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Title:	Proton Radiogrphy capabilities at Los Alamos National Lab
Author(s):	Dale Tupa
Intended for:	Ohio State University Materials Science Seminar

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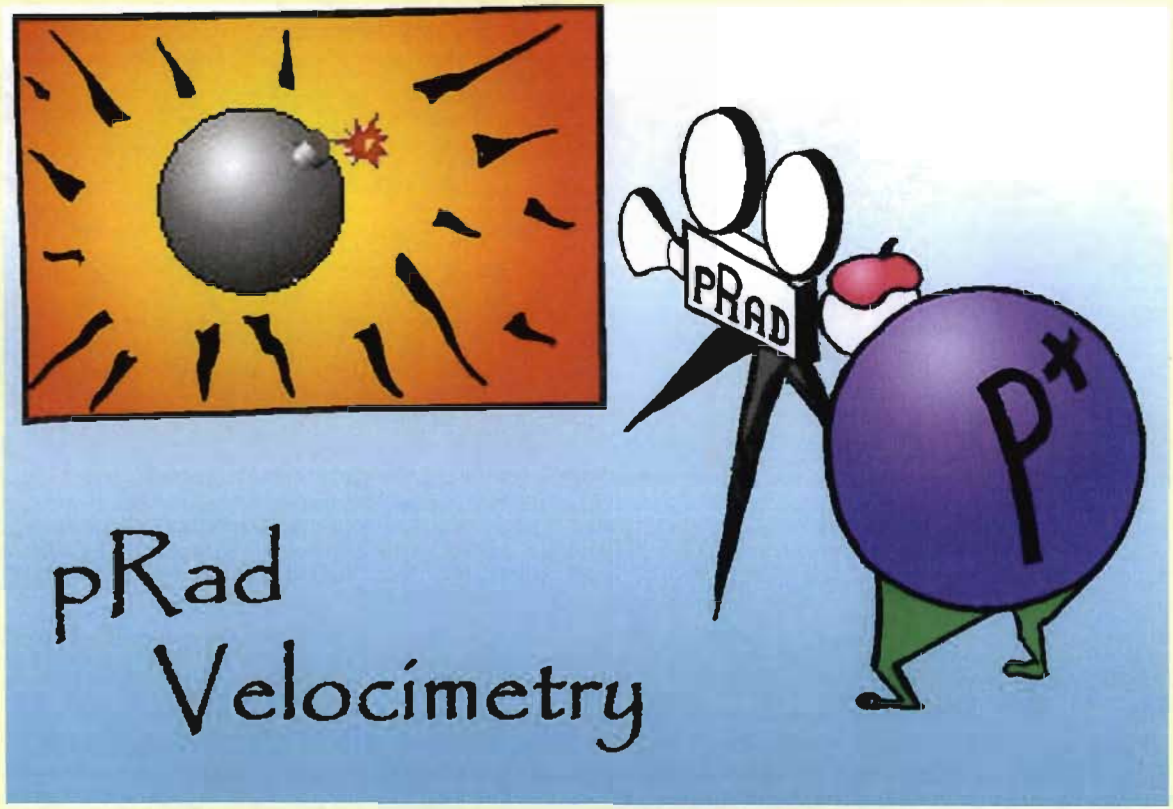
Form 836 (7/06)

Proton Radiography capabilities at Los Alamos National Lab

Dale Tupa



Proton Radiography capabilities at Los Alamos National Lab

Dale Tupa

Abstract: Proton Radiography (pRad), invented at Los Alamos National laboratory, employs a high-energy proton beam to image the properties and behavior of materials driven by high explosives. We will discuss features of the LANL pRad facility and describe some recent experiments performed there, highlighting optical diagnostics for surface velocity measurements. This talk will be given at a level accessible to graduate and undergraduate students.

University of Nebraska Physics Department Colloquium 4/21/11

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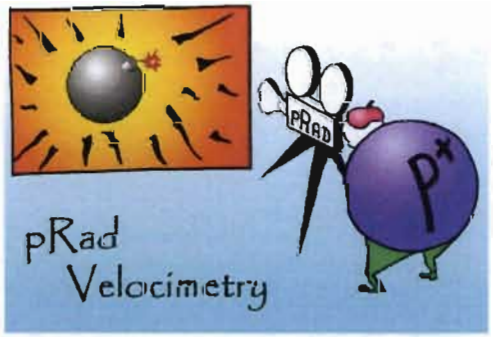

The LANL Proton Radiography facility (pRad) velocimetry team:

Dale Tupa, Brian J. Hollander

Other members of the pRad team:

Joe Bainbridge, Bethany Brooks, Eduardo Campos, Deborah Clark, Camilo Espinoza, Jeremy Fait, Gary Grim, Gary Hogan, Nick King, Kris Kwiatkowski, Doug Lewis, Armando Lopez, Julian Lopez, Robert Lopez, Luke Lovro, Wendy McNeil, Fesseha Mariam, Mark Marr-Lyon, Alfred Meidinger, Frank Merrill, Deborah Morley, Christopher Morris, Matthew Murray, Paul Nedrow, Paul Rightley, Alexander Saunders, Cynthia Schwartz, Amy Tainter, Terry N. Thompson, Josh Tybo, Aleksandra Vidisheva

Other pRad collaborators (for velocimetry work at pRad and/or data shown in this presentation):

B Briggs, W Buttler, M Byers, D Dennis-Koller, D DeVore, S DiMarino, G Dimonte, E Ferm, M Furlanetto, M Furnish, C Gallegos, B Grieves, R Hall, J Hammerberg, A Harrison, R Hixson, D Holtkamp, D Huerta, J Huttenberg, A Iverson, J Lugo, S McDaniel, M Madlener, E Marsh, R Olson, D Oro, M Osborn, T Otteson, T Pierce, P Rigg, M Rightley, V Romero, A Rutkowski, D Shampine, B Simpson, L Tabaka, M Teel, G Terrones, W Tuzel, S Walker, R Williams, J Young, D Youngs, M Zellner

*** velocimetrists in red

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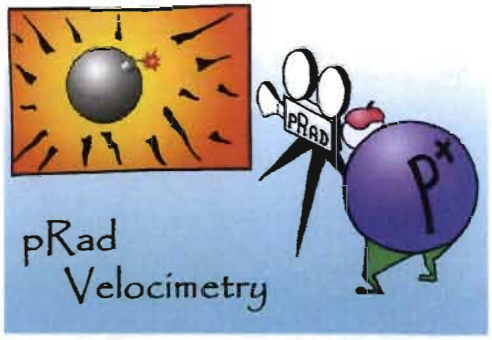
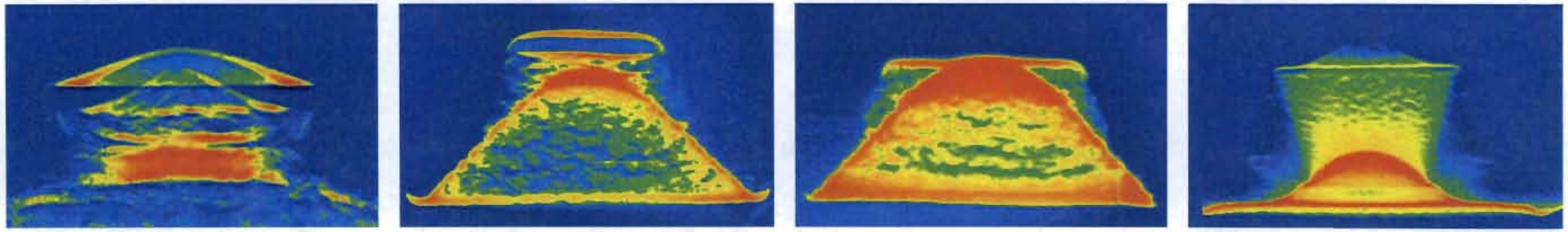


Proton Radiography at Los Alamos National Lab:

Material and component characterization under dynamic conditions for stockpile stewardship without underground testing



Aluminum Copper Tantalum Tin

A series of proton radiographs of disks that have been explosively shocked from below. The radiographs reveal the internal structure of the materials in these extreme conditions. For example, the aluminum sample shows the formation of layers of spall while the tin sample displays characteristics of melting.

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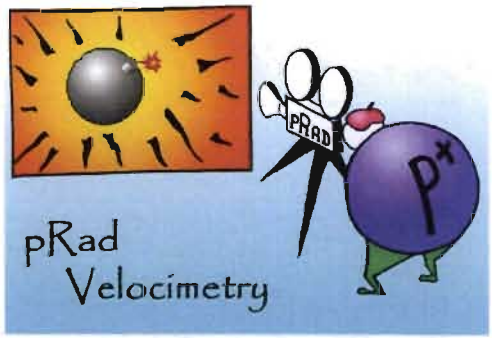
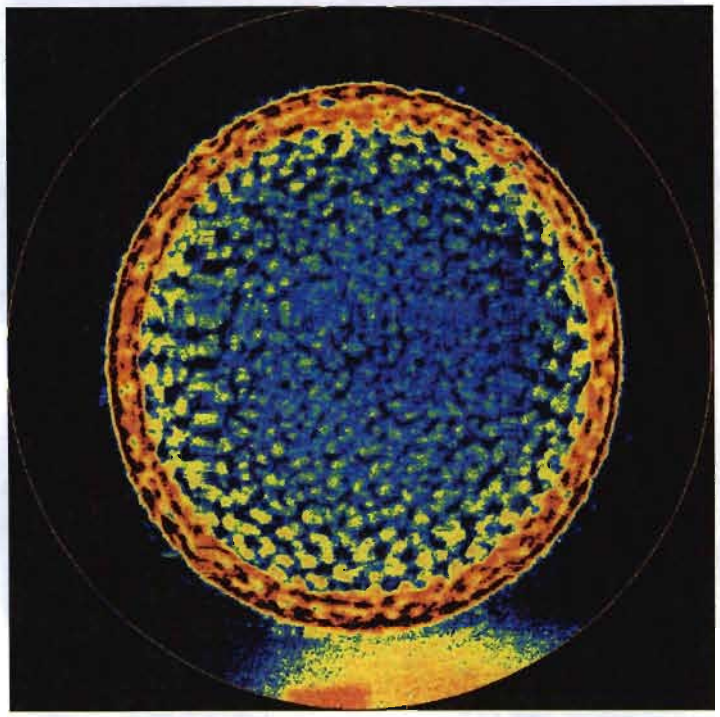


Why protons ?
(1) Penetrating power



The high energy of the beam gives it a penetrating power sufficient to see fine internal details in objects of a wide variety of densities, such as lead, plutonium, uranium, or high explosives -- shedding light on features under extreme conditions that are difficult to discern with x-ray imaging.

A hemisphere of high explosives is placed inside a hollow hemisphere of a uranium alloy and radiographed to study the failure mechanisms of U6Nb.

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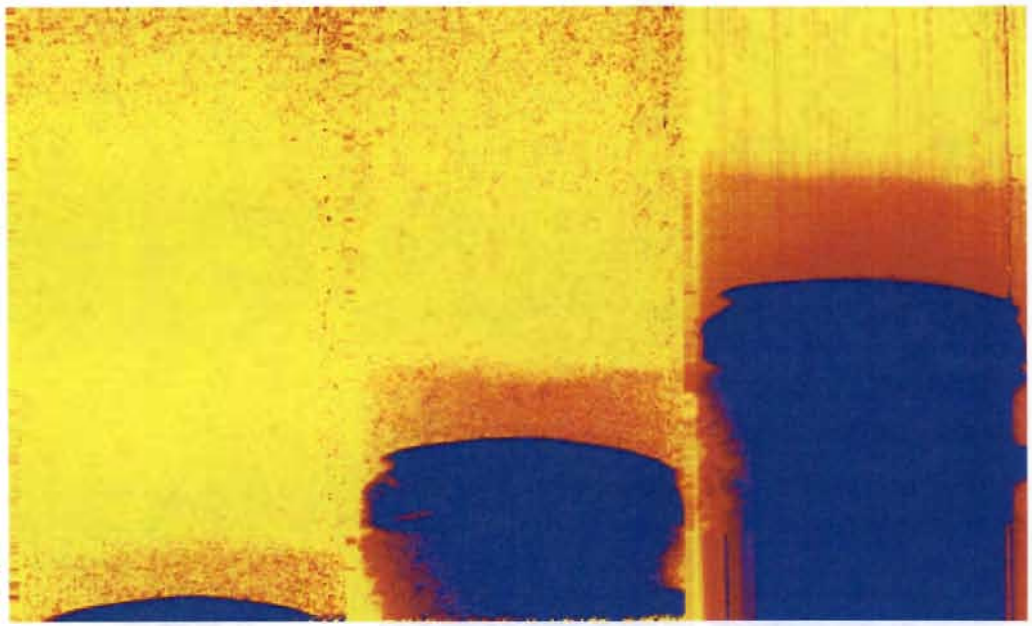
pRad
Velocimetry

Why protons ?
(2) Charged particles can be transported and imaged



Since the proton beam is composed of charged particles, the beam may be focused with magnetic lenses to form images of the object far away from the interaction region for several great advantages, for example, it is possible to enhance the signal from selected materials.

