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High-Definition Optical Velocimetry: A New Diagnostic Paradigm for Nuclear Security

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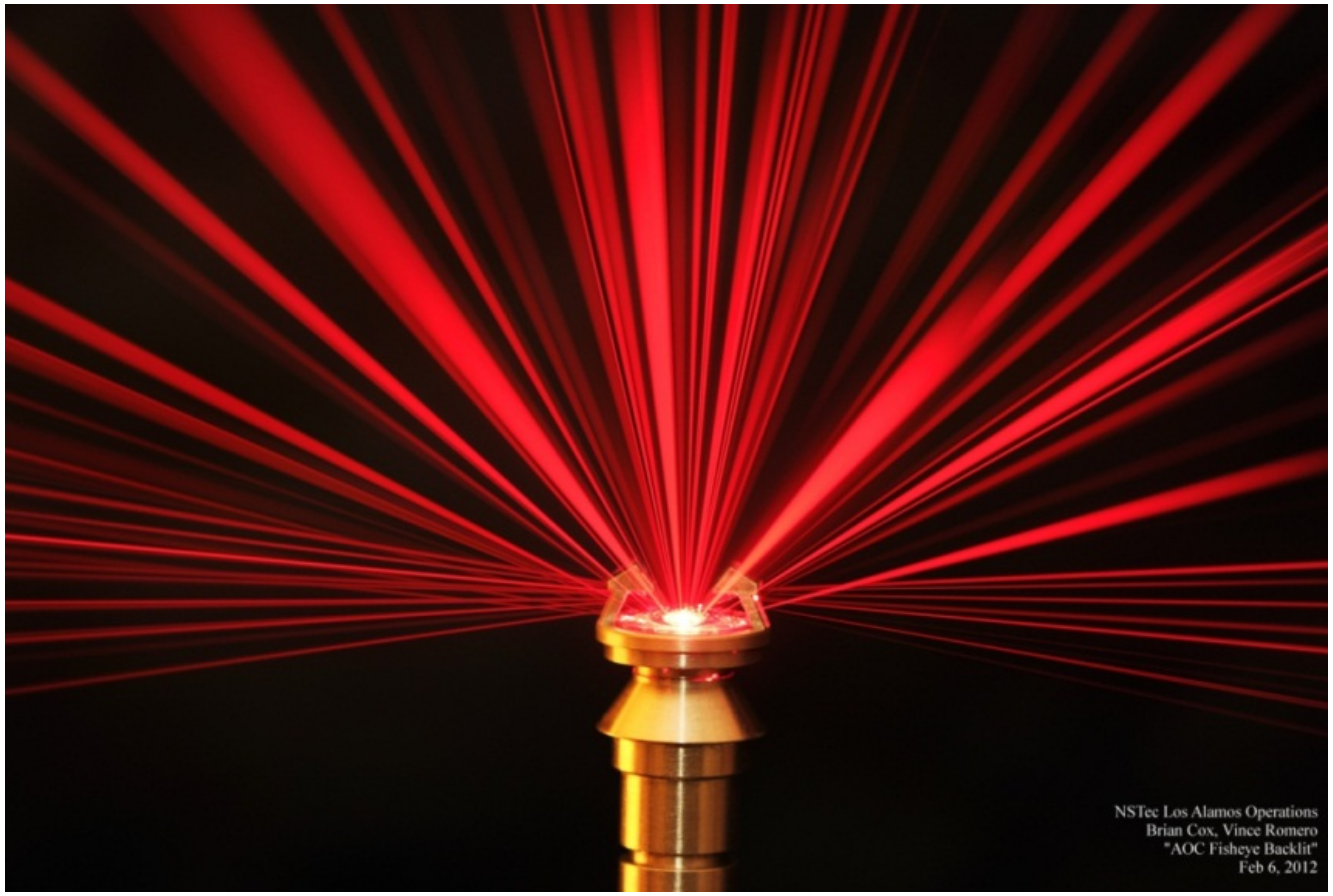
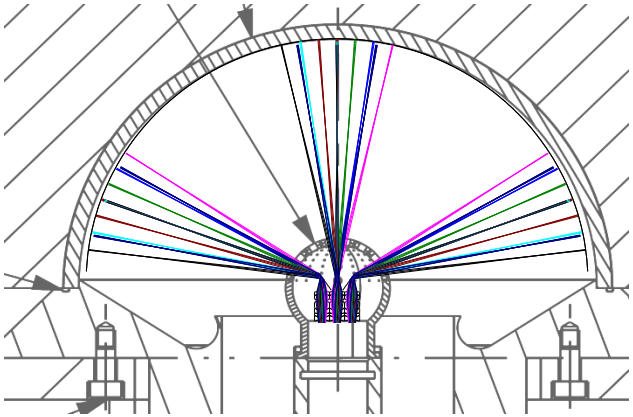
THE CHALLENGE: AN ENABLING CAPABILITY

- **High-Definition Optical Velocimetry**
  Hundred(s) of high-fidelity velocity vs. time measurements



GEMINI program optical velocimetry imaging system developed for many-point optical velocimetry applications

THE CHALLENGE: DEVELOPMENT OF MULTIPLEXED PHOTONIC DOPPLER VELOCIMETRY (MPDV)



- **Capability**. *Enable* future stockpile stewardship experimental efforts that require large data channel counts (~100) by leveraging existing diagnostic techniques and commercial technologies to expand and enhance optical velocimetry capabilities.
- **Physics**. Determine whether frequency multiplexing and heterodyne techniques could expand upon Photonic Doppler Velocimetry (PDV) measurements of surface velocity.
- **Economy**. Develop economical methods to record high-fidelity optical velocimetry data via frequency and time division multiplexing coupled with commercially available telecom technologies.
- **Operations and Logistics**. Develop an 'experimenter friendly' diagnostic capability: portable, robust, minimal 'care and feeding,' and operable within a laser-safe environment

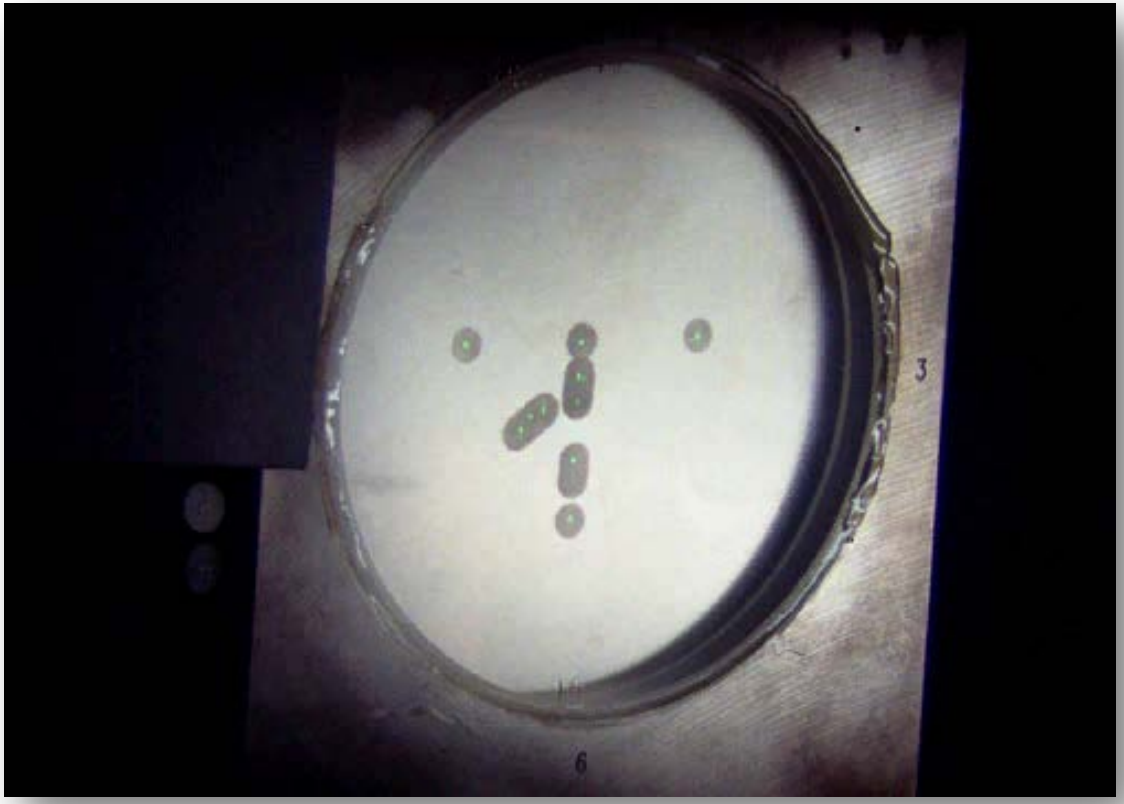
HISTORICAL CONTEXT: A 'FEW' DATA CHANNELS

- Limited number of measurements, locations strategically selected
- 2-D performance approximate—interpolation and extrapolation, assumed symmetries, and corroborating diagnostics, e.g., high-speed photography

Optical velocimetry is fundamental to shock physics research!

