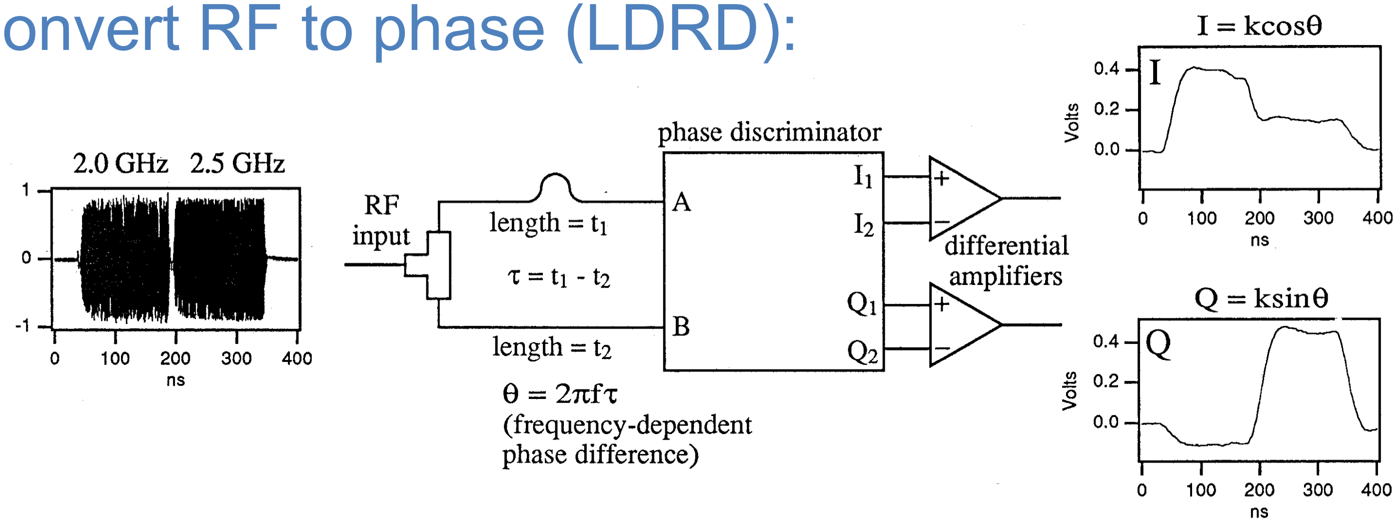
Heterodyne detection using multimode waveguide Y-couplers,
J. Salzman, U. Sivan, E. Kapon, and A. Katzir, Applied Optics 22(24), 3931-3934 (1983)

Convert RF to amplitude (LDRD):



Can measure resulting waveforms at slower digitizing rates,
But--
Hard to characterize for, say, 1% measurements.
Need multiple bandpass 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.

Convert 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 requires up-conversion.

We built this box and tested with mixed results—
good in the lab but not so good on tests.

By 2000, we realized we had requirements for 2 frequency regimes on sub-critical exp’ts:

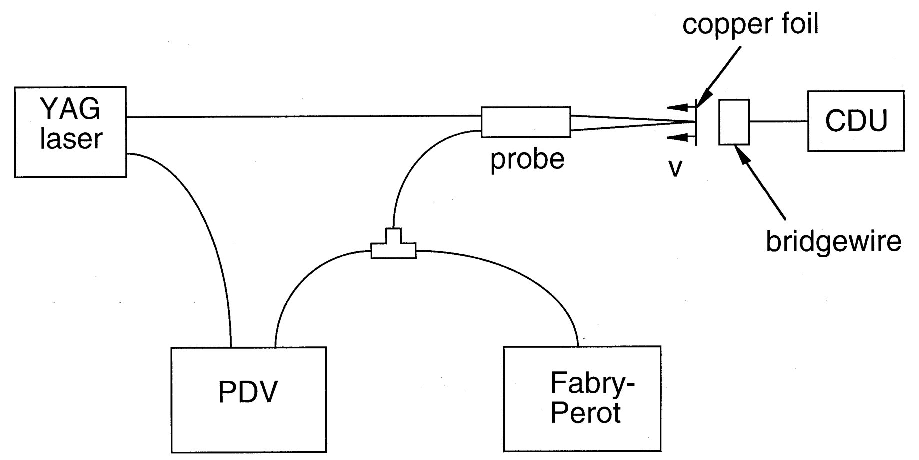
Low frequencies: use direct record method

- CDU-driven flyer foils
- Asay foils
- Beat frequency is low enough to record directly with standard digitizers

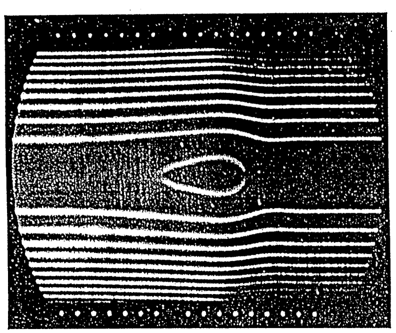
High frequencies: use phase discriminator method

- HE-driven experiments
- Gas gun experiments

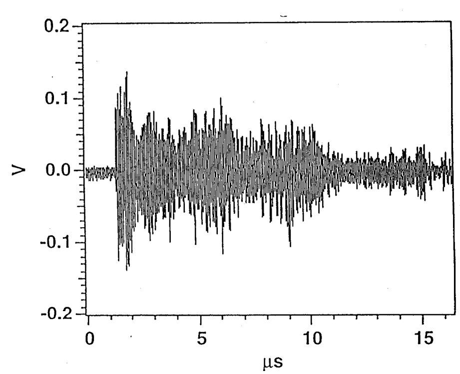
We compared direct record PDV with Fabry-Perot (532nm)