These images depict an aluminum flyer plate traversing, from the bottom, a cylinder of xenon gas. The "bow wave" of denser shocked xenon gas can be seen as the reddened area preceding the flyer. Proton radiography is capable of imaging this tiny change in xenon thickness of 0.055g/cm2.

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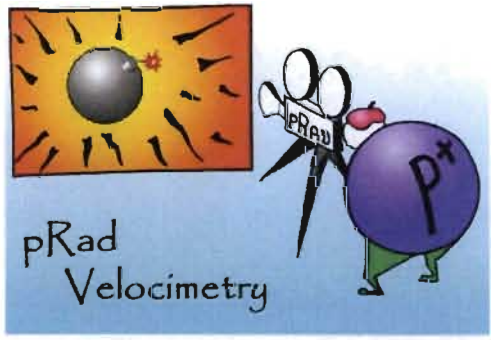
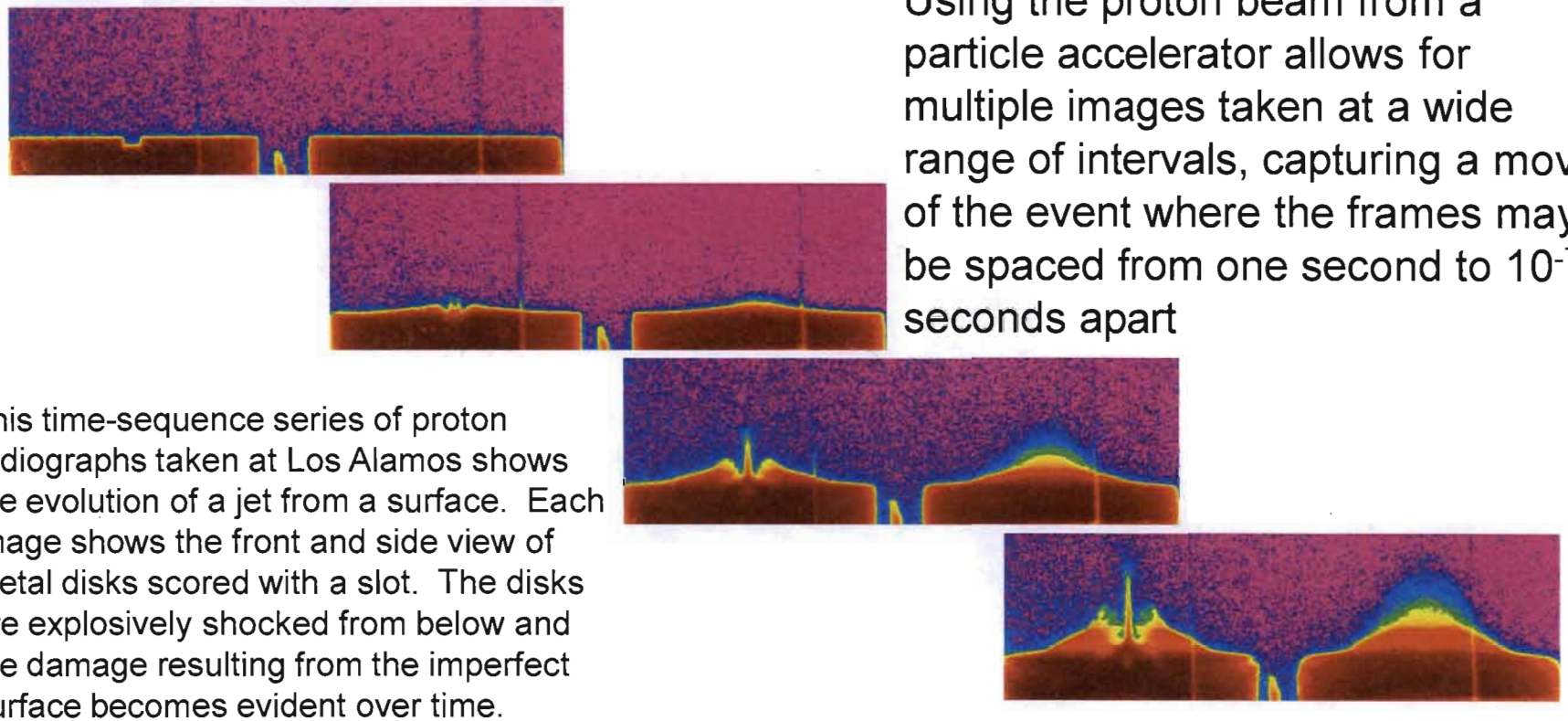


Why protons ?
(3) multiple images allow for radiographic movies



Using the proton beam from a particle accelerator allows for multiple images taken at a wide range of intervals, capturing a movie of the event where the frames may be spaced from one second to 10^{-7} seconds apart

This time-sequence series of proton radiographs taken at Los Alamos shows the evolution of a jet from a surface. Each image shows the front and side view of metal disks scored with a slot. The disks are explosively shocked from below and the damage resulting from the imperfect surface becomes evident over time.

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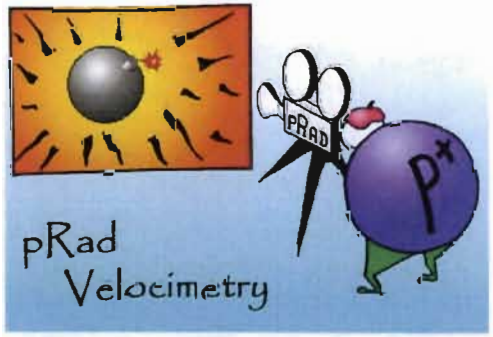

Why protons ?
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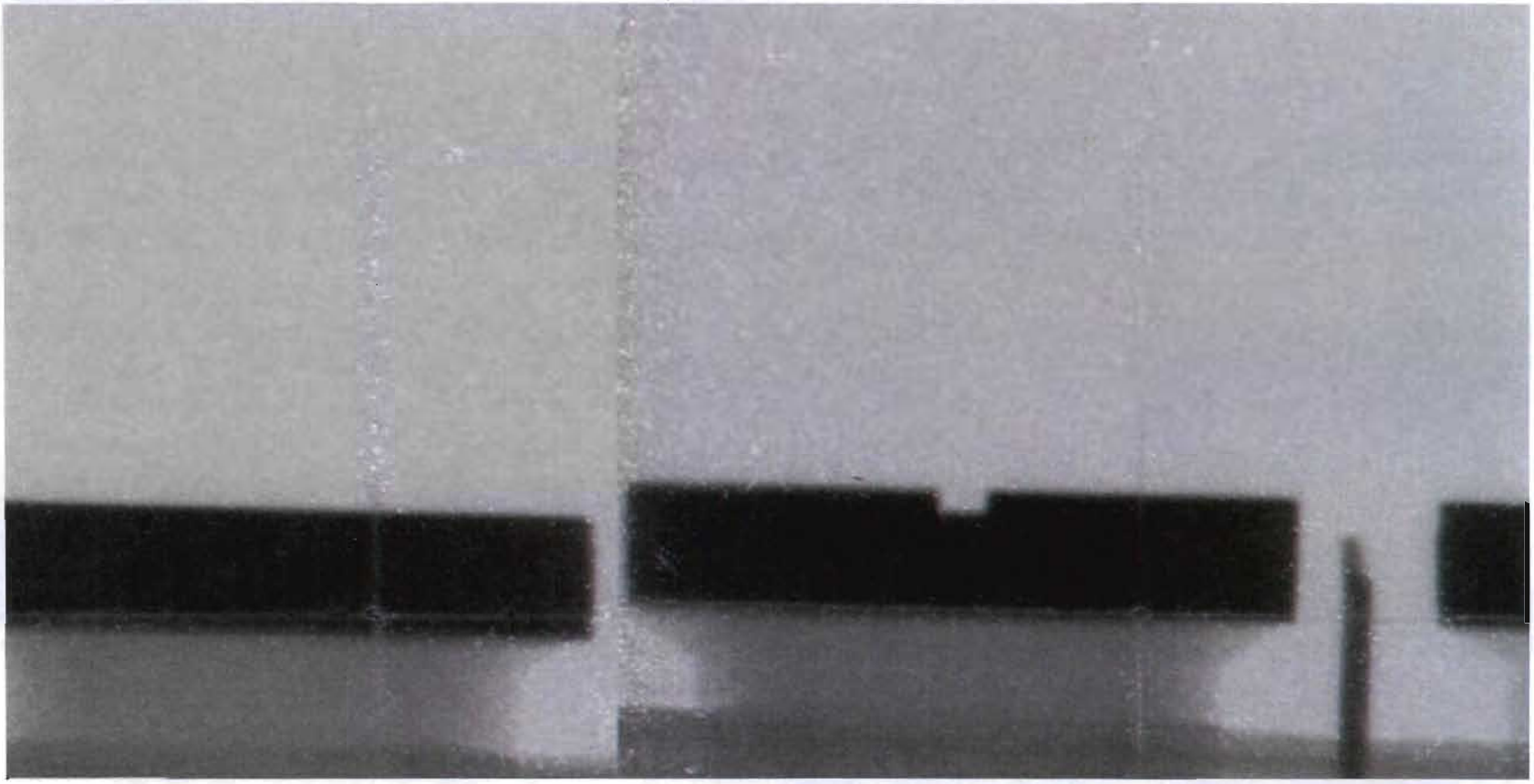

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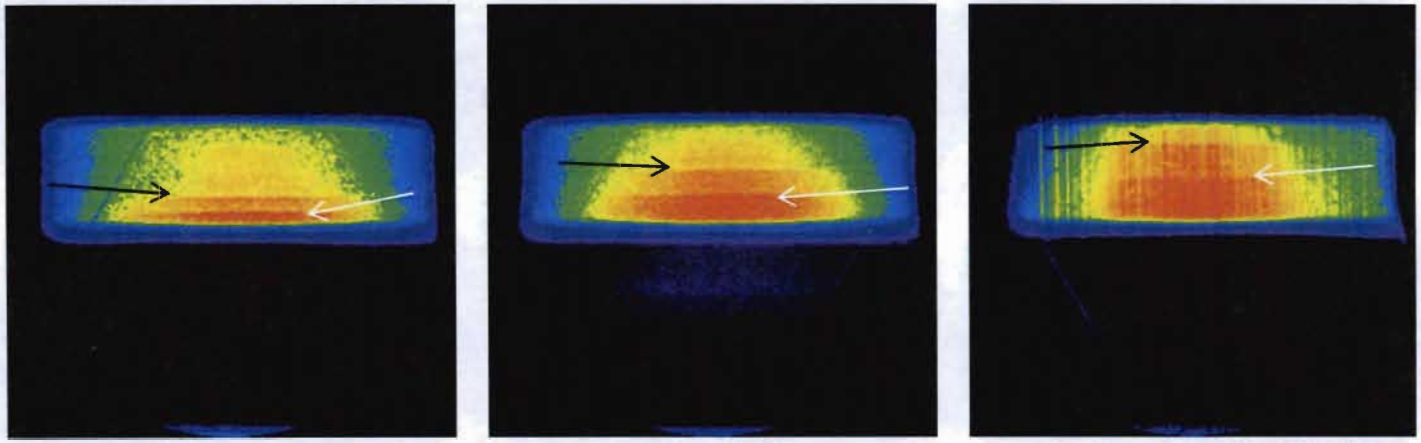
pRad
Velocimetry

Why protons ?
(4) quantitative thickness measurements

Proton radiography makes possible quantitative measurements of material densities under extreme conditions, providing a diagnostic capable of predicting the performance of untested weapons components or aged components in the stockpile. This precision makes possible a range of fundamental science measurements as well.