→ **Material physics**

→ **'Integrated' experiments**



High-speed photography of experiment with 10 channels of Fabry-Perot velocimetry

HISTORICAL CONTEXT: VISAR & FABRY-PEROT

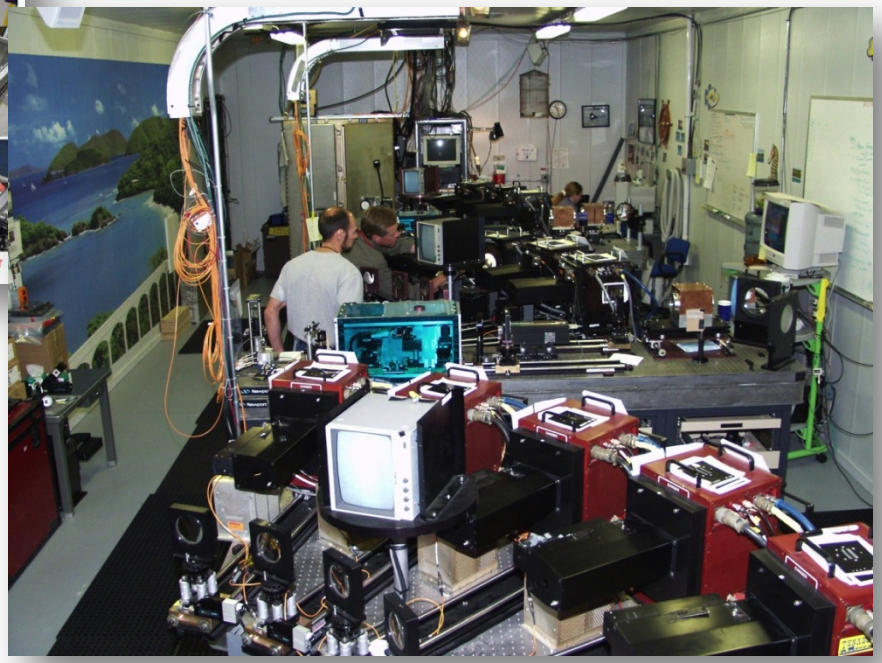
36-Point VISAR System Trailer

Developed 1970s—1990s

Complexity and cost limited our capacity

High-Fidelity Data at a High Cost

- Expensive
- Extensive 'Care and Feeding'
- Extensive Expertise Required



15-channel Fabry-Perot at NTS U1a (circa 2003)

HISTORICAL CONTEXT: PDV DEVELOPMENT

- Improved diagnostic capability, opened door to increased channel count and portable diagnostic
- Limitations: requires high-bandwidth ($$$$) digitizers, high-power lasers, unable to discern direction-of-travel

4-channel Gen 1 portable PDV (circa 2004, LLNL)

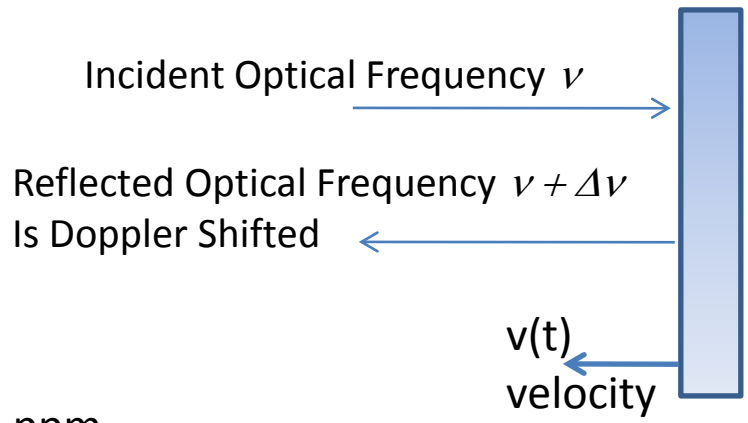
PDV

- Measures heterodyne beat frequency directly onto high-bandwidth digitizer
- Leverages telecom components
- Portable and user friendly
- Improved cost effectiveness
- Channel count: 1 probe per digitizer channel
- Channel counts: 4 to 8 (typical) to 20 (large effort)

VELOCIMETRY: BACKGROUND PHYSICS

- Optical velocimetry is a prime diagnostic for shock physics, pulsed power and hypervelocity experiments
  - Measure the Doppler shift of laser light reflected off of a moving target surface

Doppler Shift
$\Delta\nu/\nu = -2\,v(t)/c$



Frequency shifts are small

Example

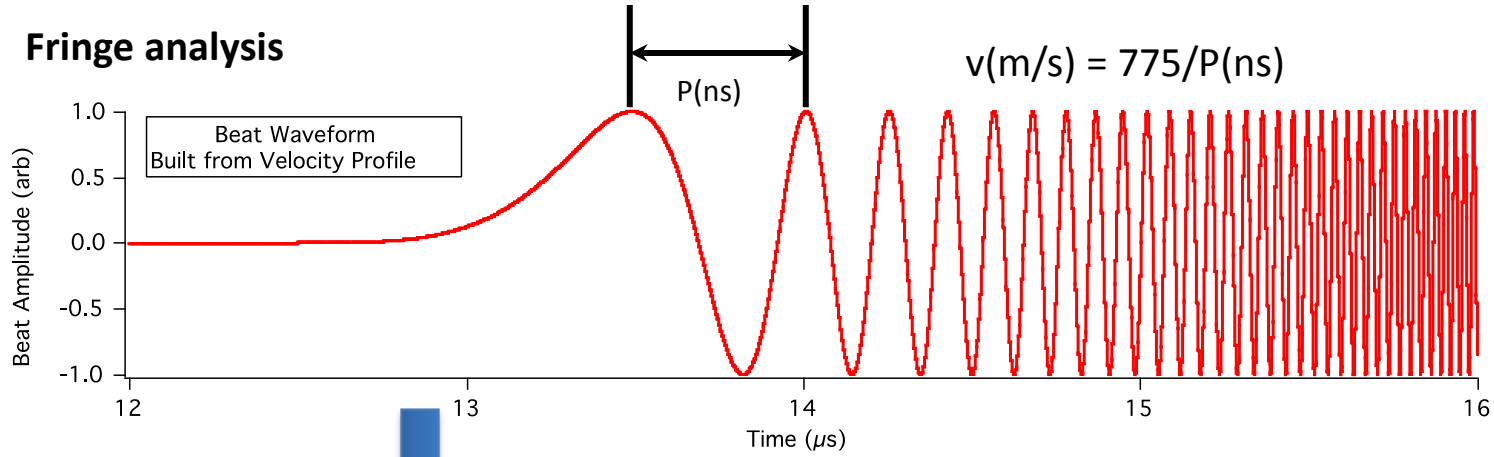
Surface v(t) = 1 km/s ➔ $\Delta\nu/\nu$ = 7 ppm

➡ Use interferometry to measure these small frequency shifts

1) Michelson ➔ VISAR, Initial Development 1970s
2) Fabry-Perot ➔ Fabry-Perot, Developed 1980–1990s
3) Heterodyne ➔ PDV, Initial Development ~2003