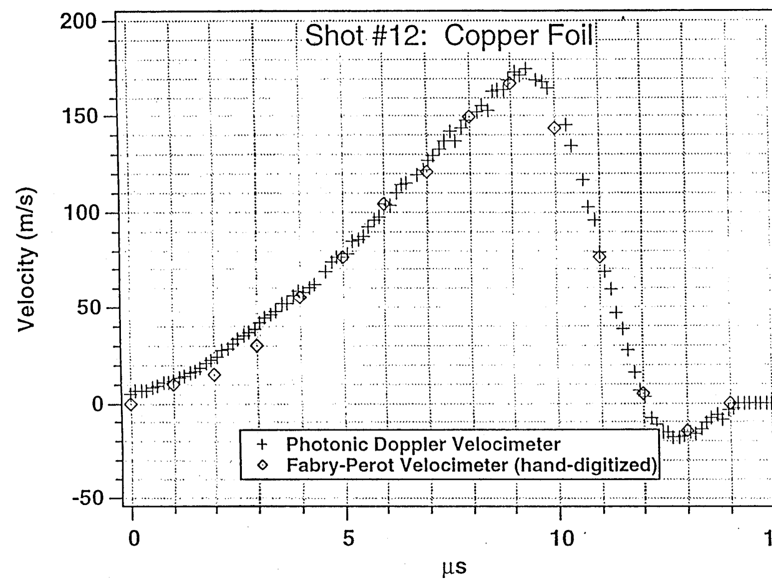


Fabry-Perot Velocimetry

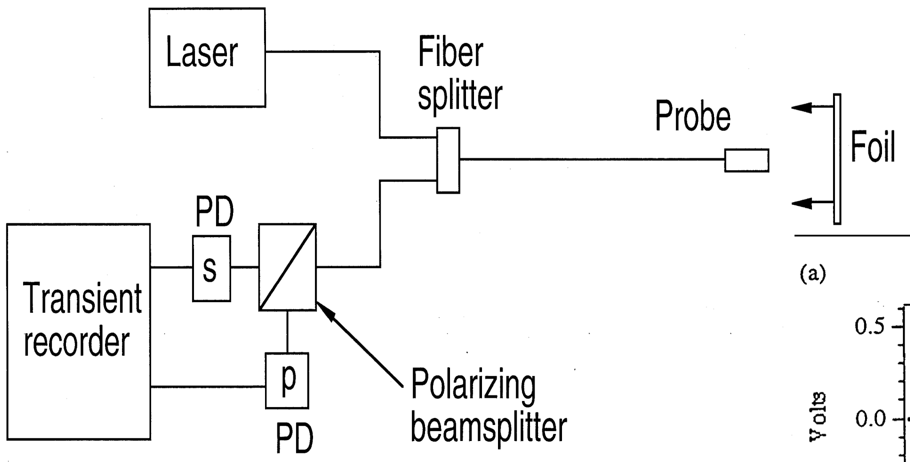


Photonic Doppler Velocimetry





We observed polarization effects with direct record method



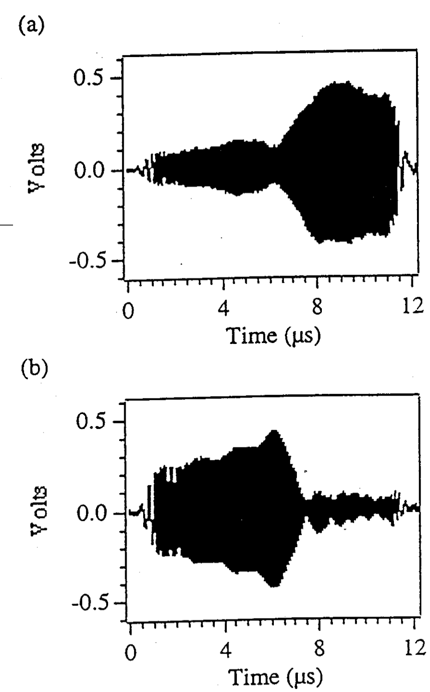


Figure 4. Raw data from niobium foil experiment: (a) S polarization, (b) P polarization.

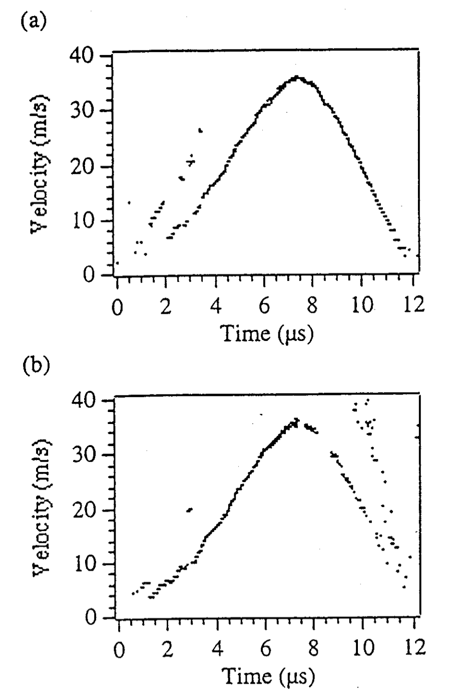
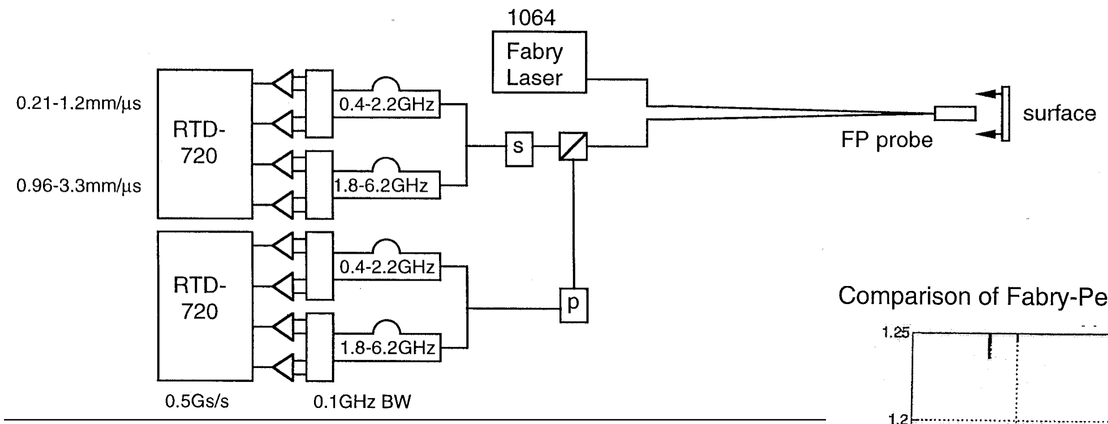
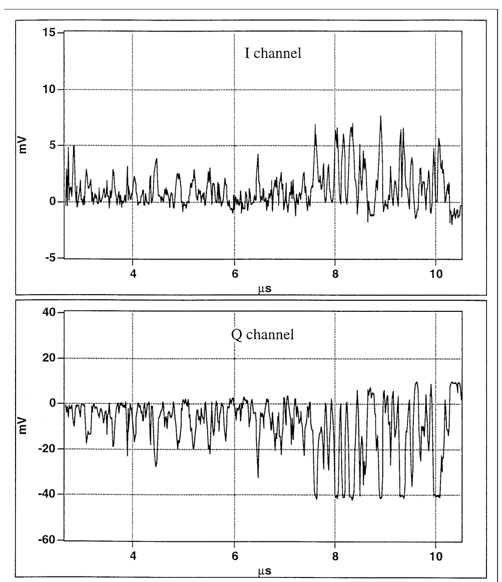
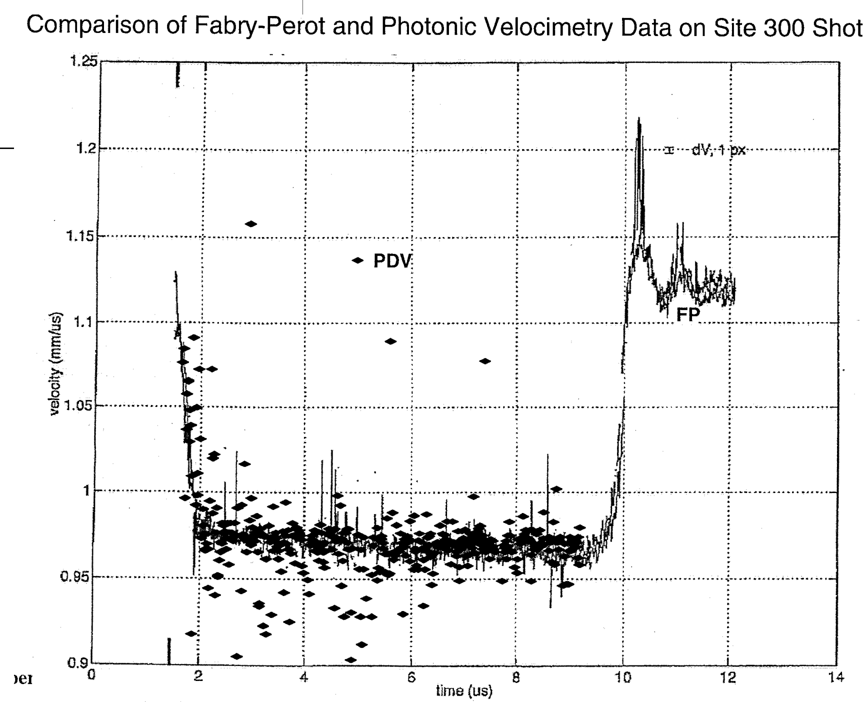


Figure 5. Processed data from niobium foil experiment: (a) S polarization, (b) P polarization.

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

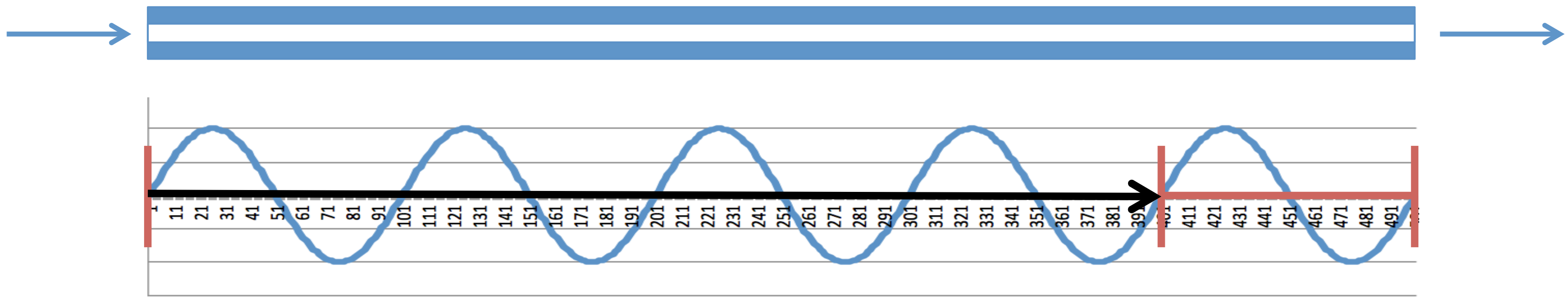






By 2002, we had to admit that MM fiber was giving us low SNR.