An iron disk hit from below by an aluminum flyer plate displays a shock front (denoted by the black arrows) and a region of denser iron (white arrows), where the extreme pressures have induced a phase change

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pRad
Velocimetry

How pRad works
(1) proton beam is provided by LANSCE

The efficacy and versatility of pRad stems from the ability to produce multiple proton pulses in an accelerator and use magnets to manipulate the proton beam. The beam for pRad is provided by the Los Alamos Neutron Science Center (LANSCE.) The proton beam is available in a wide range of timing sequences to meet the specific needs of each experiment. In this picture of the Los Alamos Proton Radiography facility, the proton beam enters from the left-hand side.

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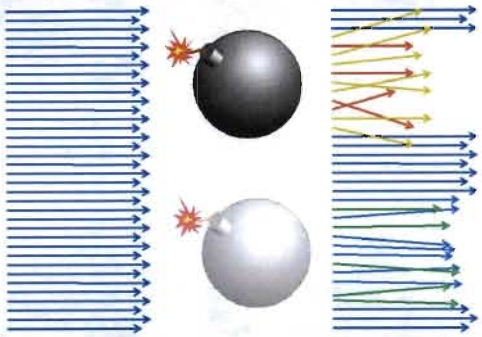
pRad
Velocimetry

How pRad works
(2) protons interact with the test object



The interaction region is in a containment vessel specially designed to withstand the explosions that occur during experiments where protons pass through the test object. Here, protons are shown (in an exaggerated manner) to lose more energy and be deflected more if they traverse thicker or denser parts of the object than if they pass through thinner parts.

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Velocimetry

How pRad works
(3) protons are imaged to the camera locations

Strong magnets are used as lenses for the proton beam. (The magnets are the orange blocks – four magnets with drift regions make up one lens that images the interaction region.) This imaging process gives protons huge advantages over x-rays for imaging: The image location is far enough from the interaction region that background noise from scattered protons is minimized and explosives from the experiment do not damage the detectors. Different lens configurations can be used to magnify the view – 3x and 7x magnifiers have been built and used at LANSCE. Highly radioactive objects can be imaged without their radiation "fogging" the image.

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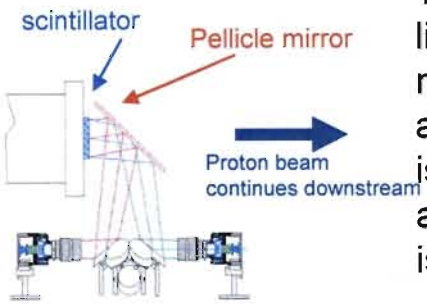
pRad
Velocimetry

How pRad works
(4) cameras capture the proton images



The protons are imaged at camera stations in gaps in the beam line. Protons pass through a scintillator sheet which is viewed by multiple cameras. Each camera is gated on a different proton pulse and takes one frame of the movie. To the right of the camera station is seen another magnetic lens setup bringing the proton beam to another camera station so it can be imaged again. Currently, pRad is capable of taking 37 images in each experiment.

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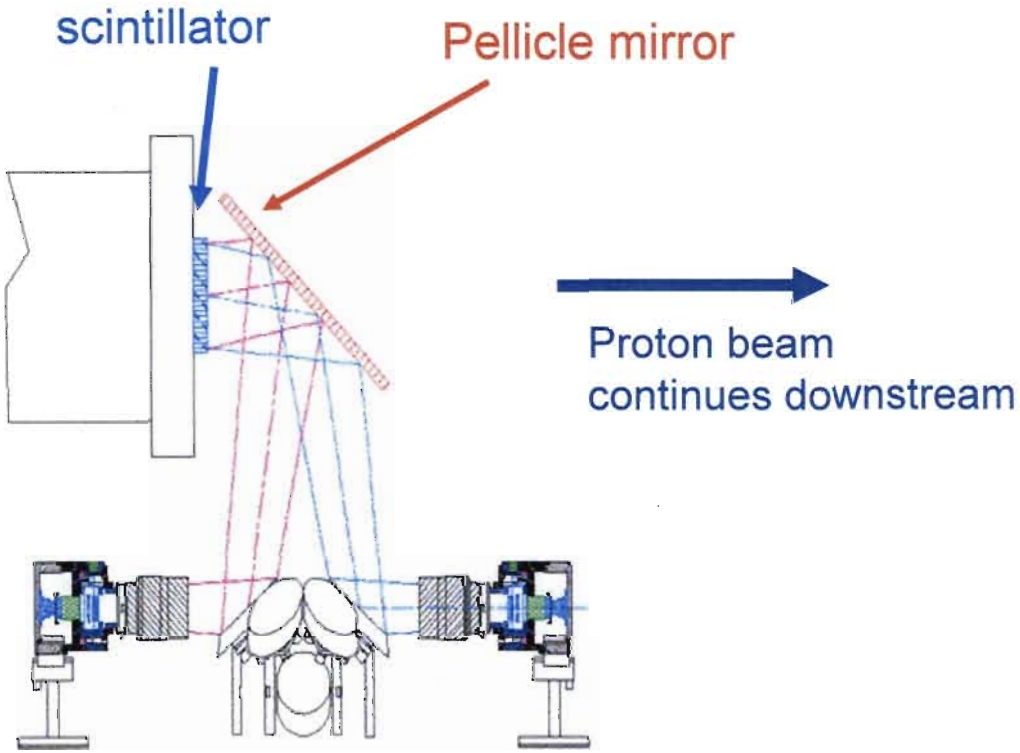
How pRad works
(4) cameras capture the proton images



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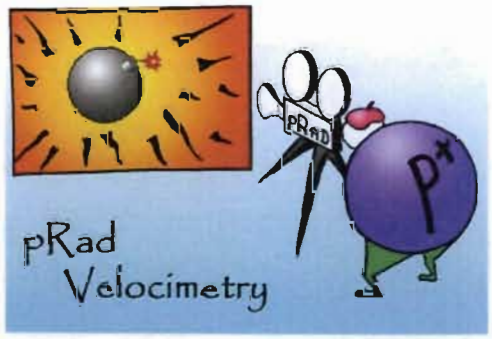
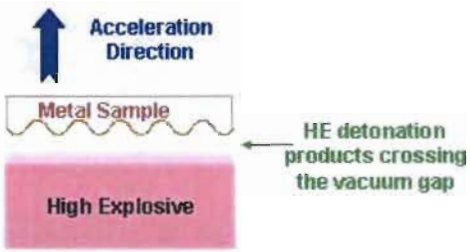
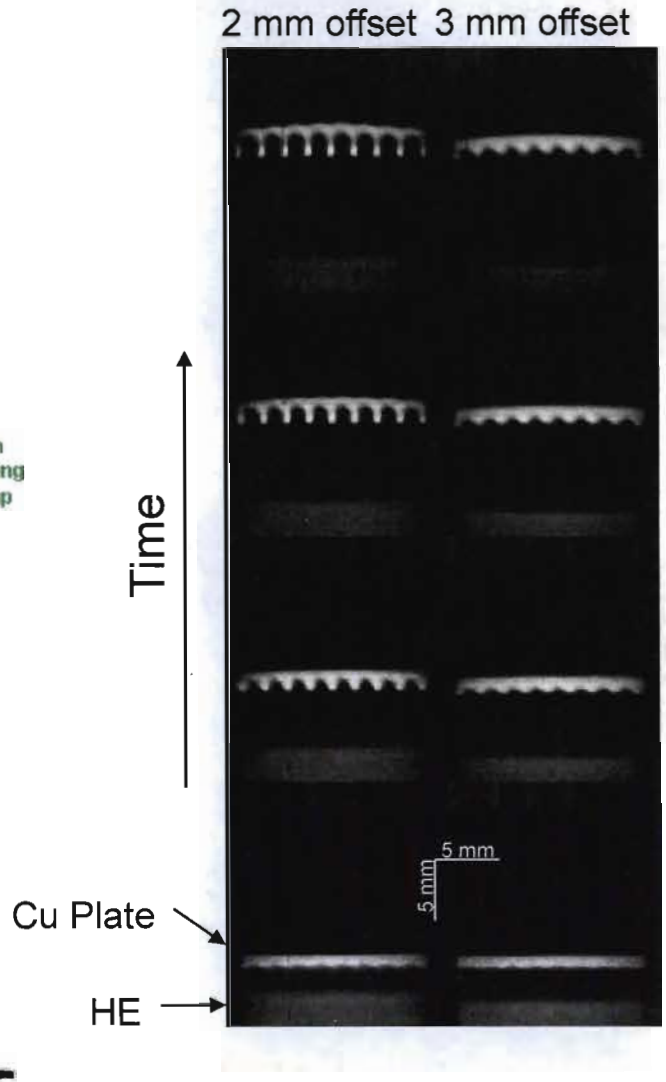
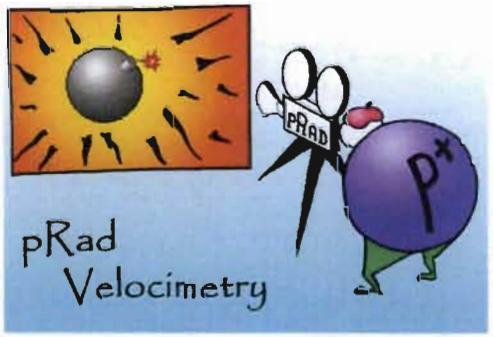


pRad experiments:
High-Strain-Rate Material Characterization





pRad is used to diagnose dynamic materials under extreme pressures, strains, and strain-rates. Here, the detonation products from high explosives (HE) rapidly accelerate a metal coupon without a shock. A sinusoidal (ripple) pattern has been machined on the coupon surface facing the HE, which encourages the onset of Raleigh-Taylor instability growth as the coupon accelerates. The strength of the metal coupon can be inferred from the growth rate of this instability. This technique has been used to understand the high-strain-rate strength of different metals manufactured under various processing techniques.



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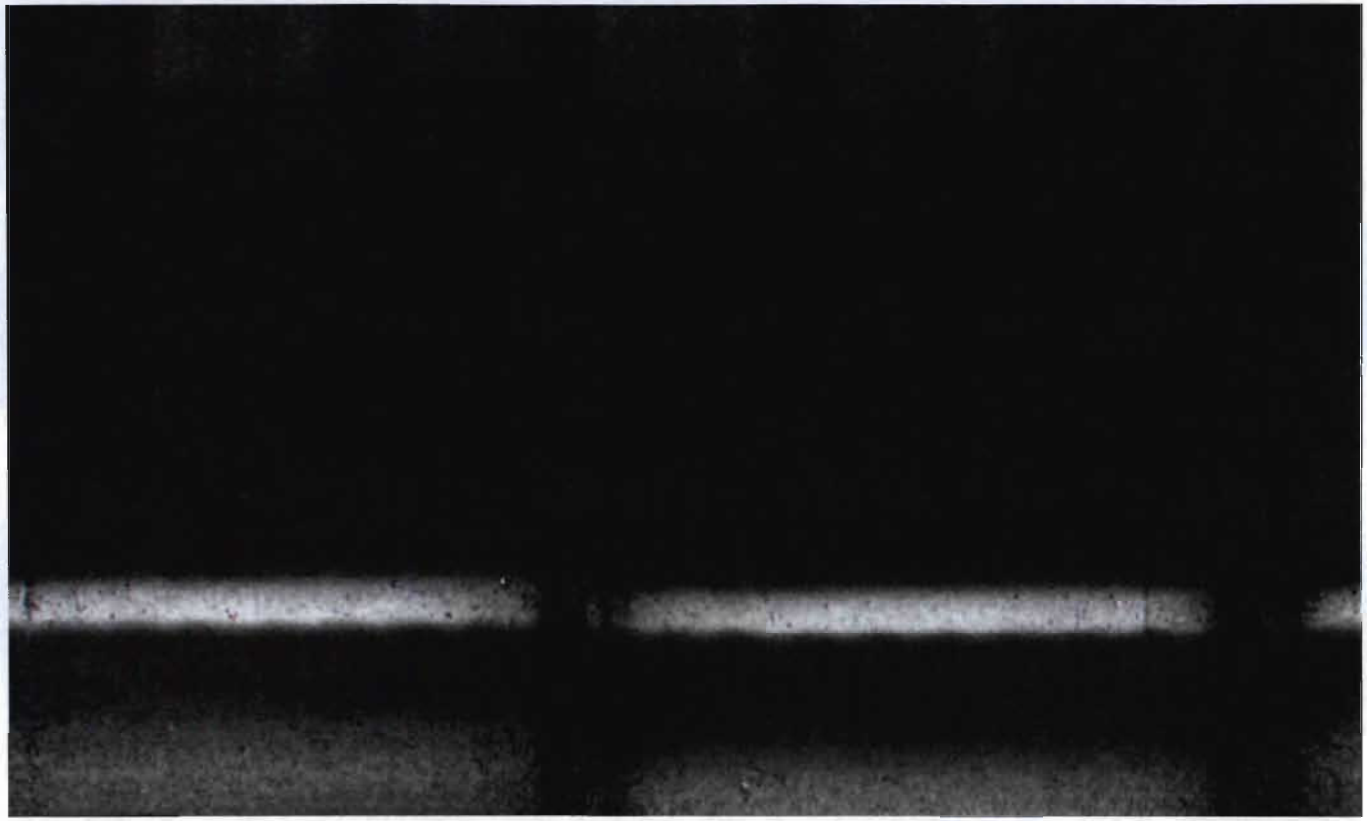
pRad experiments:
High-Strain-Rate Material Characterization