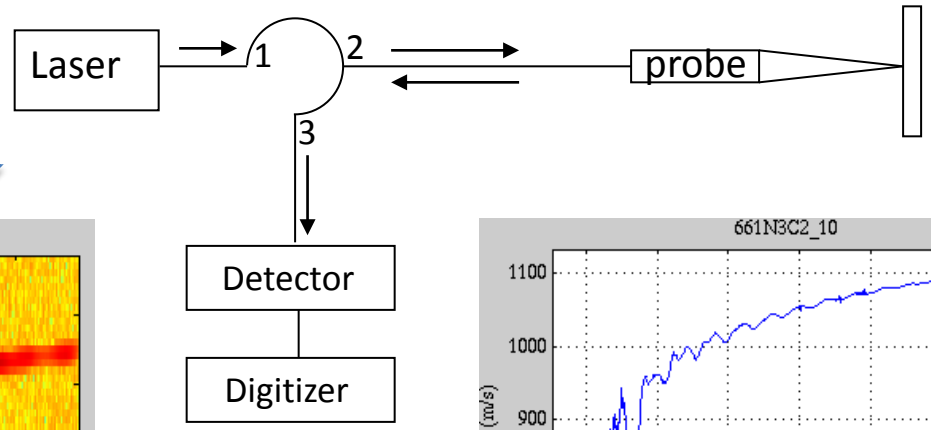
HOW PDV WORKS

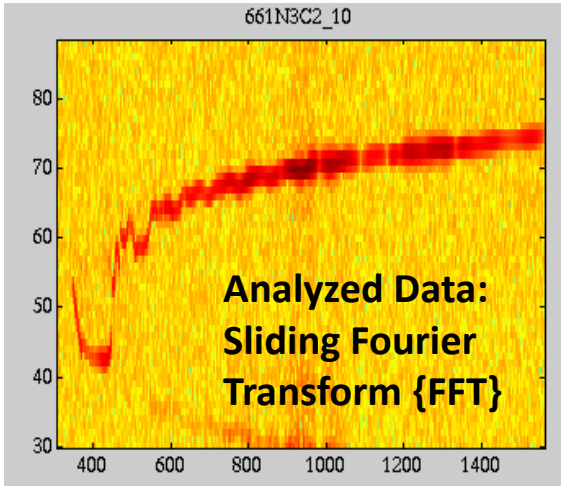
Fringe analysis

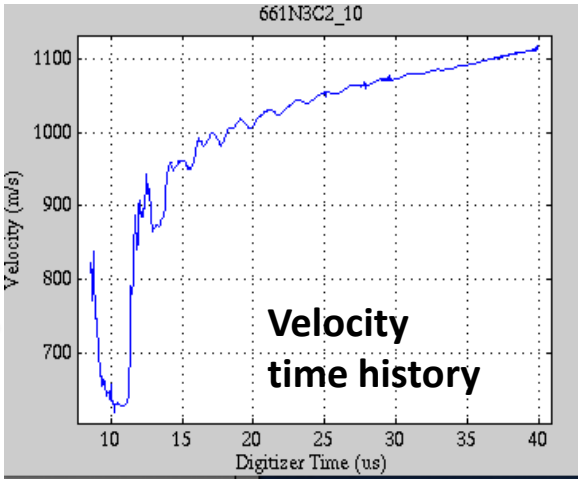


$$g(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} f(t) e^{i\omega t} dt$$