Modal dispersion in step-index fiber spreads information.



information
at one instant
in time here

gets spread out
in time over here

If the modal dispersion = one beat period, then the contrast goes to zero!!

We finally admit defeat with MM fiber.

PDV: 532 nm system
There are problems with multi-mode fiber

For λ = 532 nm and v = 1 mm/μs:

$f = 5.6 \times 10^{14}$ Hz

$2(v/c)f = 3.8$ GHz

There were 2 issues to overcome:

1) How to measure 4 GHz for 30 μs?
2) Beat amplitude?

Paul Sargis solved the first issue fairly quickly

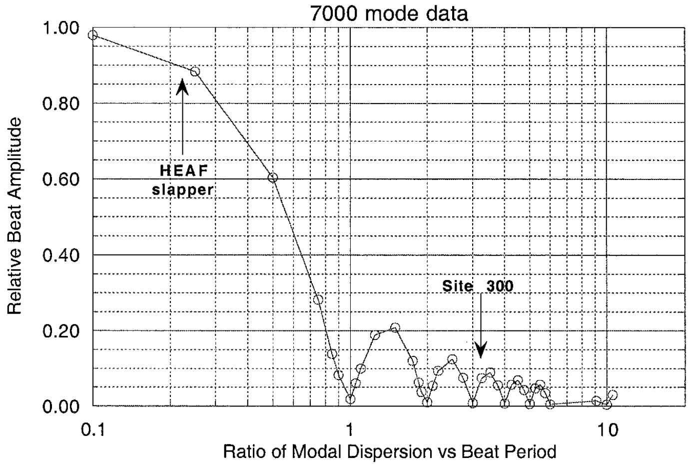
Use phase discriminators to convert high frequency to phase information

But, the beat amplitude problem was harder to solve

Modal dispersion in the step-index fiber reduced the signal contrast

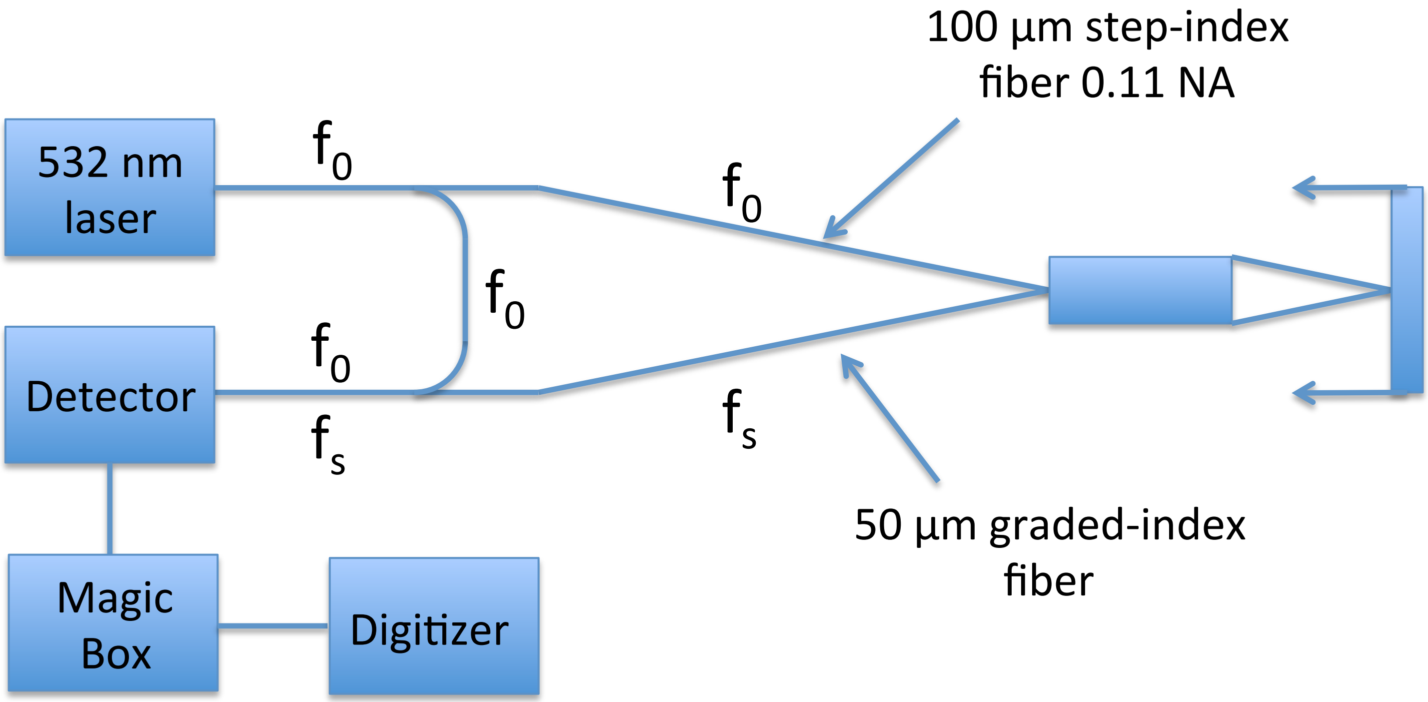
At 1 mm/μs, the beat period is 0.26 ns

At U1a with 80 m of step index fiber, the modal dispersion is 2.2 ns



With graded-index fiber, the modal dispersion is 9 ps

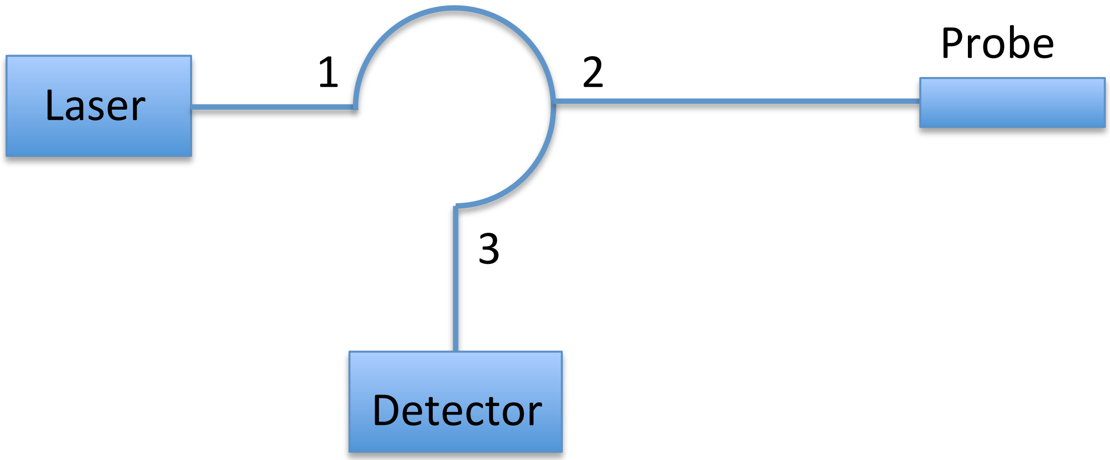
But, suppose we use graded index fiber?



I had just finished building a probe with GI return fiber…

Tony walked into my office with some literature on a device called a "circulator".

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 switch from 532 nm to 1550 nm."