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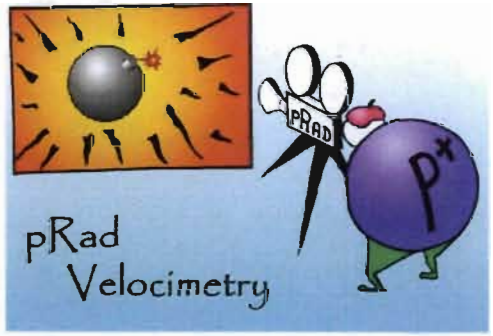
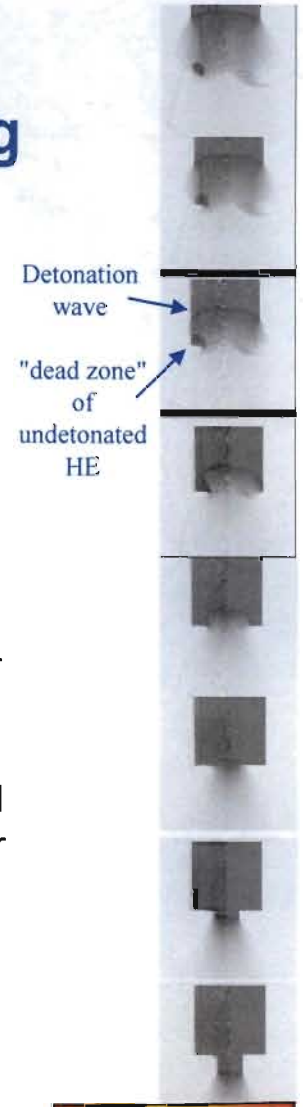
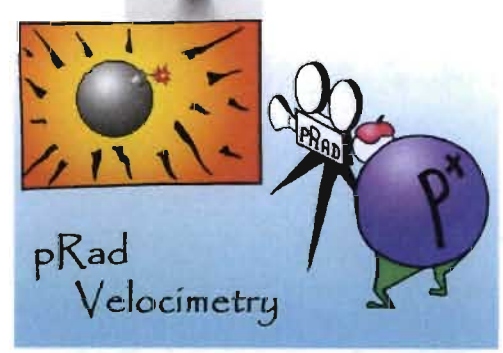


pRad experiments:
HighExplosives Burn Corner Turning



Insensitive HE is used in nuclear weapons to make them safer. Proton radiography experiments help assure the reliability of weapons incorporating insensitive HE by fully characterizing the detonation properties. The picture on the right, from bottom to top, shows a time series of radiographs (left of the centerline) compared to a series of simulations (right of the centerline) for a detonation wave propagating through a cylinder of HE into a second HE cylinder of larger diameter. With insensitive HE, some undetonated HE remains when the detonation wave tries to turn the corner. The simulation did not predict this dead zone. This experiment provided valuable information for modeling efforts for stockpile stewardship.



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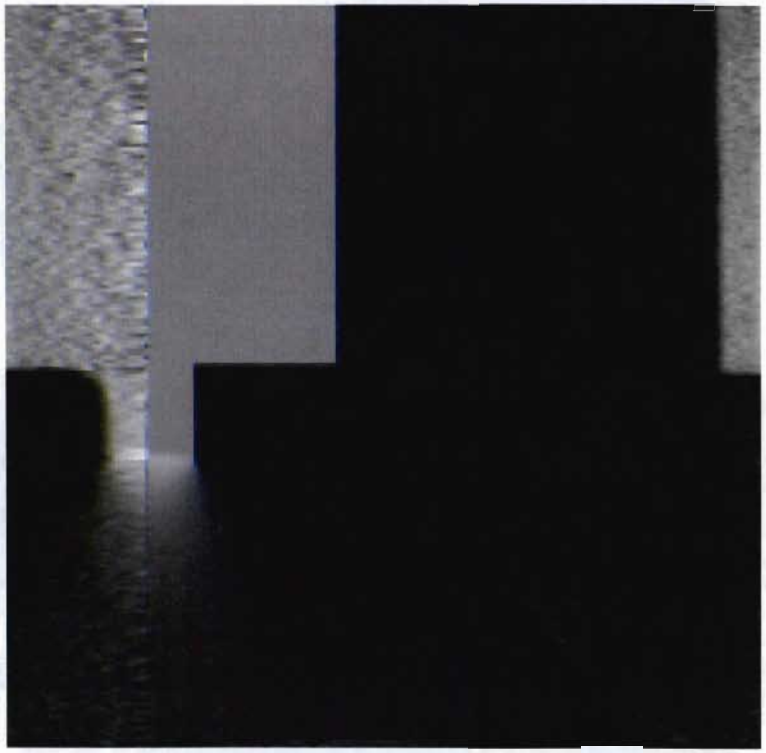
pRad experiments:
HighExplosives Burn Corner Turning



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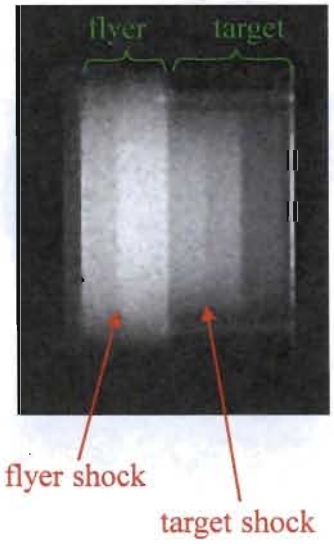
pRad
Velocimetry

pRad experiments:
Material Characterization with a Powdergun



In addition to explosive experiments in containment vessels, the pRad team conducts experiments with a powdergun. This series of experiments with the pRad powdergun demonstrates the ability to observe the flyer impact and measure the particle and shock wave velocities in the materials. These experiments have provided direct density measurements of shocked metals with very high accuracy (<1%) and these data have been used to validate existing Equations of State for the materials studied. The radiograph at left shows an Al flyer plate (larger diameter) and an Al target shortly after impact.

Another series of powdergun experiments displays the development of two shock waves in shock-compressed iron due to a shock-induced solid-solid phase transformation.

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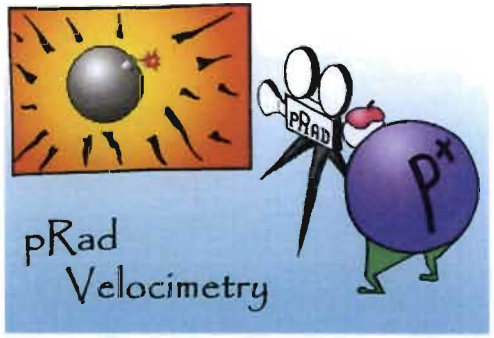
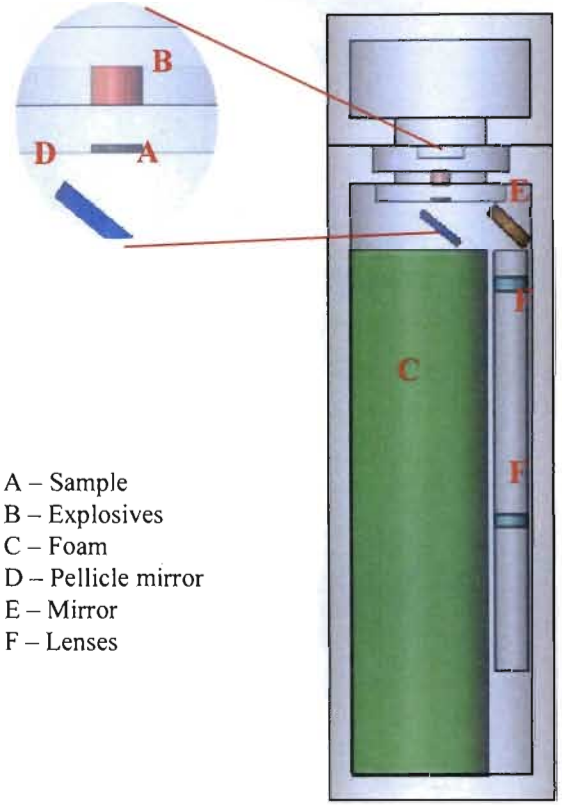
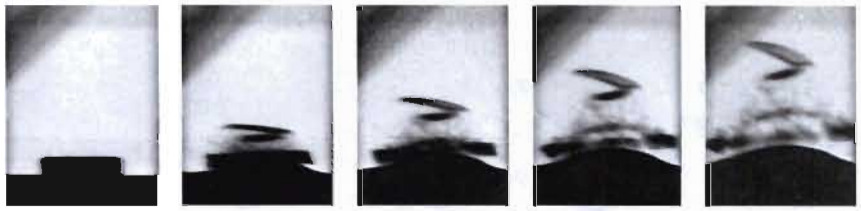


pRad experiments:
Contained "Thermos" experiments



A – Sample
B – Explosives
C – Foam
D – Pellicle mirror
E – Mirror
F – Lenses

The penetrating power of protons makes possible detailed radiographic images of experiments conducted in sealed metal containment vessels. The sealed vessel provides the safety envelope to study samples of hazardous materials such as beryllium and plutonium. Pictured at left is a containment canister designed to catch the shocked sample in foam for later metallographic examination and also allow for optical velocimetry of the front surface of the sample. Below is a time series of radiographs of tin from this same configuration to compare its behavior to model predictions.