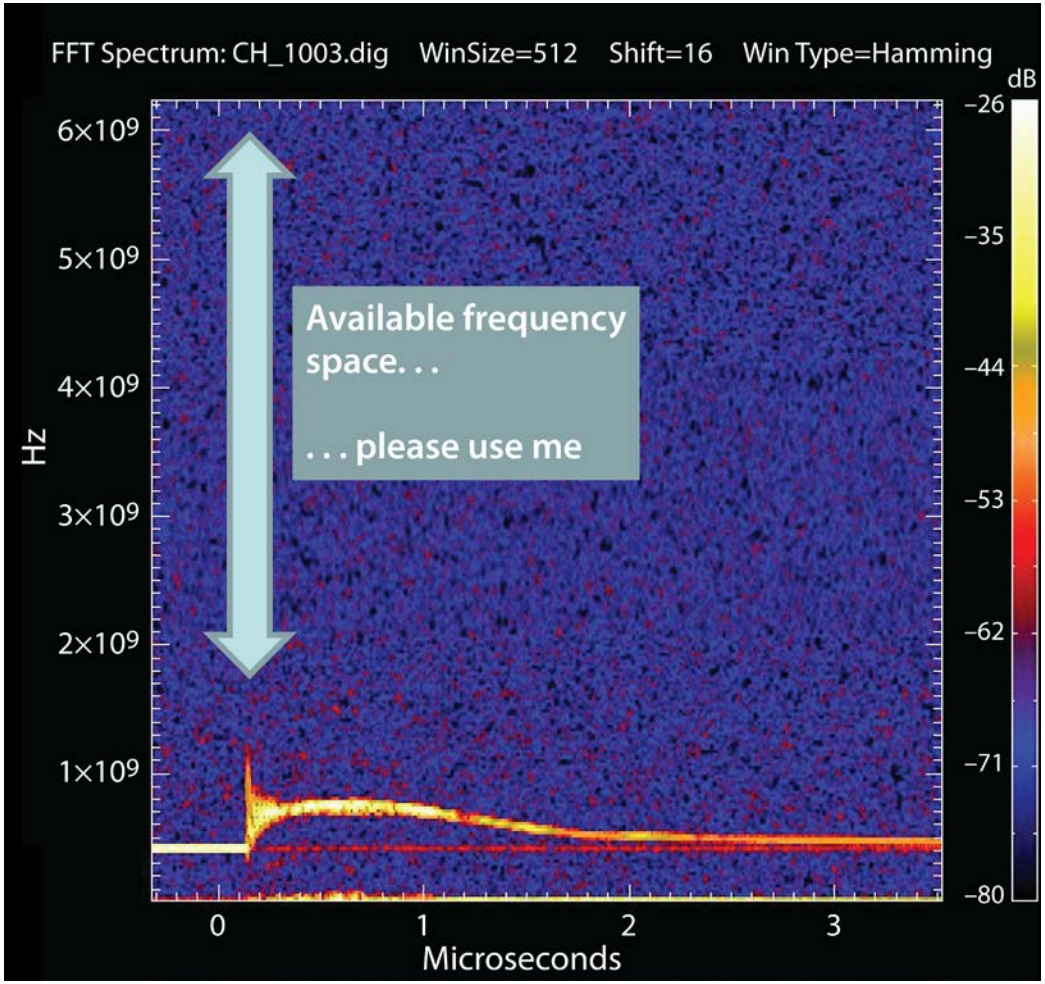
Fourier transform







SDRD MOTIVATION: LEVERAGE WHAT WE HAVE



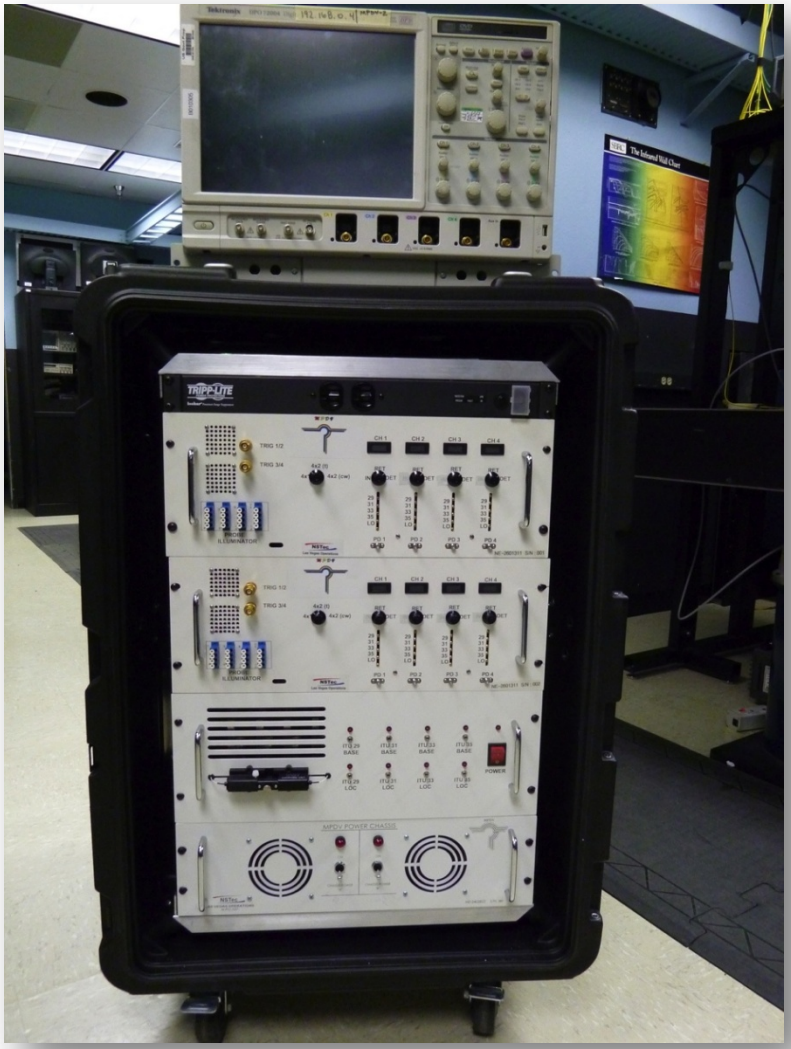
SDRD Proposal Leveraged

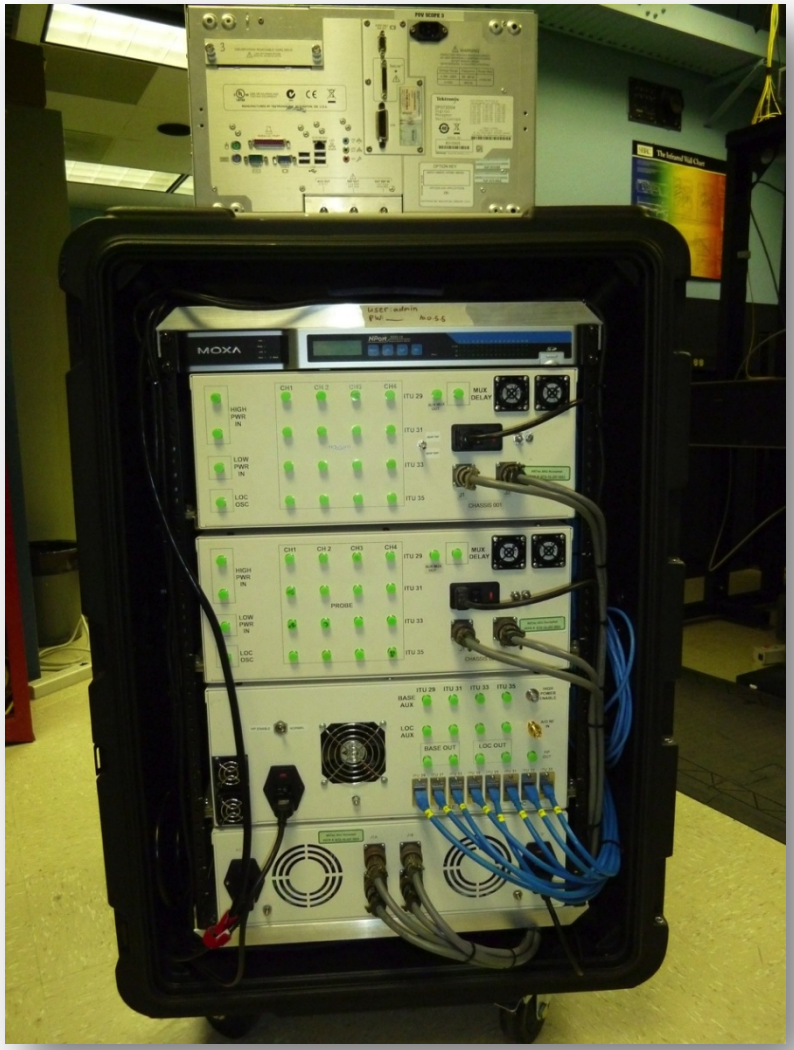
- PDV
- Available frequency space
- Available digitizer memory
- Heterodyne techniques and telecom products to frequency and time multiplex

Technical Risks

- Telecom products
- Telecom DWDM techniques
- Heterodyne technique effect on data fidelity
- Experiment vs. model
- The unknown

OUR INNOVATION: MPDV

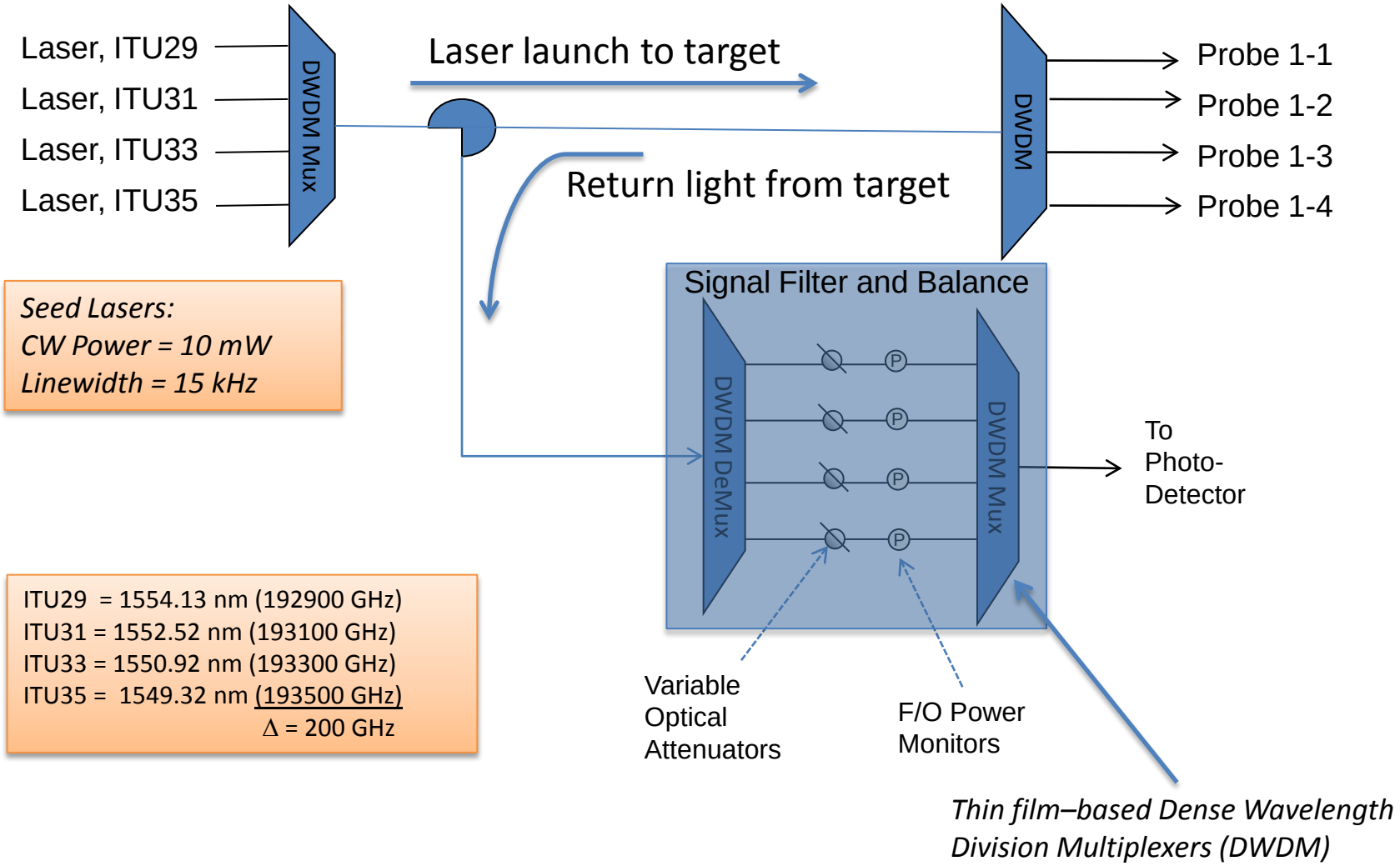




MPDV Prototype 32-Probe System with selectable 1x, 2x, 4x, 8x or 16x multiplexing (circa August 2011)

HOW MPDV WORKS: NOTIONAL ARCHITECTURE

Use Telecom Components and Dense Wavelength Division Multiplexing (DWDM)



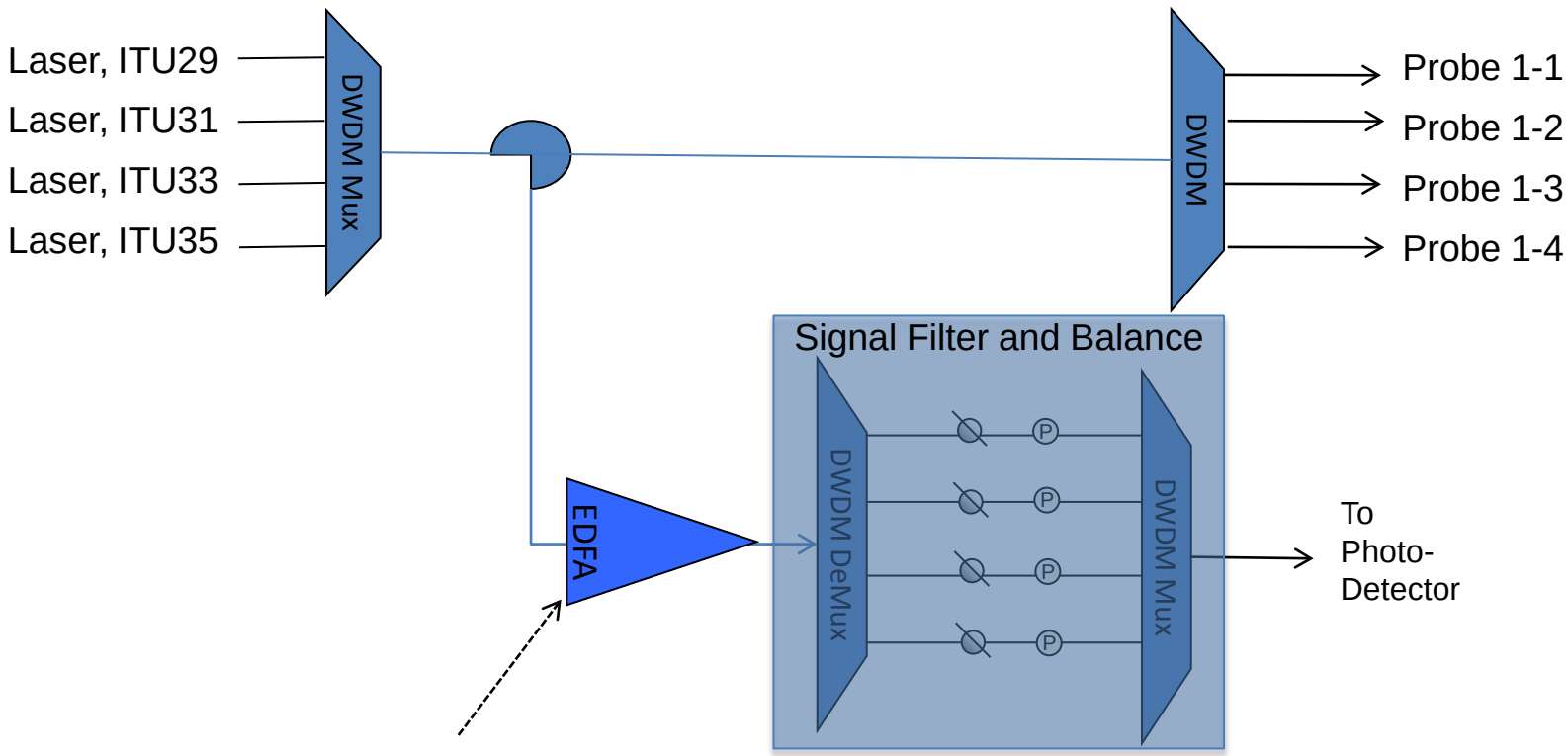
Seed Lasers:
CW Power = 10 mW
Linewidth = 15 kHz