Consequences of going from 532 nm to 1550 nm:

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

Parts for 1550 nm are commercially available

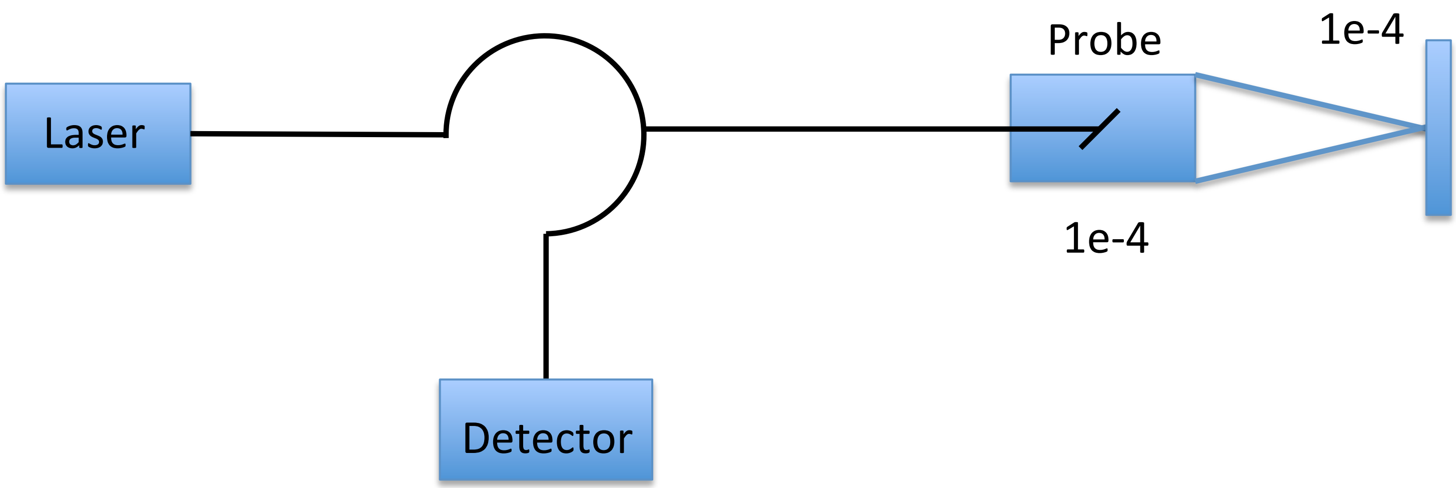
Multimode fiber (100 μm core) to single mode fiber (9 μm core)

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

Final configuration will be much smaller and 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

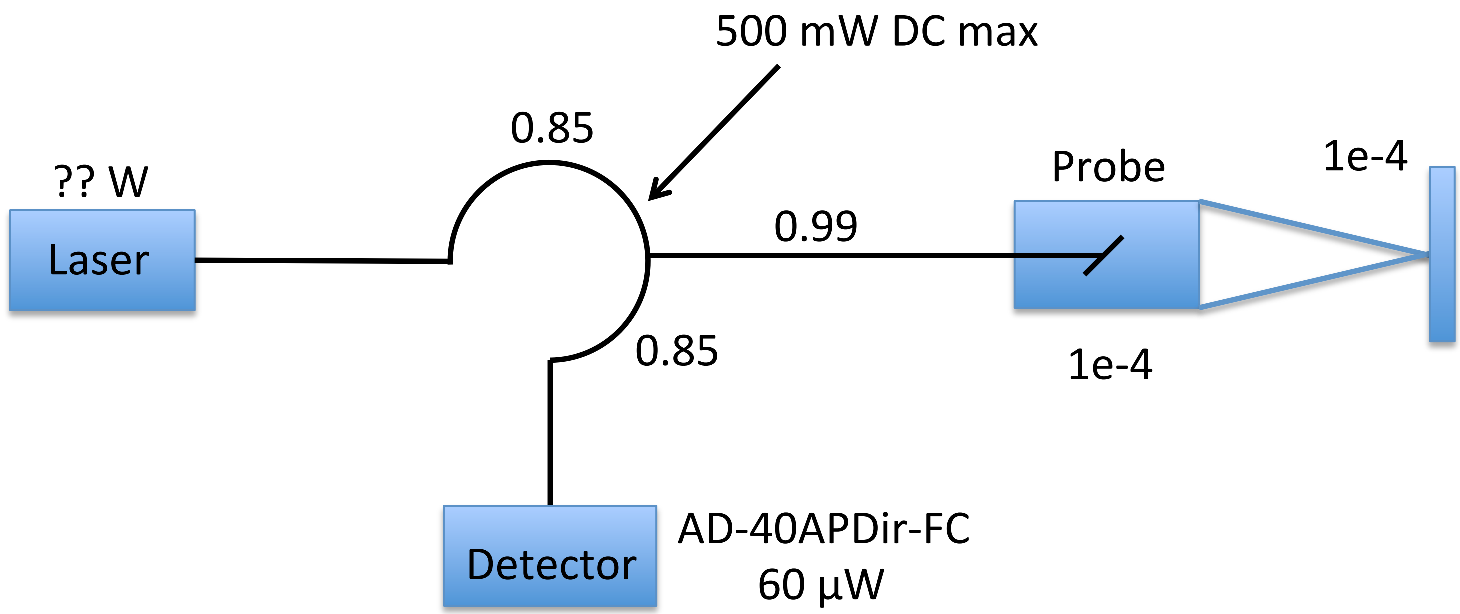
Doppler-shifted and reference follow essentially the same path

But

Less flexibility in reference level

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

Power Budget for 1550 nm PDV with circulator:

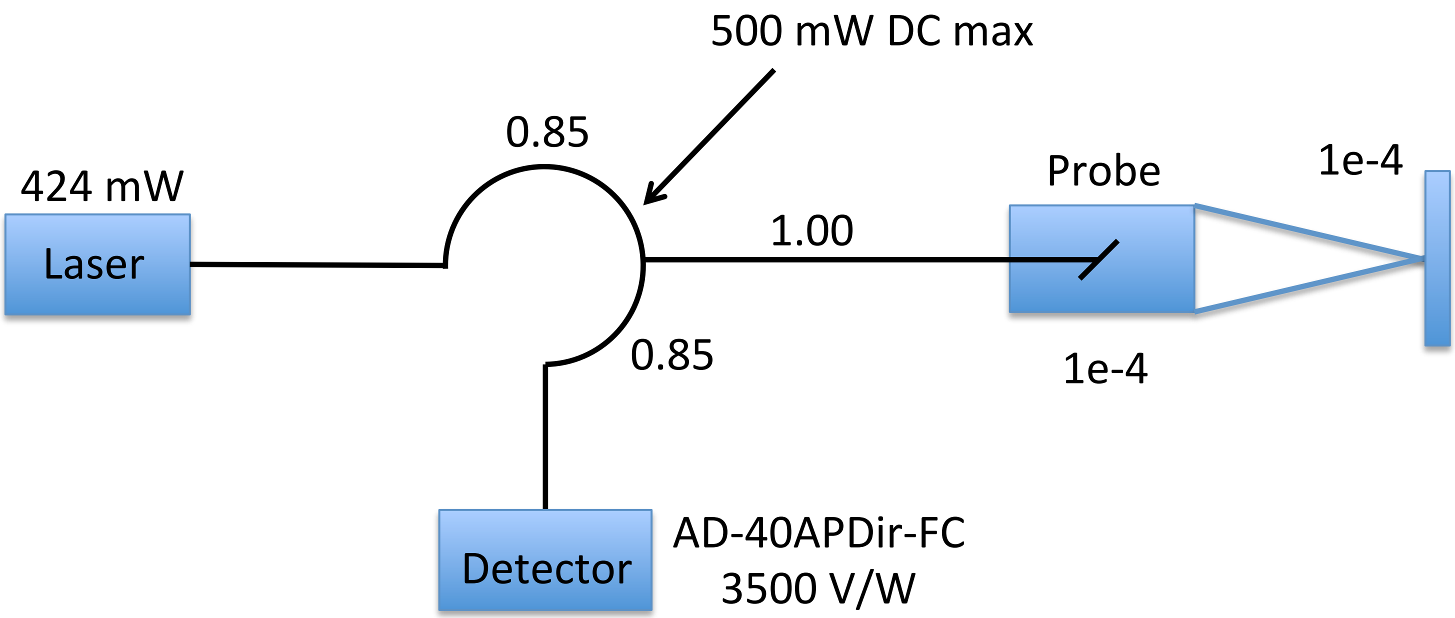


?? W x 0.85 x 0.99 x (1e-4 + 1e-4) x 0.99 x 0.85 = 60 µW

?? = 424 mW !!