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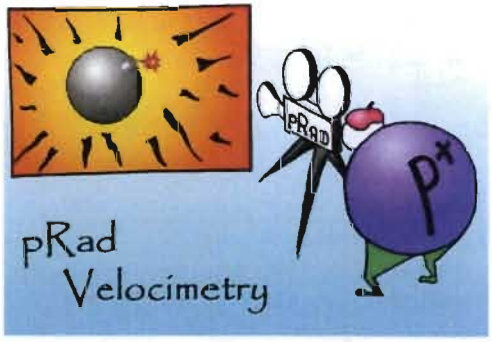
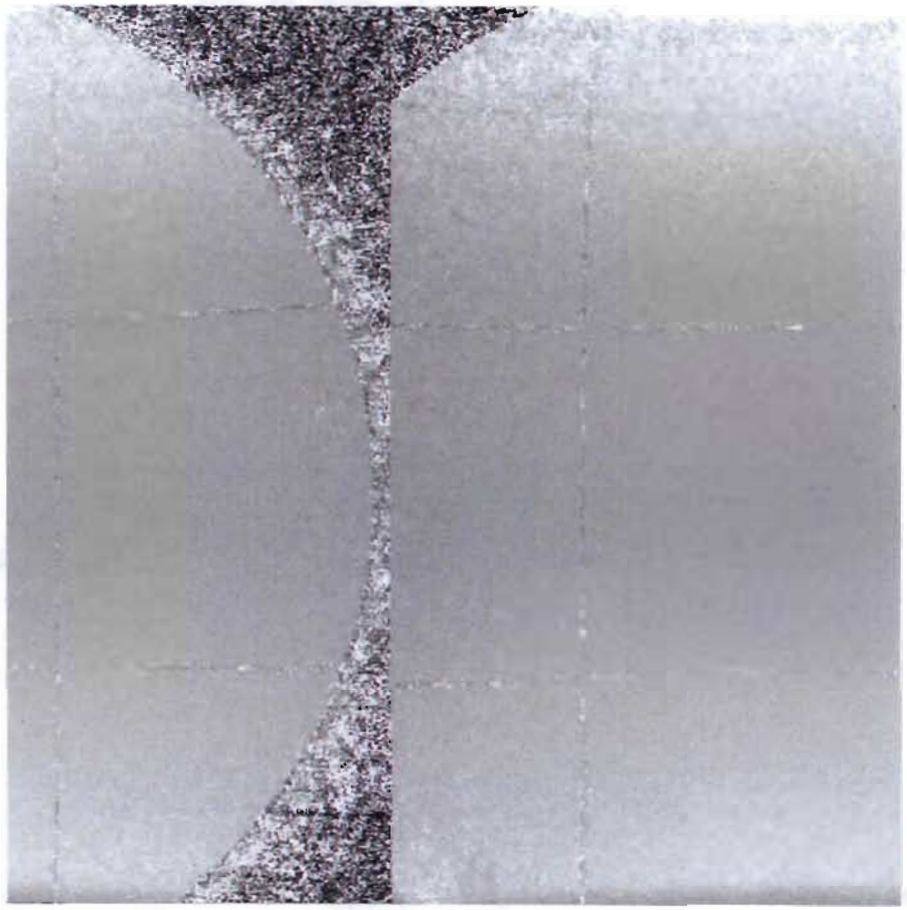


pRad experiments:
Contained "Thermos" experiments



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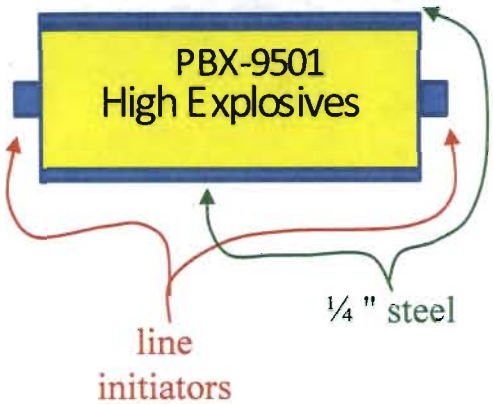
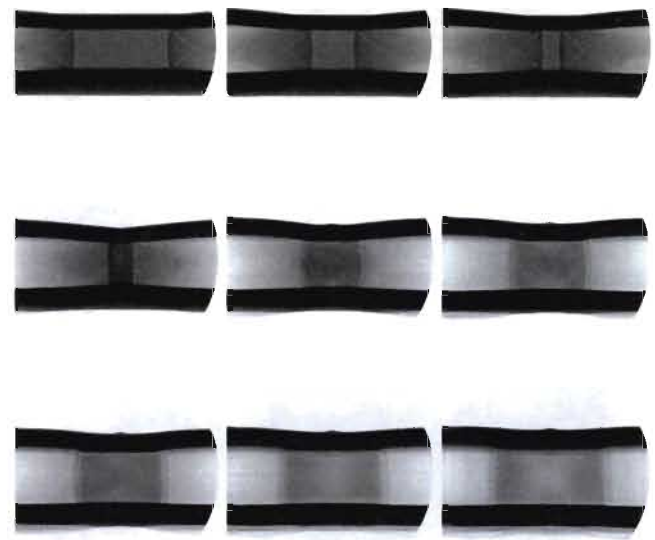
pRad
Velocimetry

pRad experiments:
High Explosives Burn Colliding Wave





800 meV proton radiography has been used to diagnose HE burn characteristics and the equation of state of the resulting HE detonation products. Here, a piece of HE is line-initiated at each end. pRad images the detonation fronts as they approach each other in the explosives, and characterizes the shocks traversing the detonated HE products after pass each other.

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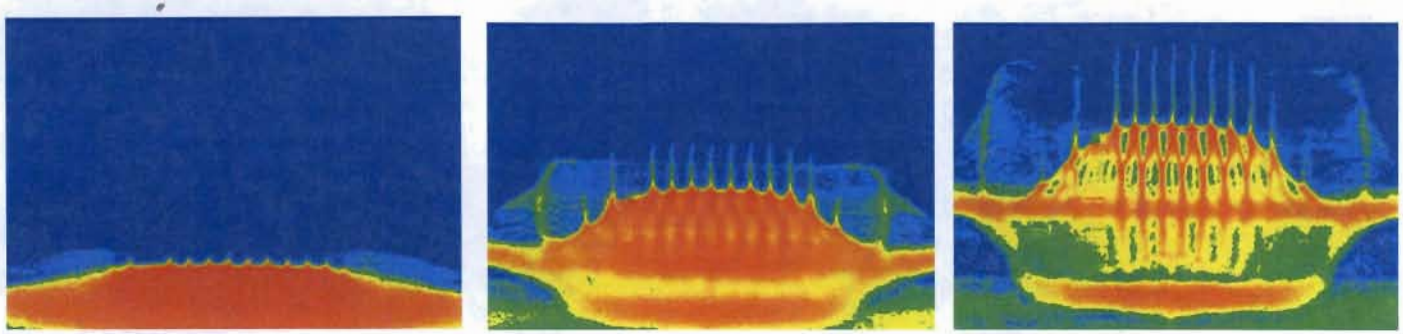
pRad experiments:
Richtmyer-Meshkov Instability



In these experiments, a disk of tin is prepared with sinusoidal perturbations on its top surface. This disk is hit from below by a fast flyer plate, causing a shock to propagate through the disk. The interaction of the shock with the perturbed top surface results in the signature spike-and-bubble of Richtmyer-Meshkov instability. These radiographs, from left to right, shows the evolution of this complicated structure, including the density variations below the surface. Data from experiments like these is used to test models vital for Stockpile Stewardship.

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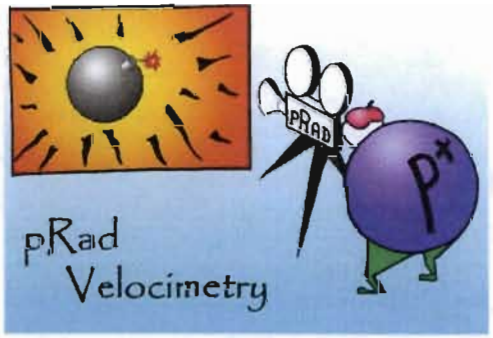
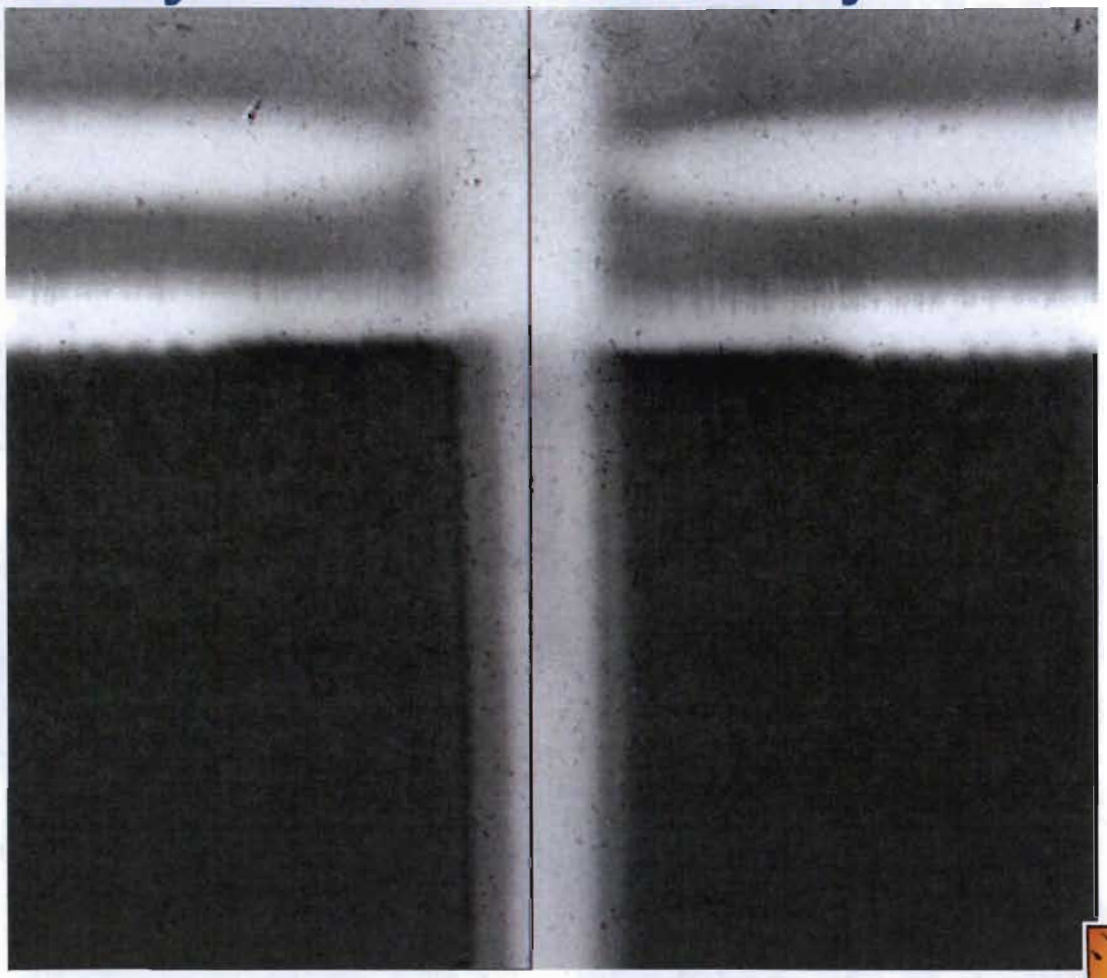


pRad experiments:
Richtmyer-Meshkov Instability



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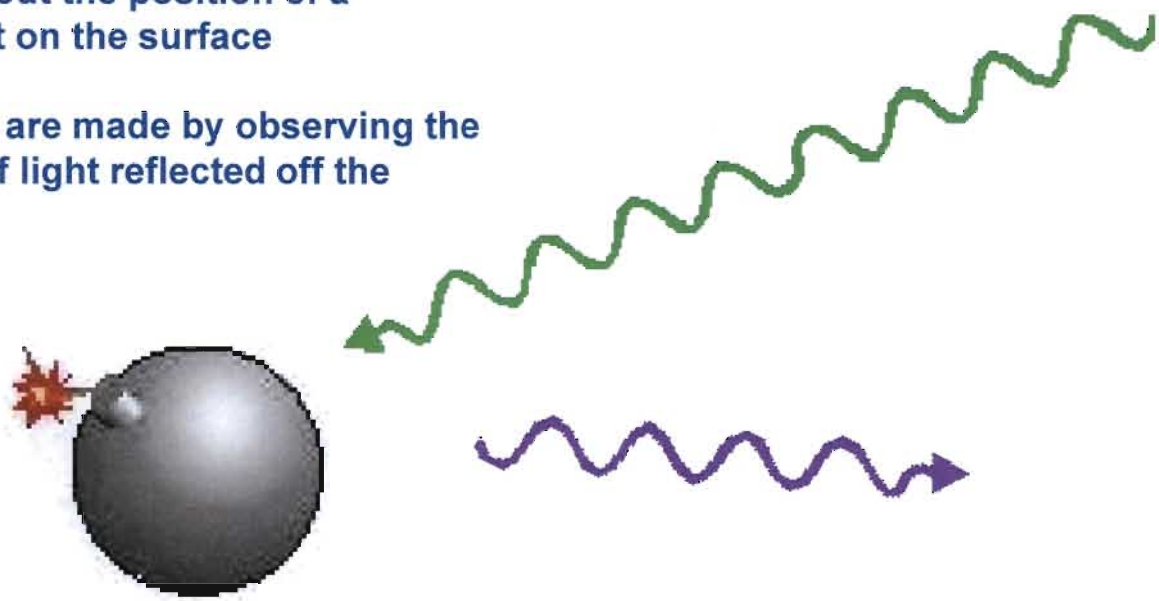
pRad
Velocimetry

Optical Diagnostics at pRad

Optical diagnostics measure the velocity of a moving surface to give detailed information about the position of a particular point on the surface

Measurements are made by observing the Doppler shift of light reflected off the surface



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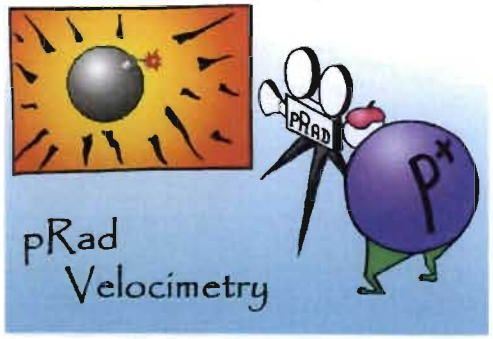

Why use optical diagnostics for these experiments?