ITU29 = 1554.13 nm (192900 GHz)
ITU31 = 1552.52 nm (193100 GHz)
ITU33 = 1550.92 nm (193300 GHz)
ITU35 = 1549.32 nm (193500 GHz)
Δ = 200 GHz

HOW MPDV WORKS: LASER SAFE OPS

Probe collection efficiency is typically 1×10^{-4} and often 10^{-5} to 10^{-6}

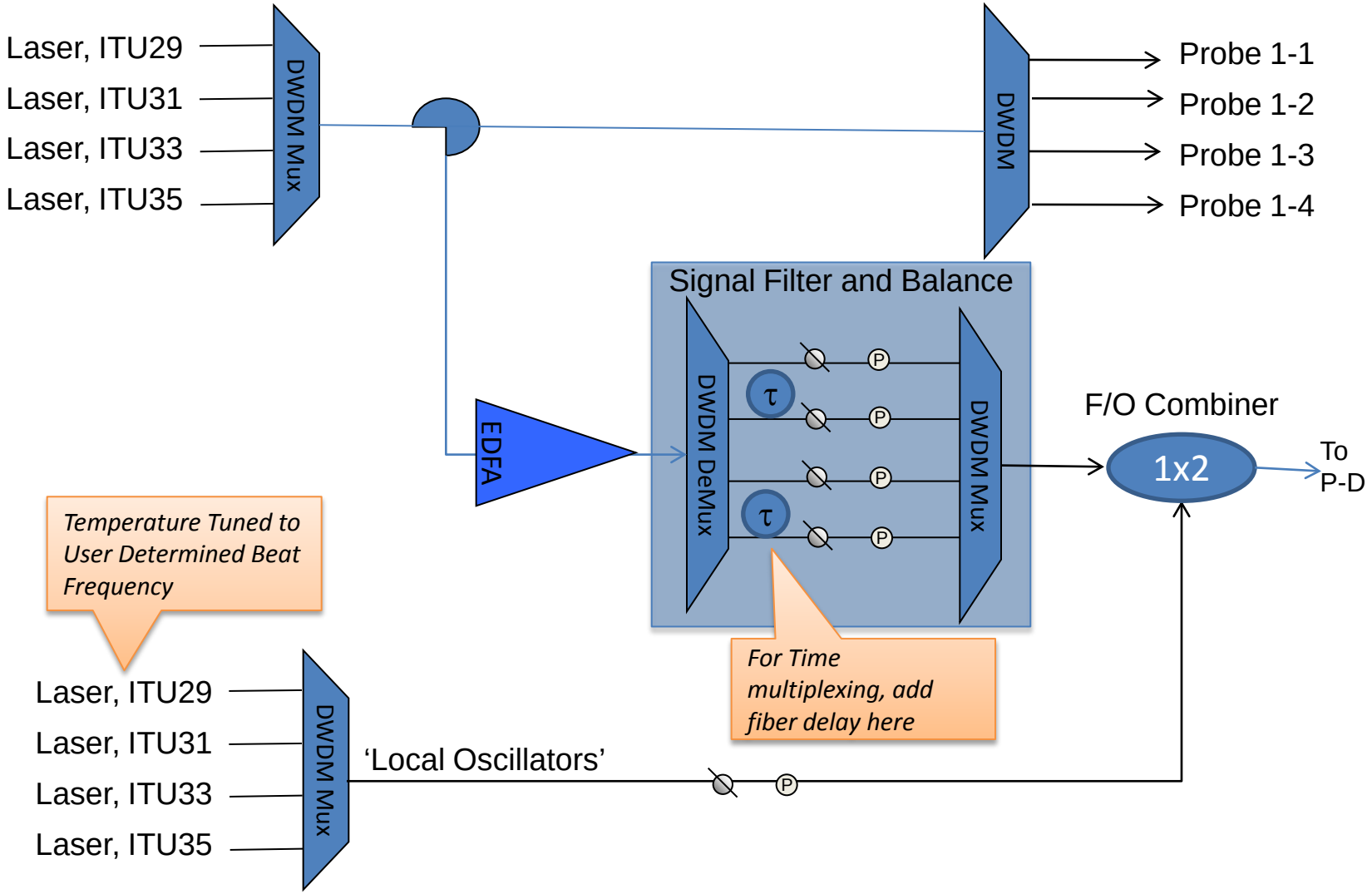
➔ Require either high laser power onto target (PDV) or amplification of small signals (MPDV)



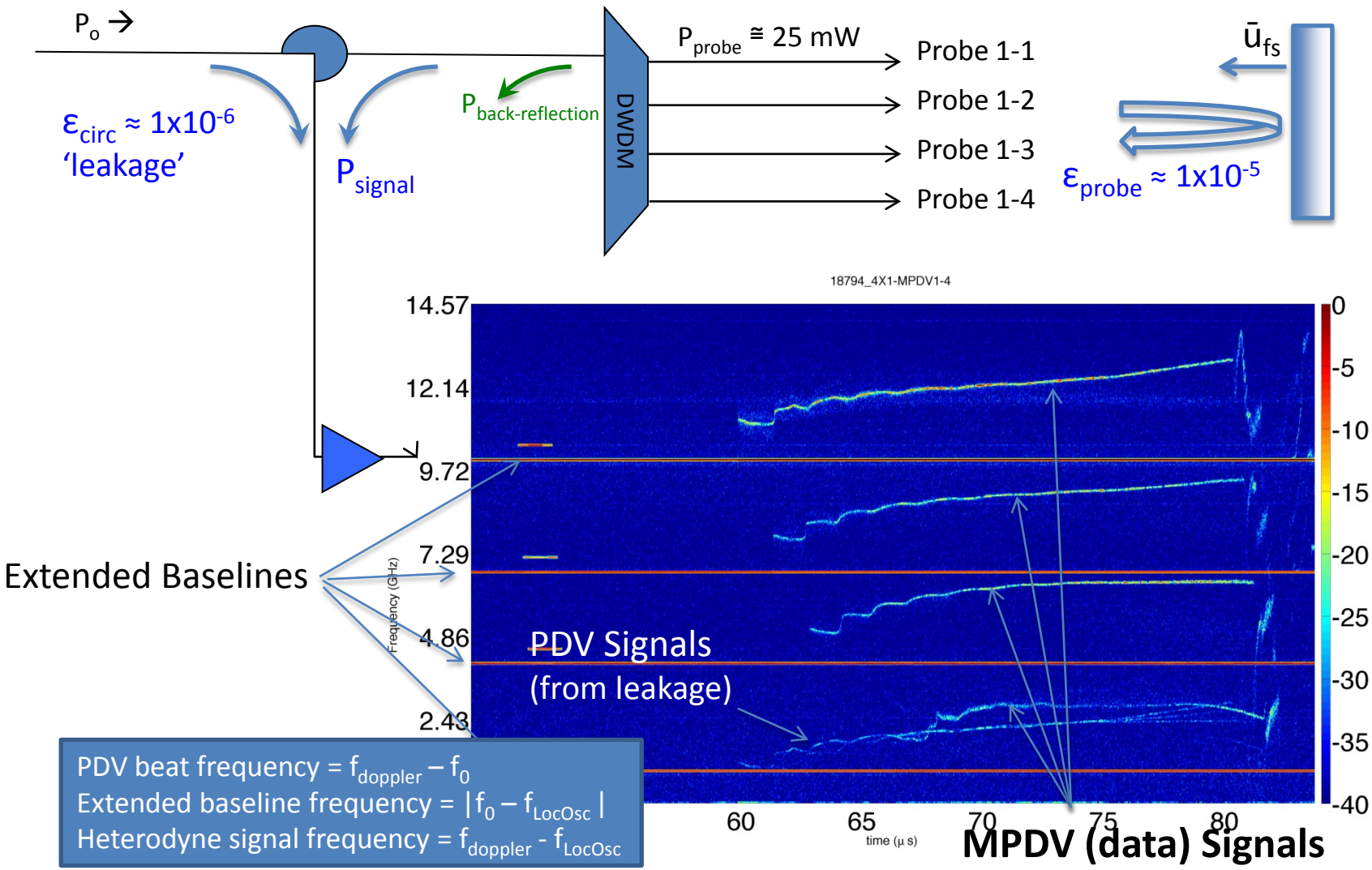
Optical Pre-Amp, Gain = 200
Erbium-Doped Fiber Amplifier (EDFA)
… allows for laser-safe operations