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

Calculate Signal from Probe



60 µW x 3500 V/W = 210 mV total

Half = 105 mV from surface
Half = 105 mV from reference

Calculate Beat Amplitude

$$I(t) = I_0 + I_d + \sqrt{I_o I_d}\,\sin[f_b(t) + \phi]$$

beat amplitude beat frequency

$I(t)$ = total signal
I_0 = reference signal
I_d = doppler-shifted signal
$f_b(t)$ = beat frequency
ϕ = phase

I_{beat} = sqrt(105mV x 105mV) = 105 mV

should be a useable signal—let's start checking it out

Tony started gathering up parts:

30 mW linearly polarized fiber-coupled laser diode

1550 nm single mode fiber

Polarized Circulator

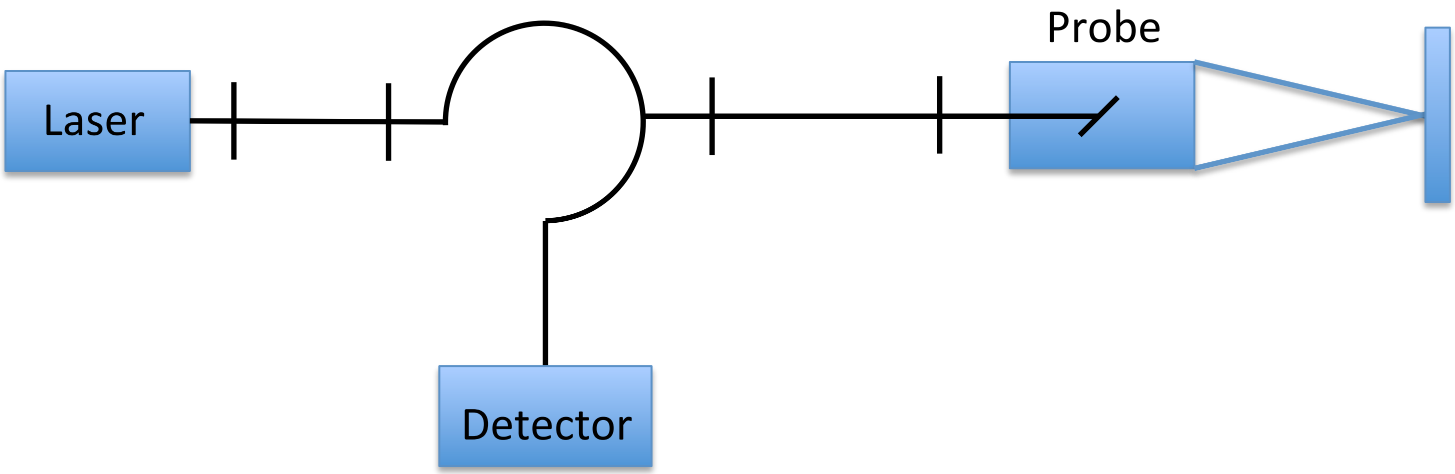
Focuser and collimator probes from DSA

Thorlabs detector

Woofer speaker

High Voltage spark gap bridge wire (safety people loved it)

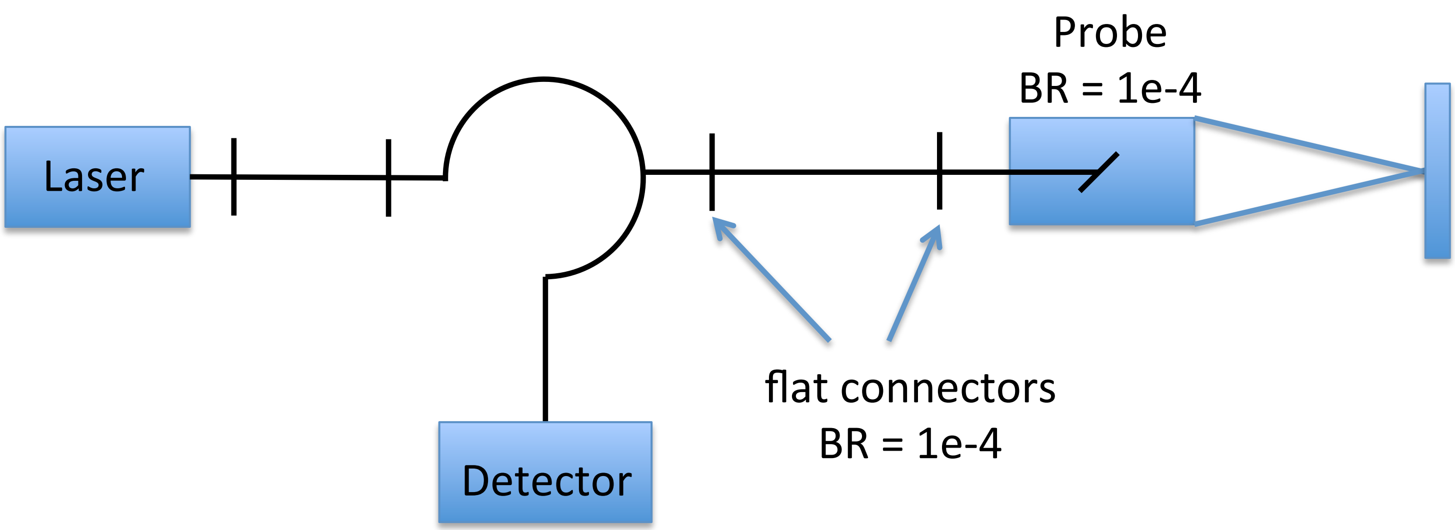
Tony set a basic system up in the lab



We had a very difficult time maintaining good beat amplitude.

The slightest touch would make the signal change wildly.

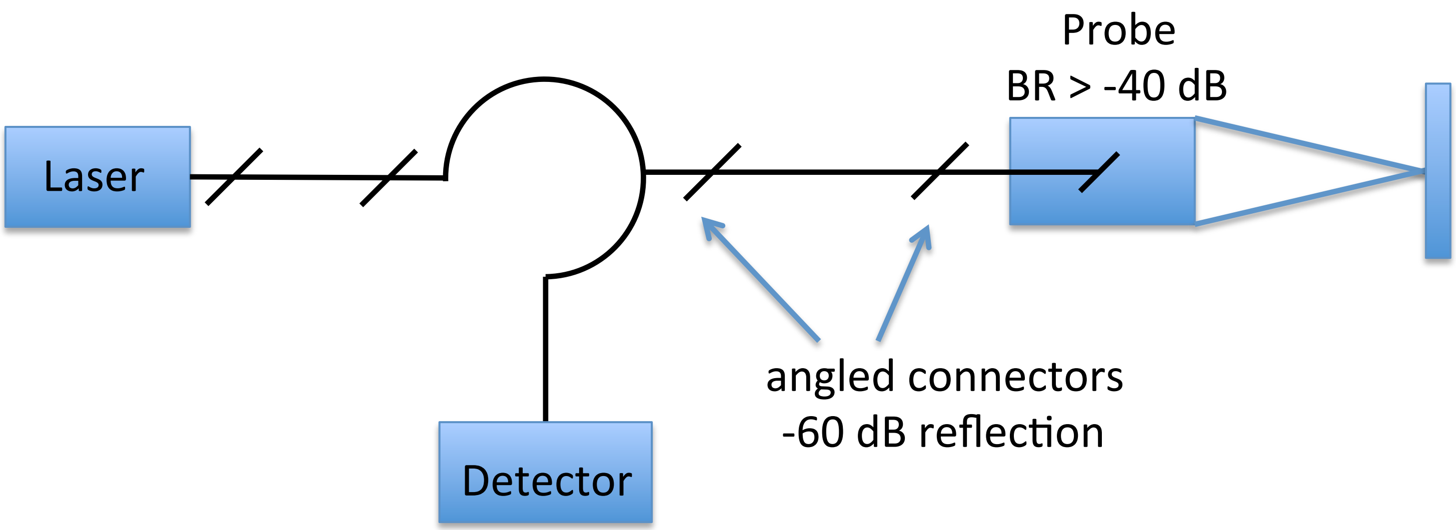
We realized we had more than one reference source



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 between circulator and probe



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

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

By this time, fiber lasers had become available.
We bought a 1-watt unpolarized model.

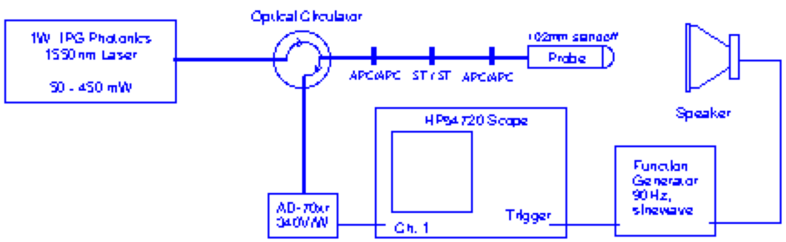
We bought polarization insensitive circulators.