Proton radiography sees both the inside AND the surface, so why would you want to use a diagnostic that only sees the surface??

⟶ Surface measurements complement the information obtained with radiography

1. Optical diagnostics have been in use for decades; new optical measurements used in conjunction with proton radiography can help understand older optical data

2. Optical diagnostics can tell you the velocity and position of a surface every few nanoseconds, and take a thousand data points per experiment; proton radiography takes positions a couple hundred ns apart and takes ~30 pictures per experiment.

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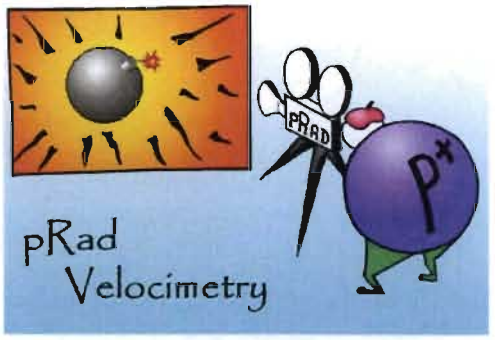
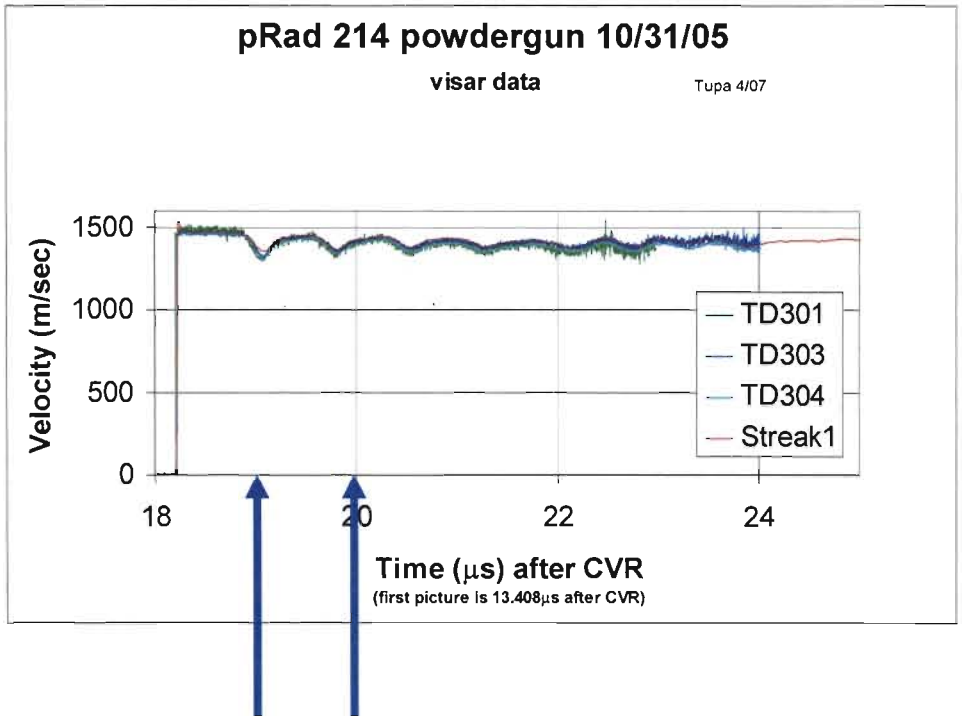


Timing: surface velocity vs. proton radiograph



Pictures from pRad typically ~1μs apart

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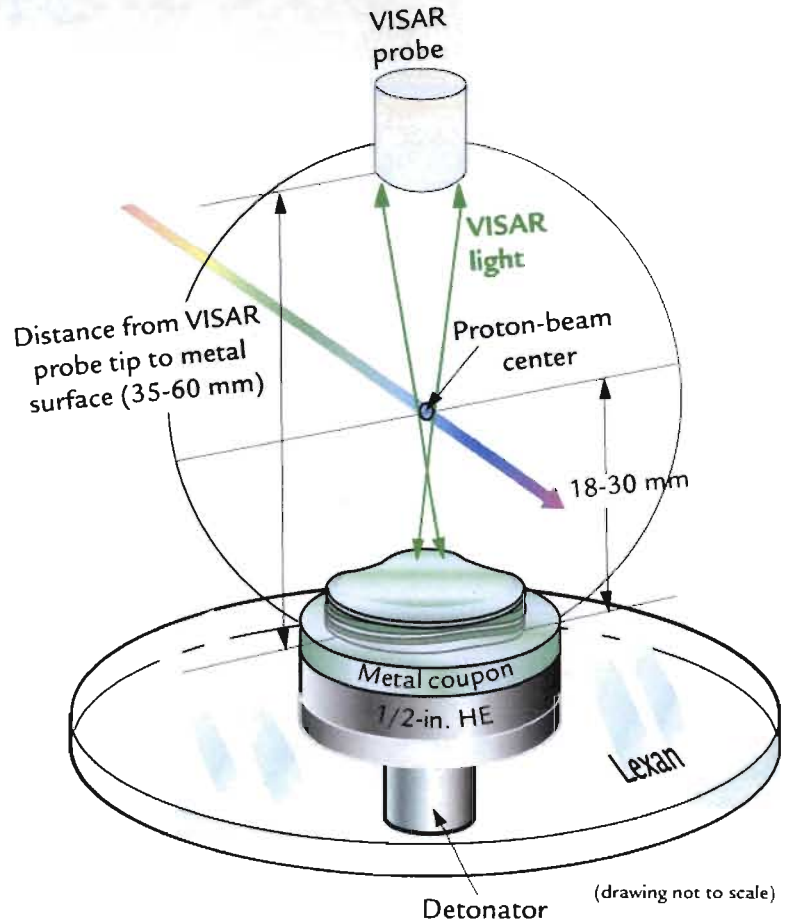
pRad
Velocimetry

Typical setup for optical measurements

Monochromatic light bounces off the surface. When the surface moves, the reflected light is Doppler-shifted. This shifted return light is gathered and sent to the diagnostic



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pRad Velocimetry

Types of optical diagnostics for dynamic physics experiments:

Fabre-Perot (not used at the Proton Radiography facility)

Visar

PDV

Typical surface velocities in dynamic experiments are ~ 1000m/s; need to measure Doppler-shifted laser frequencies on the order of ~10-5, typically GHz frequency shifts

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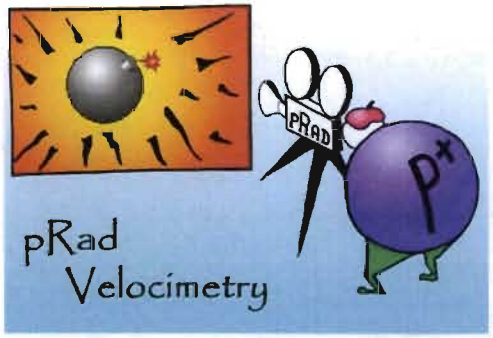
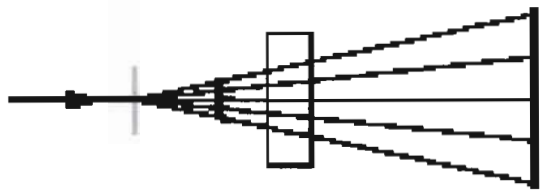
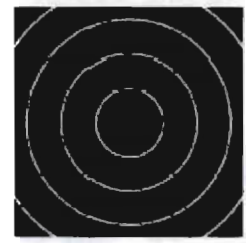


Fabre-Perot

Based on the transmission of an etalon (two precisely-placed mirrors)





Light is incident on two spaced mirrors; the amount of light transmitted depends on the wavelength and the exit angle from the etalon.

Light of a particular frequency is emitted in a ring pattern. If the light shifts frequency up or down, the rings shift to bigger or smaller diameters.

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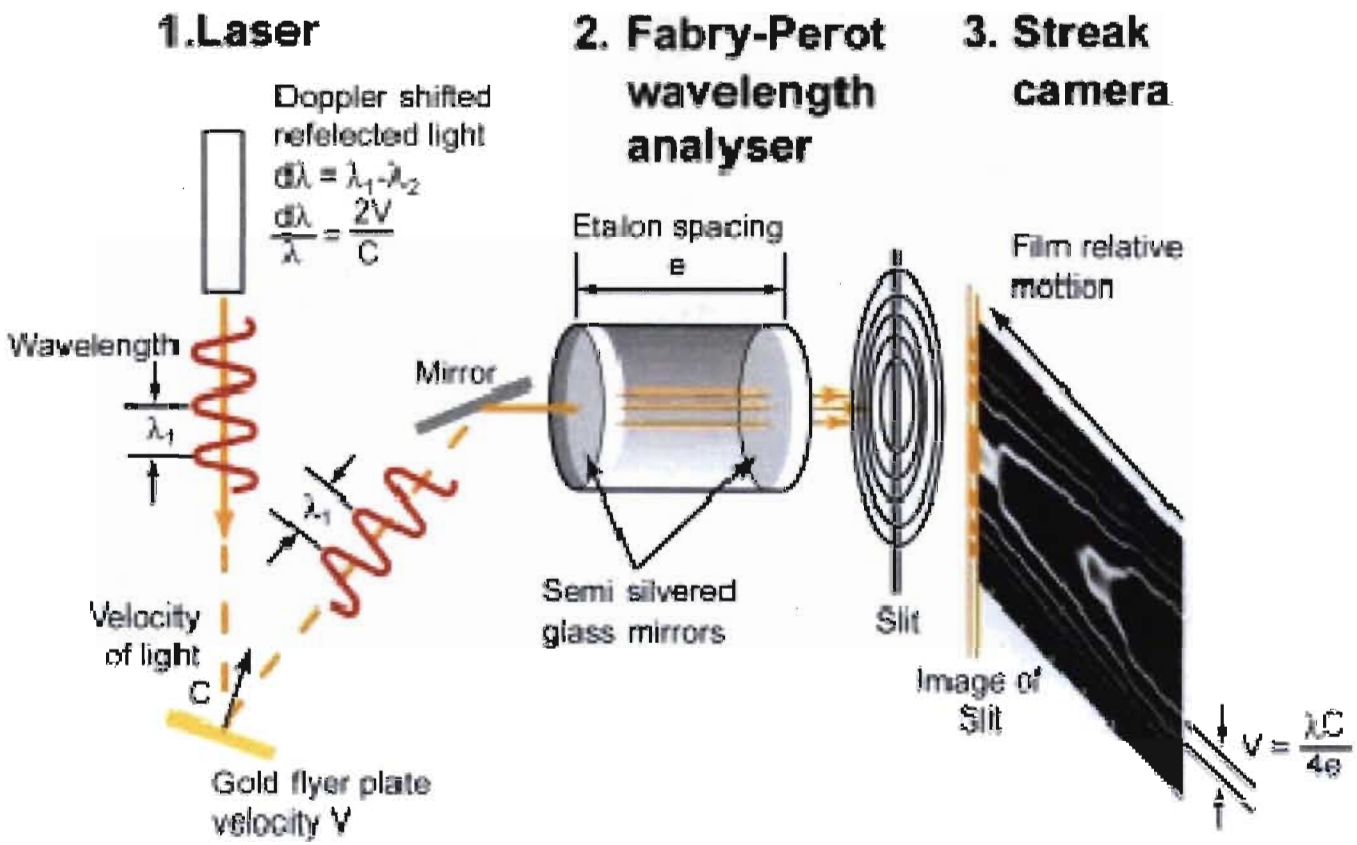
Velocimetry