HOW MPDV WORKS: OPTICAL HETERODYNE

Provides frequency shifting, i.e., makes use of frequency space



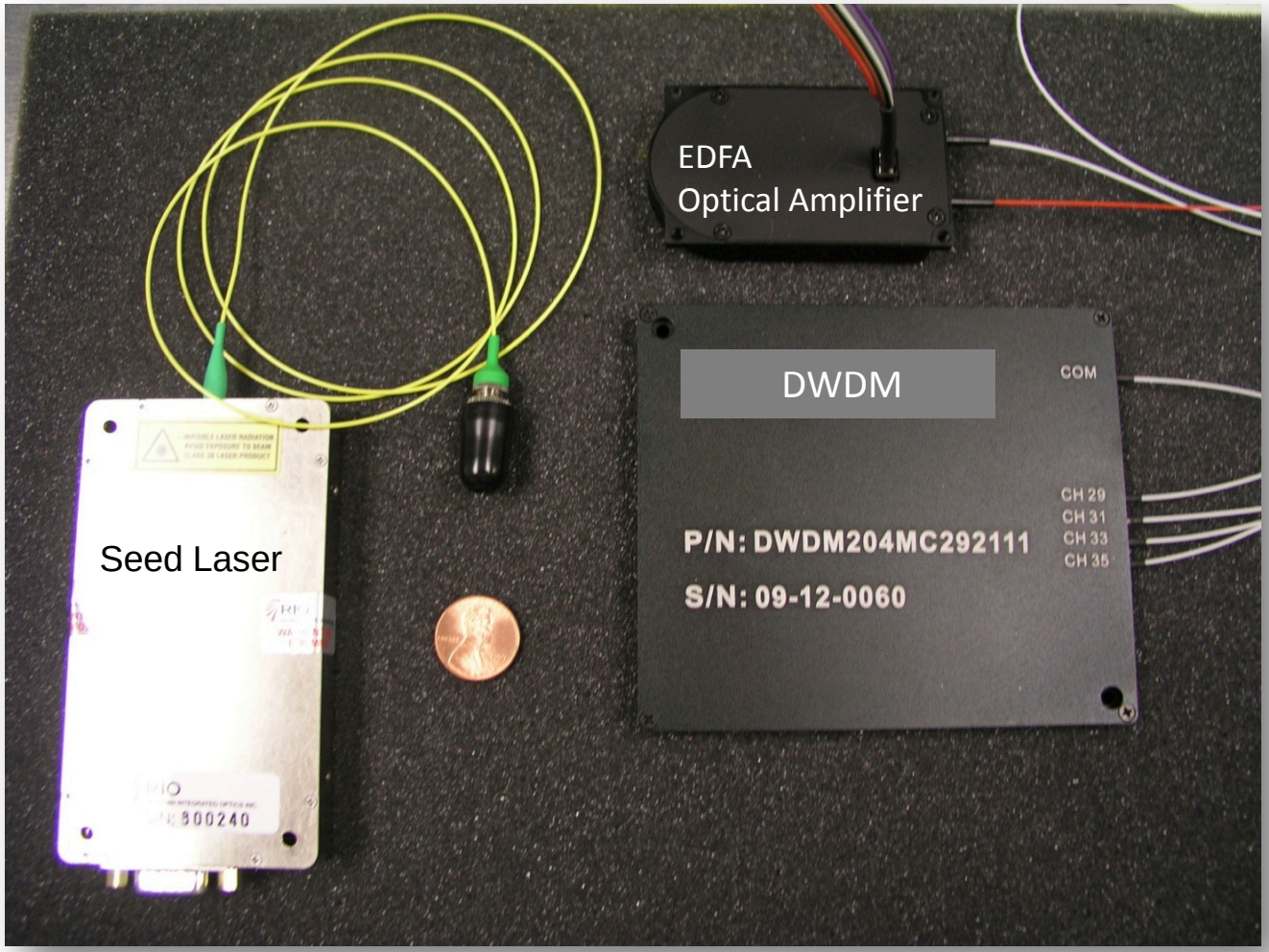
HOW MPDV WORKS: PERFORMANCE



PDV beat frequency = $f_{doppler} - f_0$
Extended baseline frequency = $|f_0 - f_{LocOsc}|$
Heterodyne signal frequency = $f_{doppler} - f_{LocOsc}$