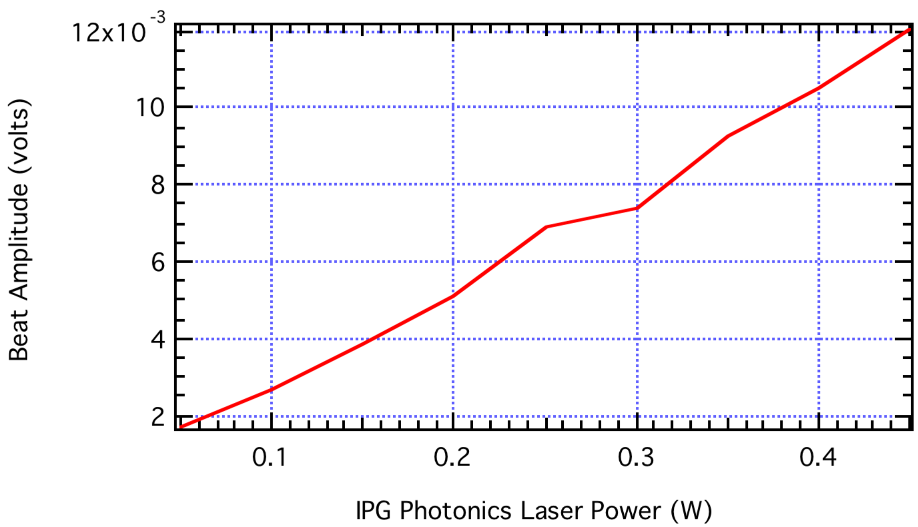
We used angle polished connectors everywhere.

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

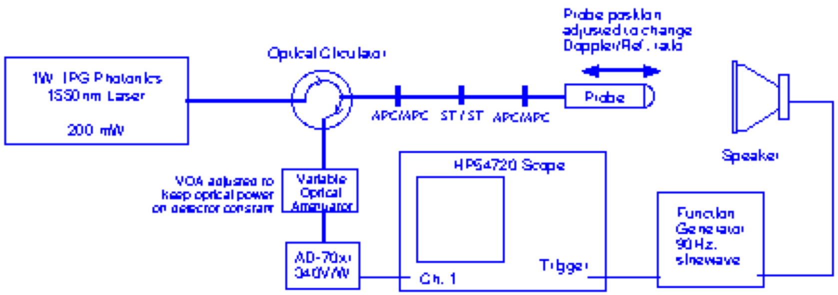
Tony got busy…

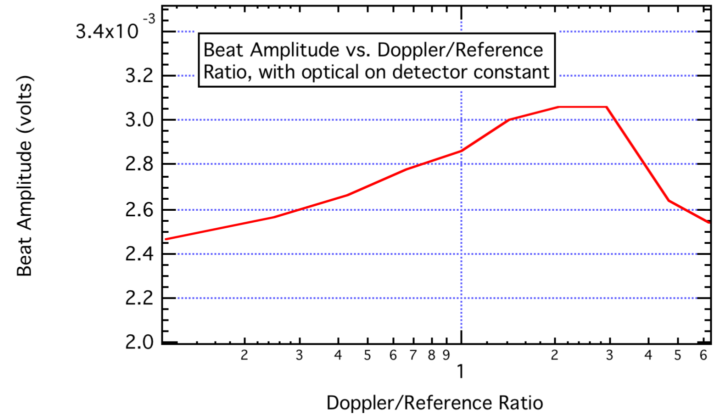
Beat amplitude vs laser power is linear as expected. (doppler-shifted signal equal to reference signal)



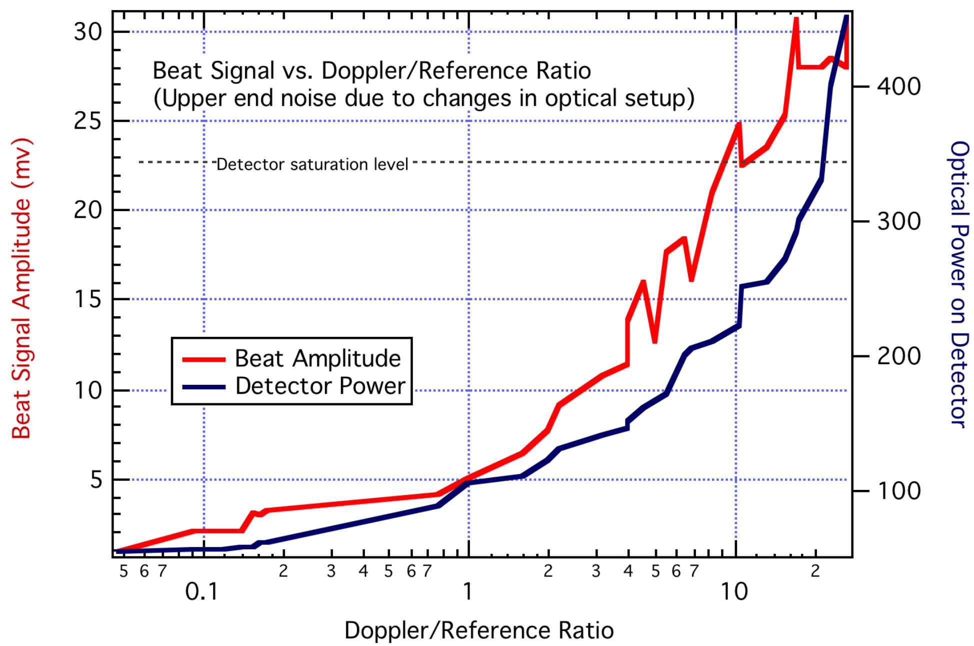


Beat signal vs ratio of reference to doppler-shifted light. Should peak at 1:1, but these are difficult measurements when the probes have large back reflection.





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



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

Could not impact shot schedule

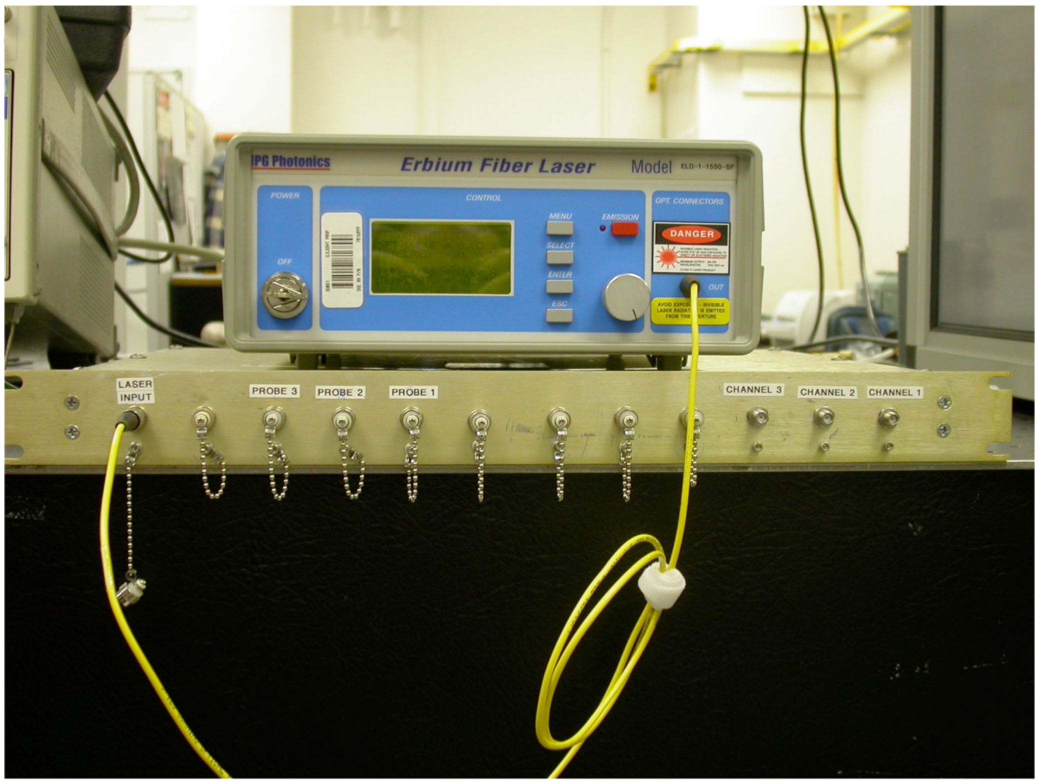
Poor geometry = poor data

This went on for quite a while

Finally, Leon Berzins arranged with Vlad Georgvich of LLNL to let us field our PDV on one of his shot series

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.