Schematic of Fabry-Perot (from AWE lab, England)



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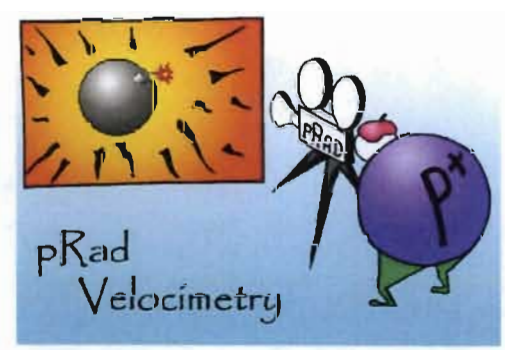
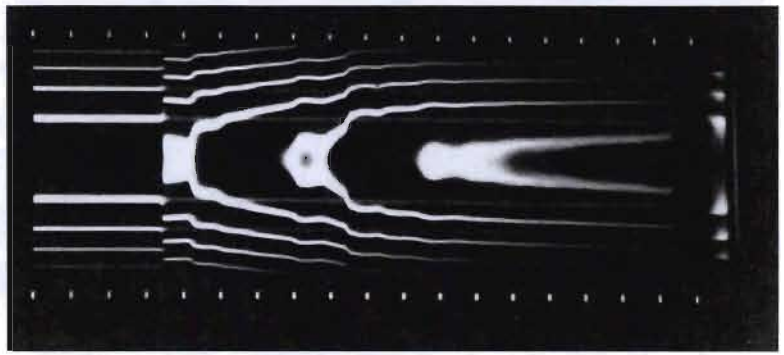


Data from Fabry-Perot (from AWE lab, England)



Streak camera picture of Fabry-Perot data. The vertical axis is a slice through the Fabry-Perot rings. The horizontal axis shows the rings evolving with time as the frequency of the Doppler-shifted light changes

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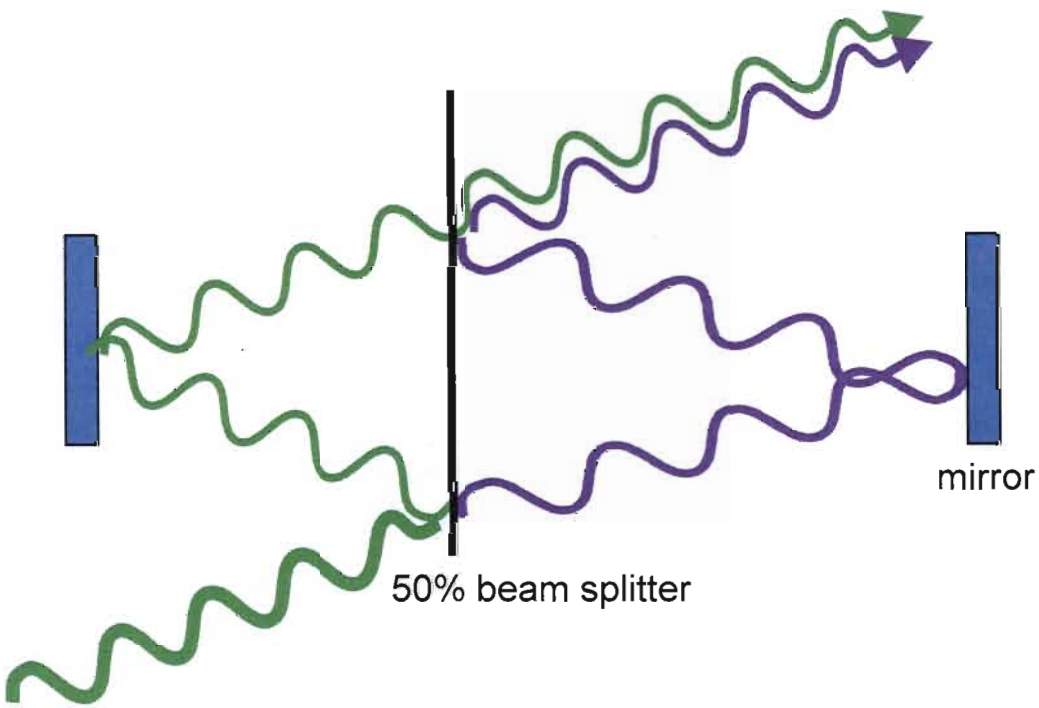
pRad
Velocimetry

VISAR (Velocity Interferometer System for Any Reflector)

Visar measurements are made with an interferometer



If the path difference between the right- and left-hand sides of the visar equals an integer number of wavelengths, strong light exits to the right of the interferometer

So, whether you get a strong output or no light exiting depends on the wavelength of the light. As the light changes wavelength, the output blinks on and off

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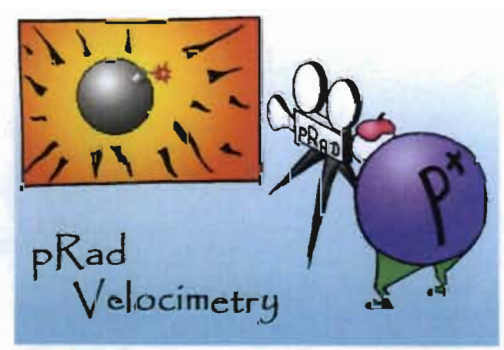
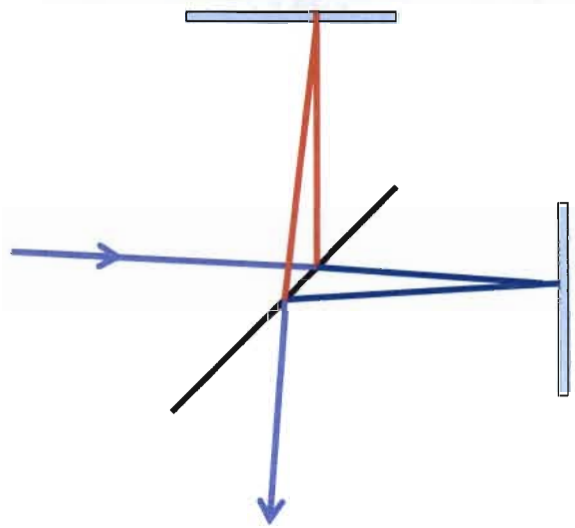
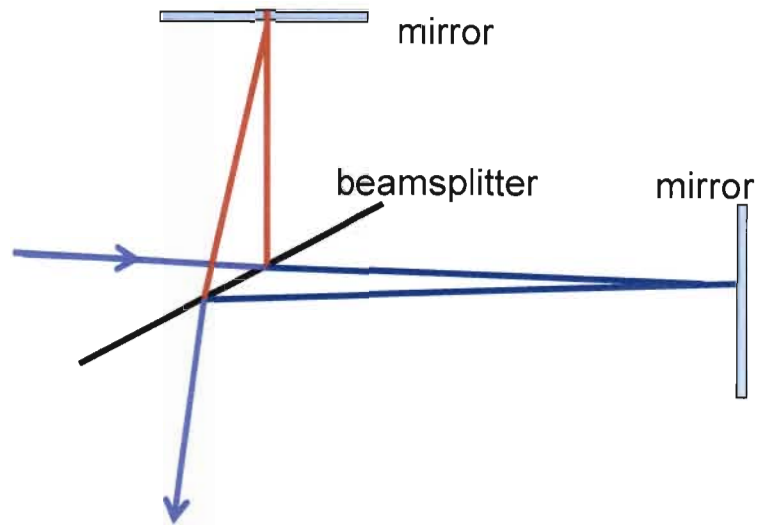


Visar interferometer: more details



Michelson geometry: both legs of identical length

⟶ all frequencies and phases of light experience constructive interference always.



Unequal path lengths

⟶ changing the light frequency moves the system through cycles of constructive/destructive interference BUT input light must have uniform phase (not suitable when the input light is from a diffusely reflecting surface)

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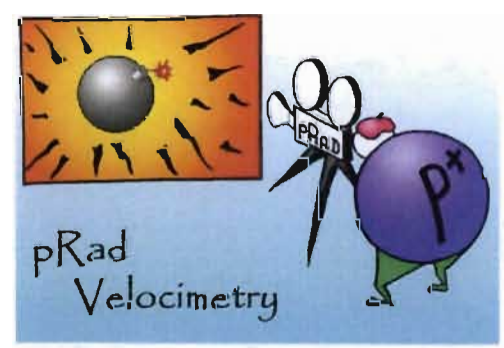
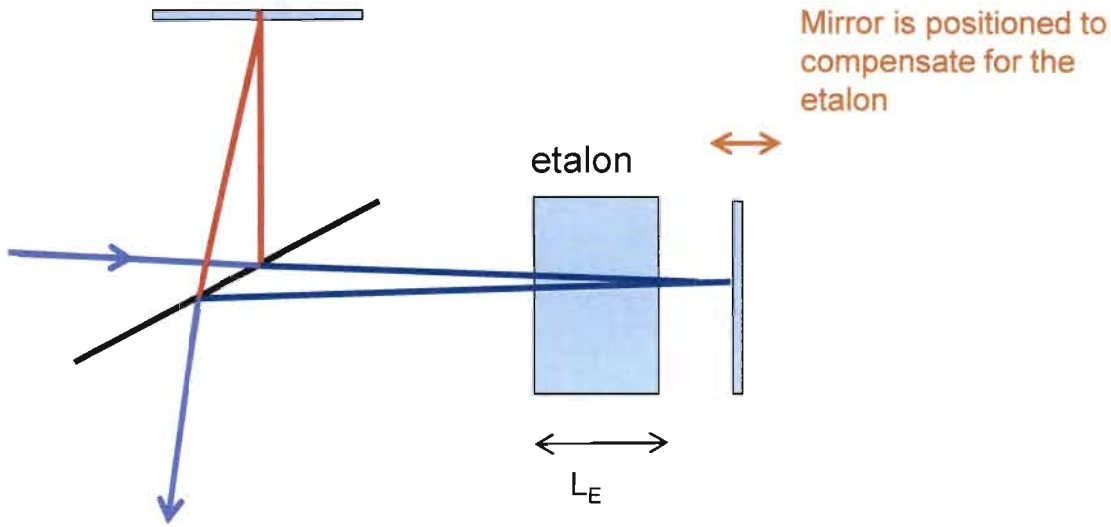


Visar interferometer: still more details



A secondary consequence of this geometry is that the interferometer input light can be imaged to the output, allowing the use of a single interferometer for multiple data points.