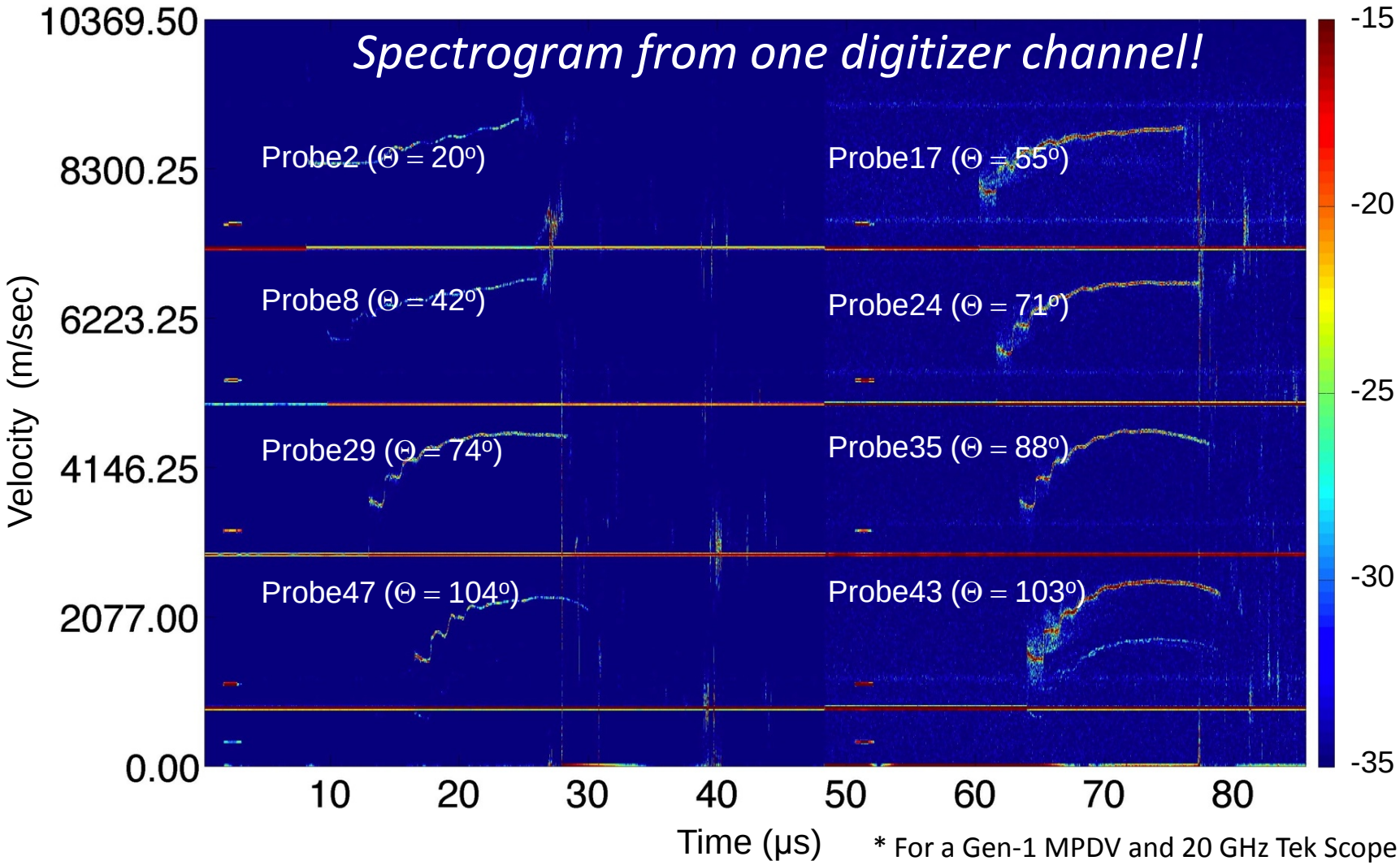
HOW MPDV WORKS: TELECOM COMPONENTS

Commercially available and economical components



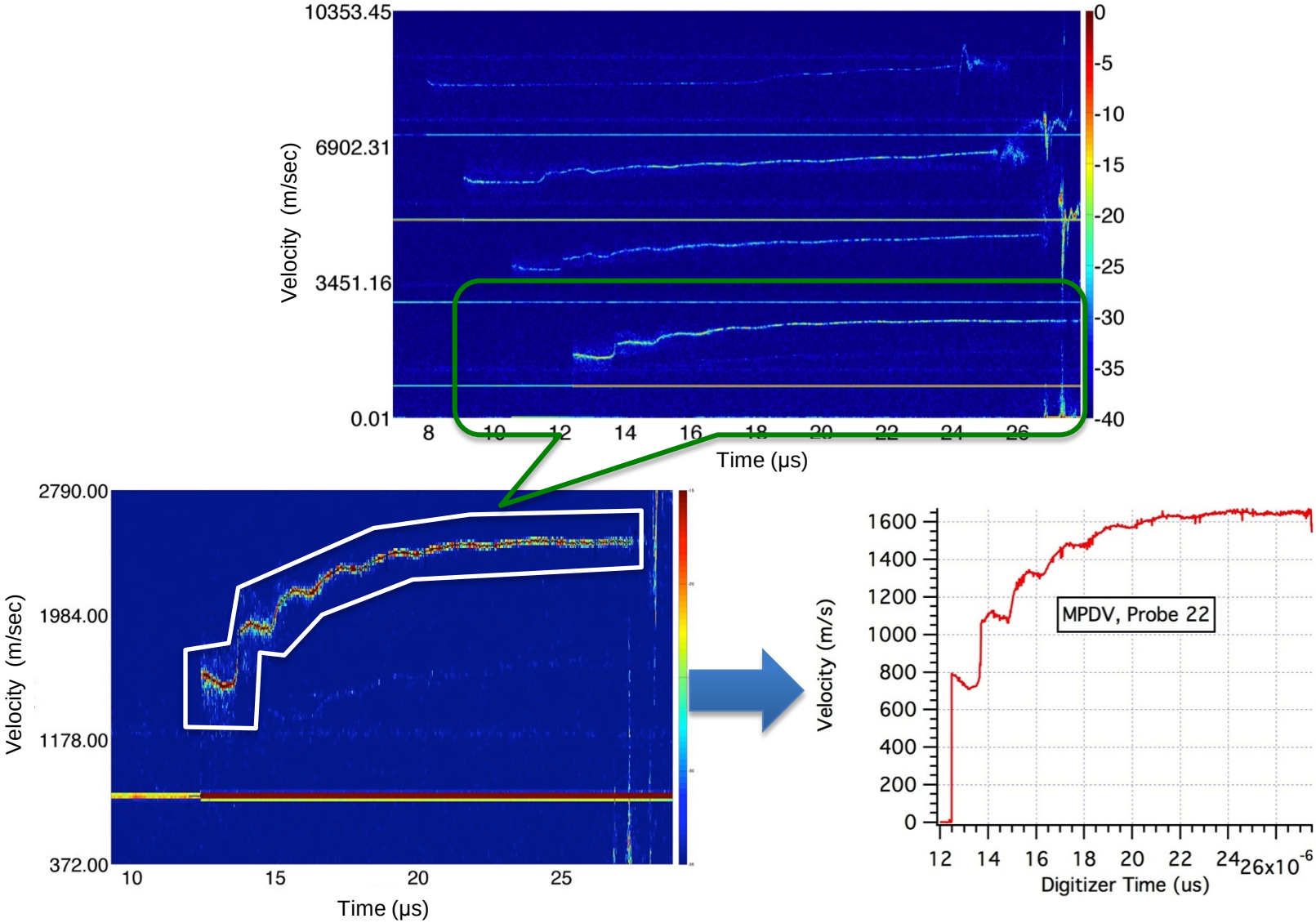
MPDV DATA: 8x MULTIPLEXING

Cost Savings: PDV ~ $50K per probe vs. MPDV ~ $10K * per probe



* For a Gen-1 MPDV and 20 GHz Tek Scope

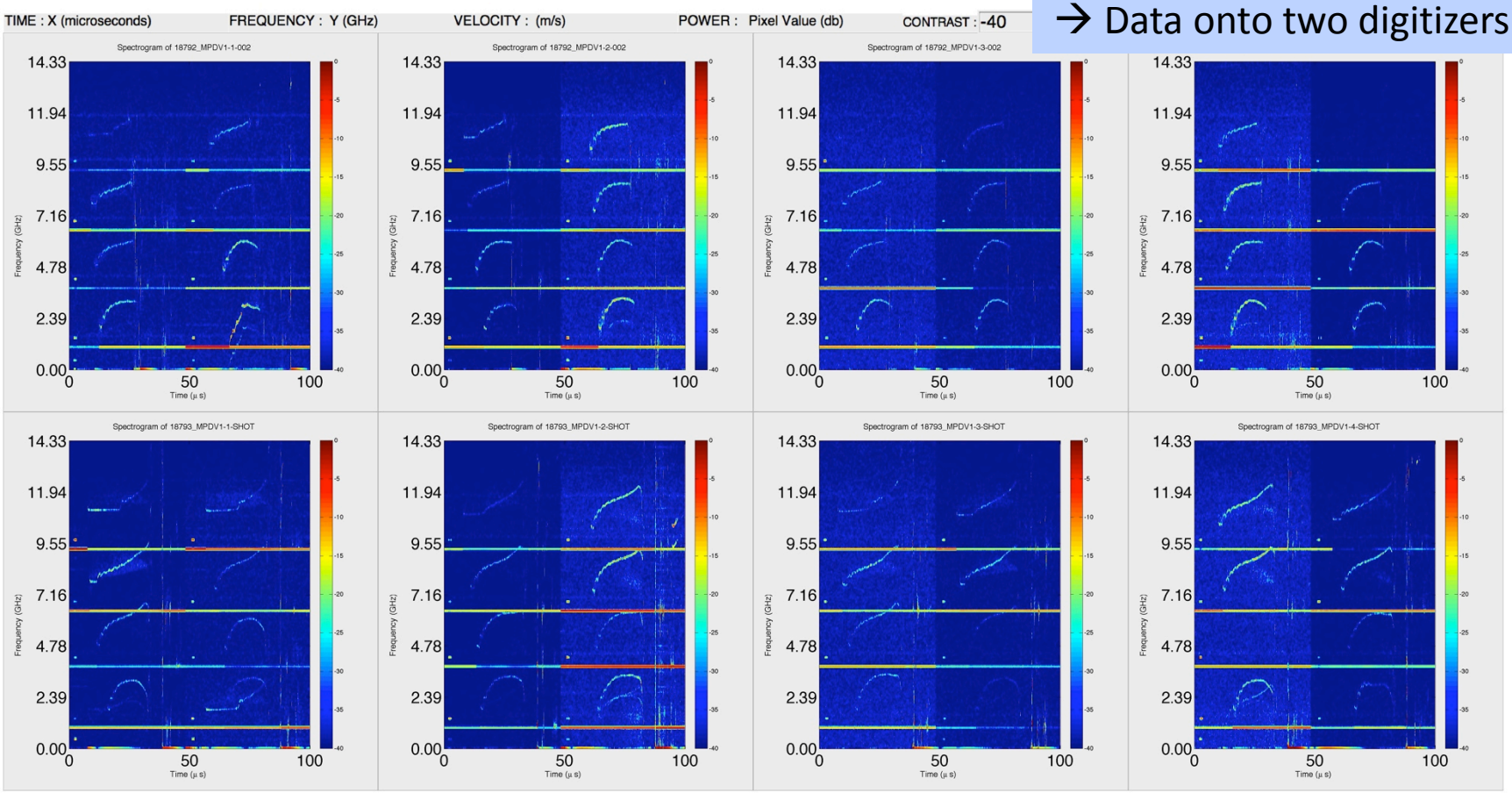
MPDV DATA ANALYSIS



HIGH-DEFINITION VELOCIMETRY: MEASURING A 'POT LOAD' OF DATA

- Less reliance on experimental symmetries and extrapolation from a small number of measurements

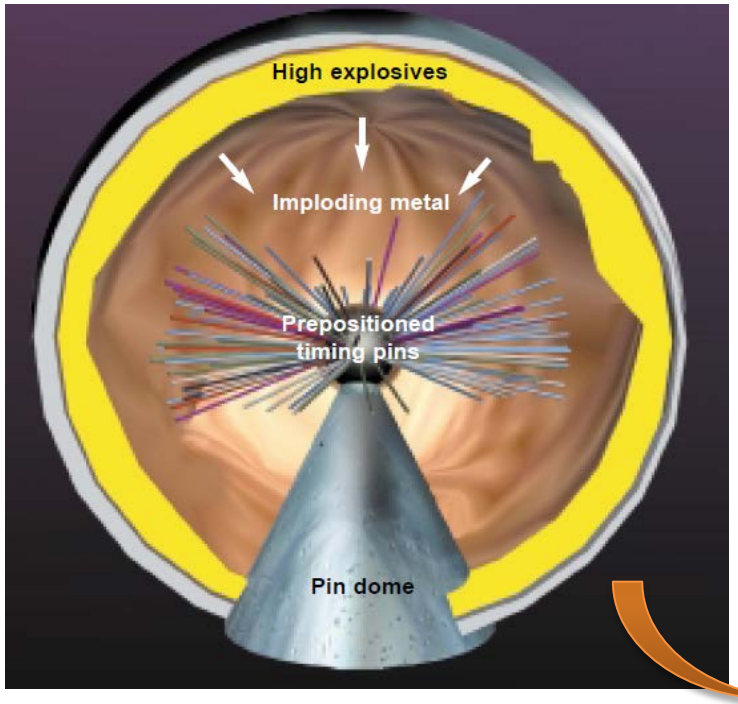
64 target points (probes)
→ Data onto two digitizers