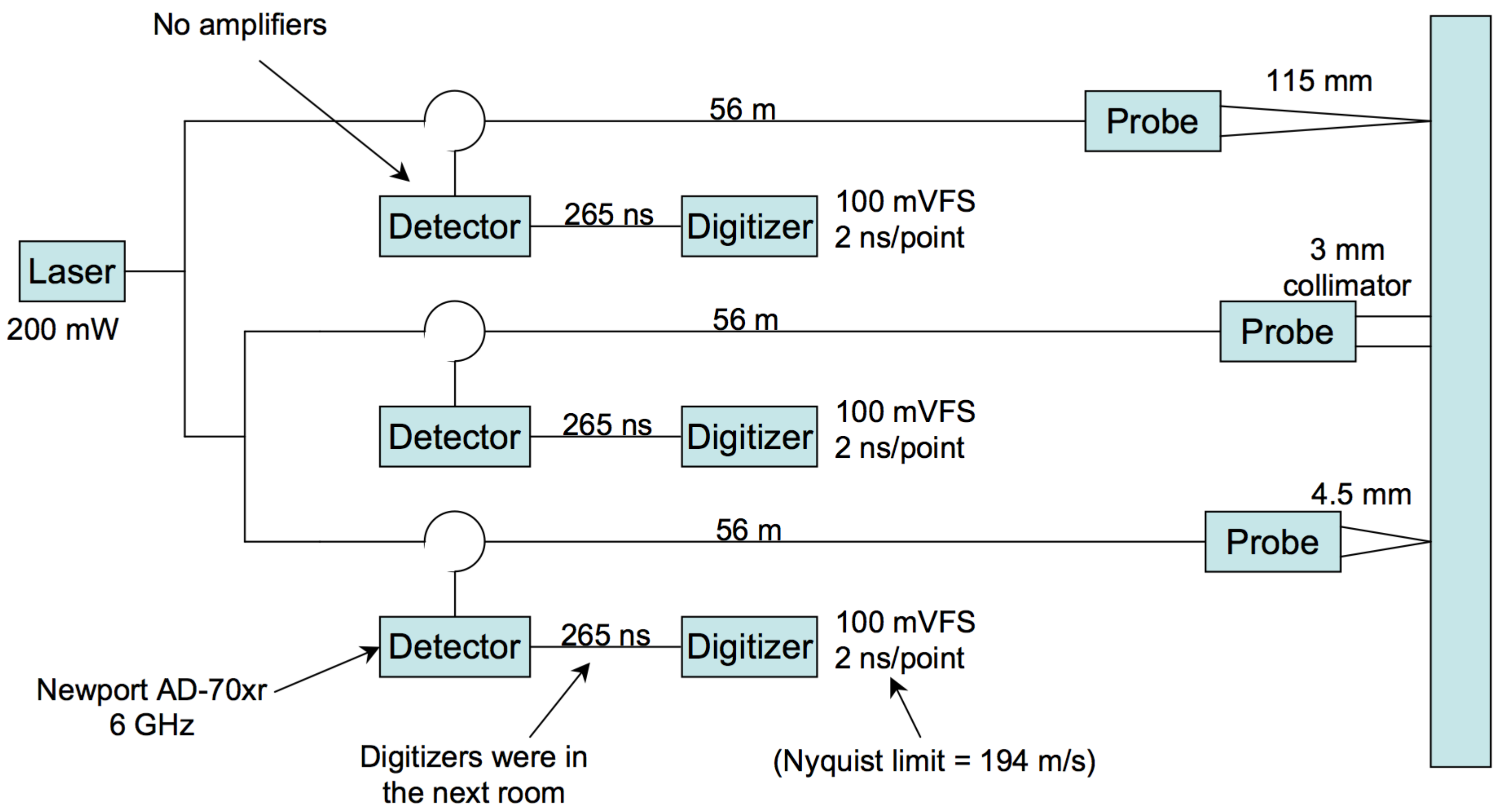


1 W laser

3 channels
(no knobs!)

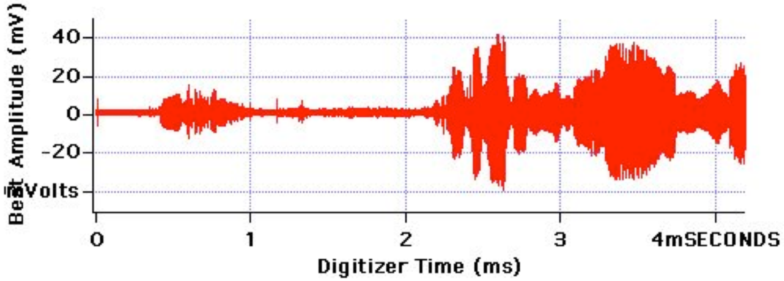
We borrowed
digitizer channels
from the bunker

We barely had enough parts for 3 channels



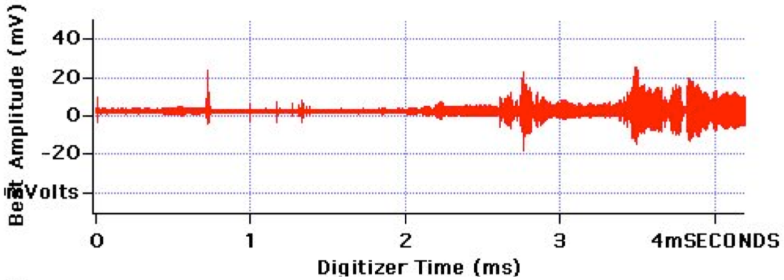
The data was less than perfect…

Probe 1
115 mm



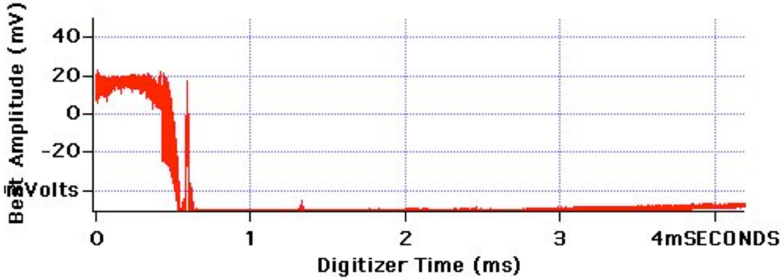
Looks good!

Probe 2
3 mm
collimator



Anything here??

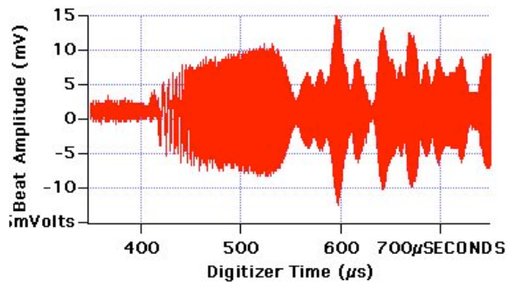
Probe 3
4.5 mm



Electrical noise here

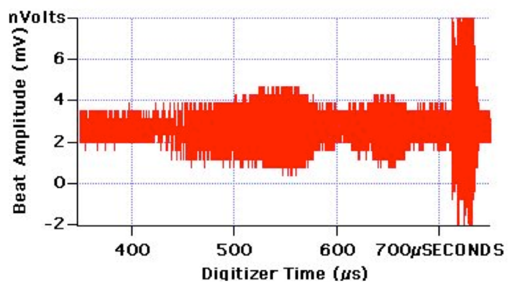
But at least we got something!

Probe 1
115 mm



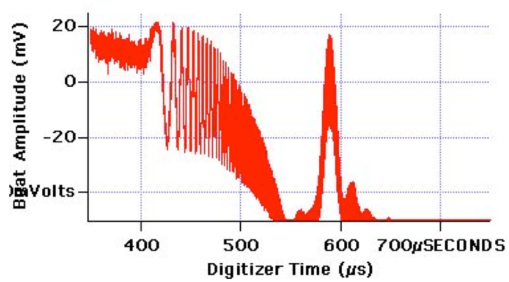
Still looks good!