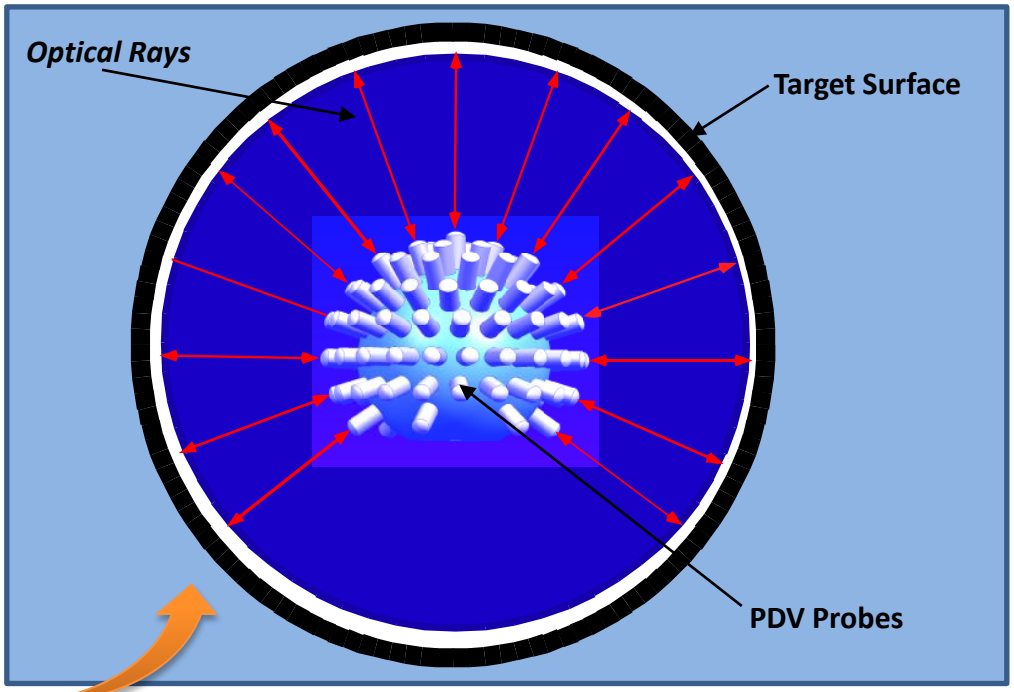


WHAT WE'VE LEARNED

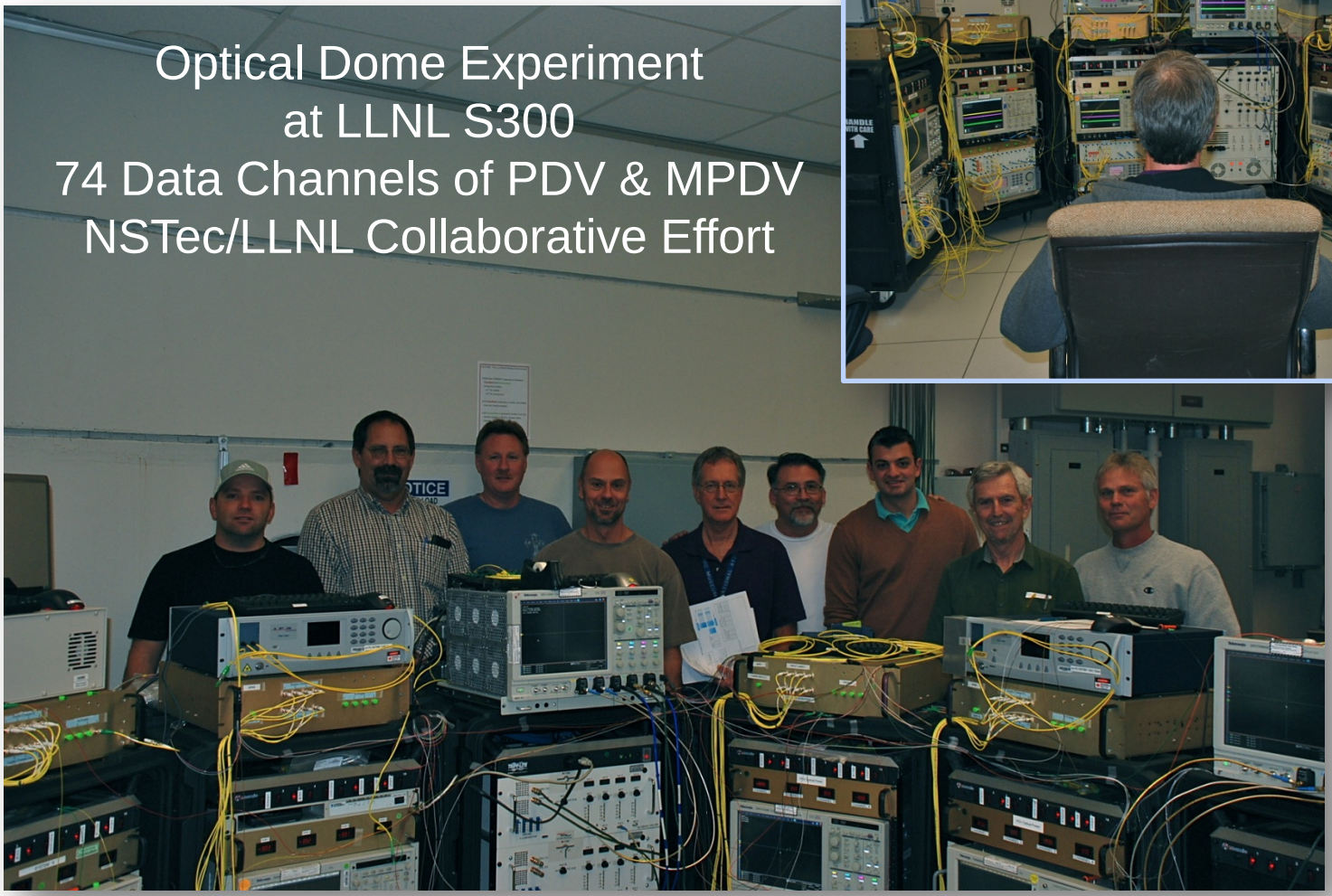
- **Photonic Technologies**. We've evaluated and leveraged telecom components–optical amplifiers, wavelength multiplexers, and seed lasers–to provide an economical, compact and rugged approach to system architecture.
- **Wavelength Division Multiplexing & Fourier Analysis**. Fourier transform data analysis is robust and capable of discriminating simultaneous data traces recorded onto a single digitizer channel.
- **Proof-of-Principle Demonstrated**. Successfully fielded demonstration MPDV system on shock driven experiments.
- **Enabling capability**. Ability for future 'integrated' experiments with 100(s) of data channels.
- **Improved measurement capabilities**
  - ✓ **Increased velocity range**. Optical down-shifting doubles max velocity range.
  - ✓ **Direction-of-travel**. Discern red shift from blue shift, e.g., oscillation.

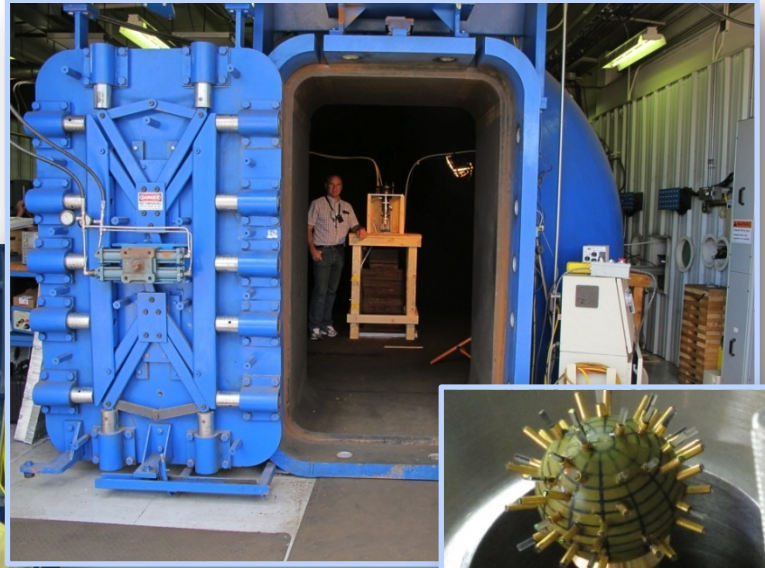
APPLICATIONS FOR NUCLEAR SECURITY





COLLABORATIVE EFFORTS FOR STOCKPILE STEWARDSHIP



SDRD: ADDING VALUE TO PEOPLE, ENABLING AND PROVIDING PROGRAMMATIC PAY-OFF

FY 2010 SDRD work on MPDV was continued under diagnostic development programs and eventually applied to optical dome (and other) experimental programs at LANL and LLNL