Probe 2
3 mm
collimator



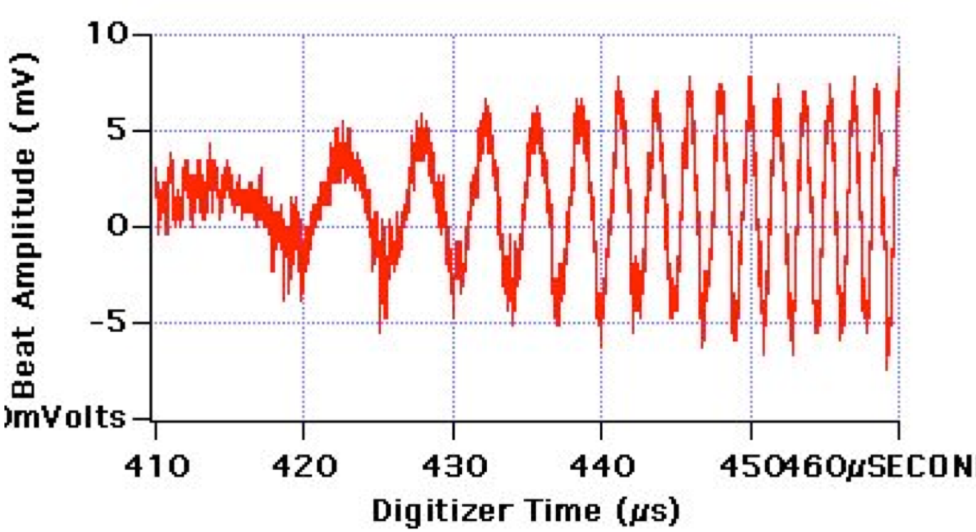
Still not sure

Probe 3
4.5 mm



Definitely have some data!

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



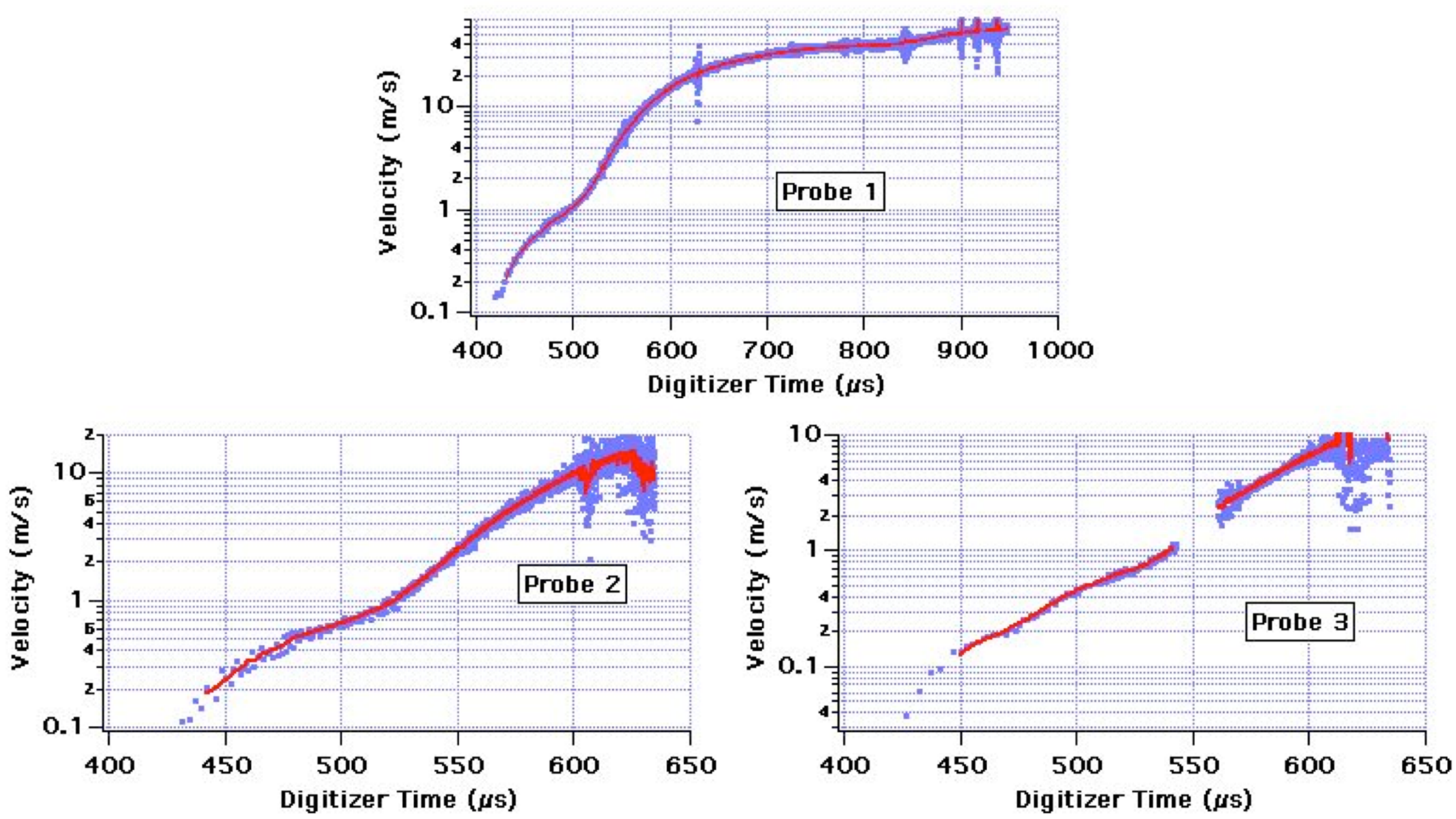
Excel can handle only 50,000 rows of data, so I needed to split the data file among 10 spreadsheets.

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



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

Agilent came out with the first digitizers that could record at 20GS/s and 6 GHz for 50µs !!

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

We still needed a backup system for Accordion.

Bechtel/Nevada bought first two Agilents.

(Accordion was eventually cancelled.)

Bill Kuhlow of Bechtel/Nevada wrote the first sliding Fourier transform code for PDV:

Used MatLab

Two parts:

- Batch mode to calculate spectrograms
- Interactive mode to define regions of interest and extract

Fixed 50% overlap

User-friendly for defining regions of interest

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

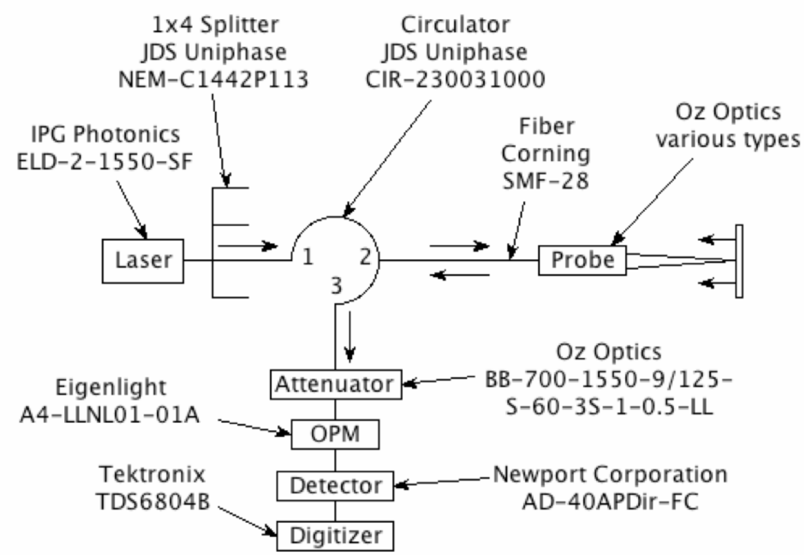


Figure 2. The heterodyne velocimeter is assembled from commercially available parts. The output of the laser is input into a 1x4 fiber splitter, which is connected to the four circulators. Each circulator transports light to a probe that launches light onto the moving surface. The Doppler-shifted light is collected by the probe and sent to the detector. The back-reflection from the fiber endface inside the probe provides the undoppler-shifted light.

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Conclusions

The development of the PDV was driven by programmatic requirements (SCE).

LDRD funding was instrumental in getting the process started.

Using multi-mode fibers did not work out (modal dispersion).

Converting the beat frequency to a more easily measured quantity was difficult.

As we were working the problem, the technology advanced to the point
that recording the beat frequency directly with single mode optics became possible.

At LLNL, the Fabry-Perot system was abandoned in favor of the PDV.