The solution: the "Wide-Angle Michelson Interferometer," for which each leg has a different path length but identical imaging

⟶ changing the light frequency moves the system through cycles of constructive/destructive interference independent of the input phase

⟶ VISAR (Velocity Interferometer System for Any Reflector)

(including diffuse reflectors)

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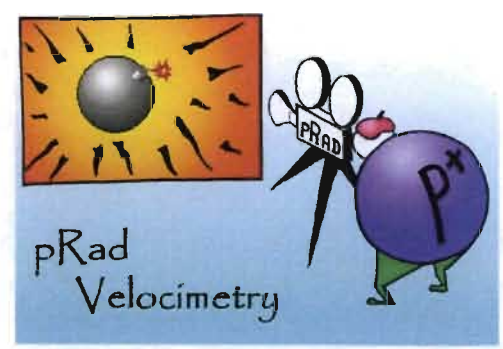
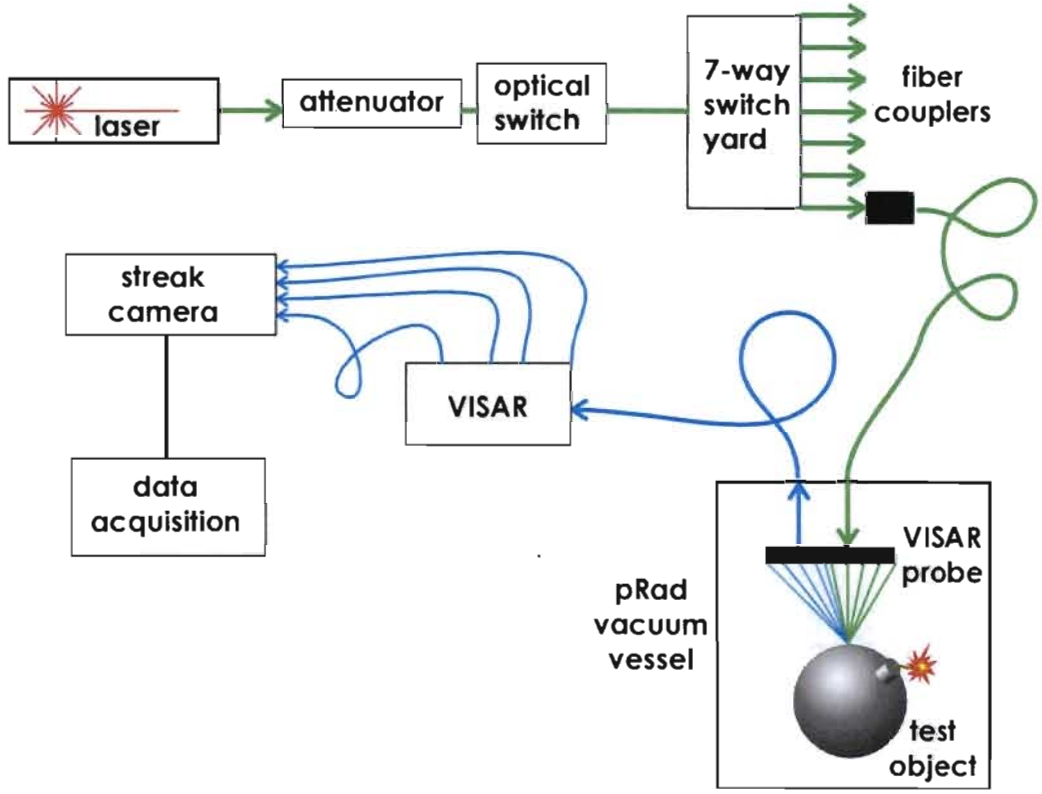


Overview of Visar measurements with the pRad system



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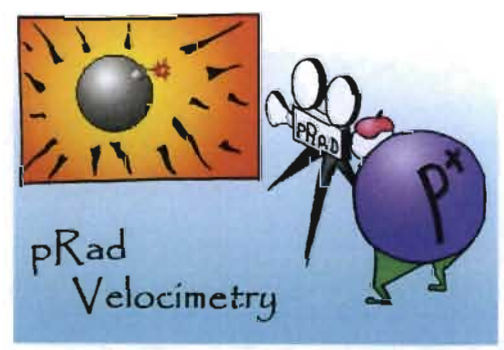
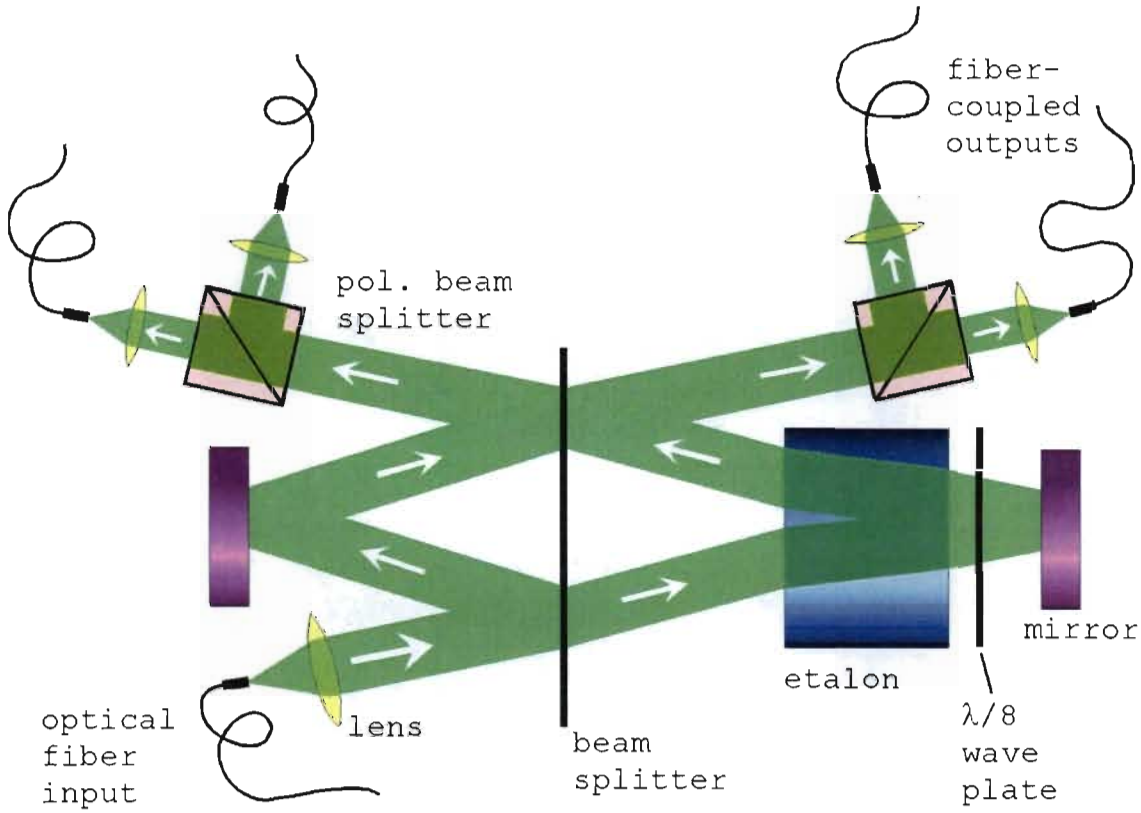


Schematic of the pRad Visar interferometer



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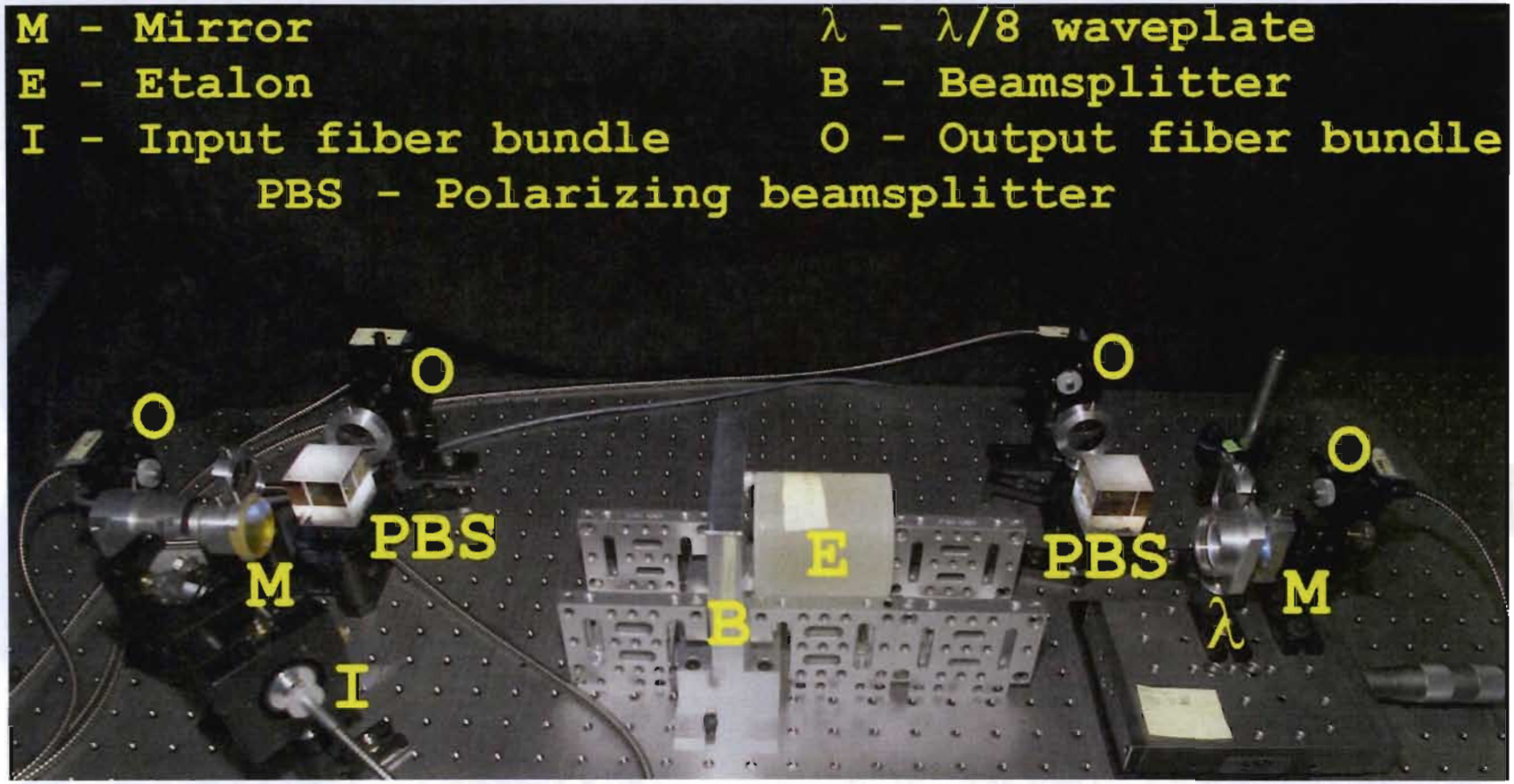
pRad
Velocimetry

Photo/schematic of the pRad Visar interferometer



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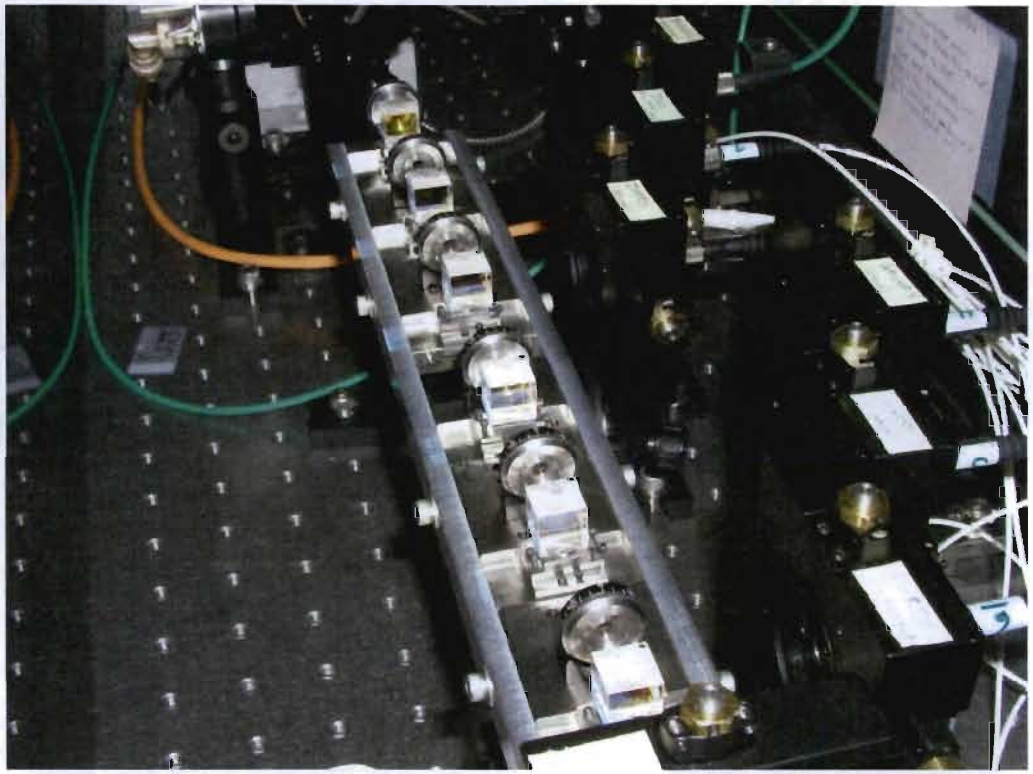
Measuring 7 points simultaneously with the pRad Visar interferometer



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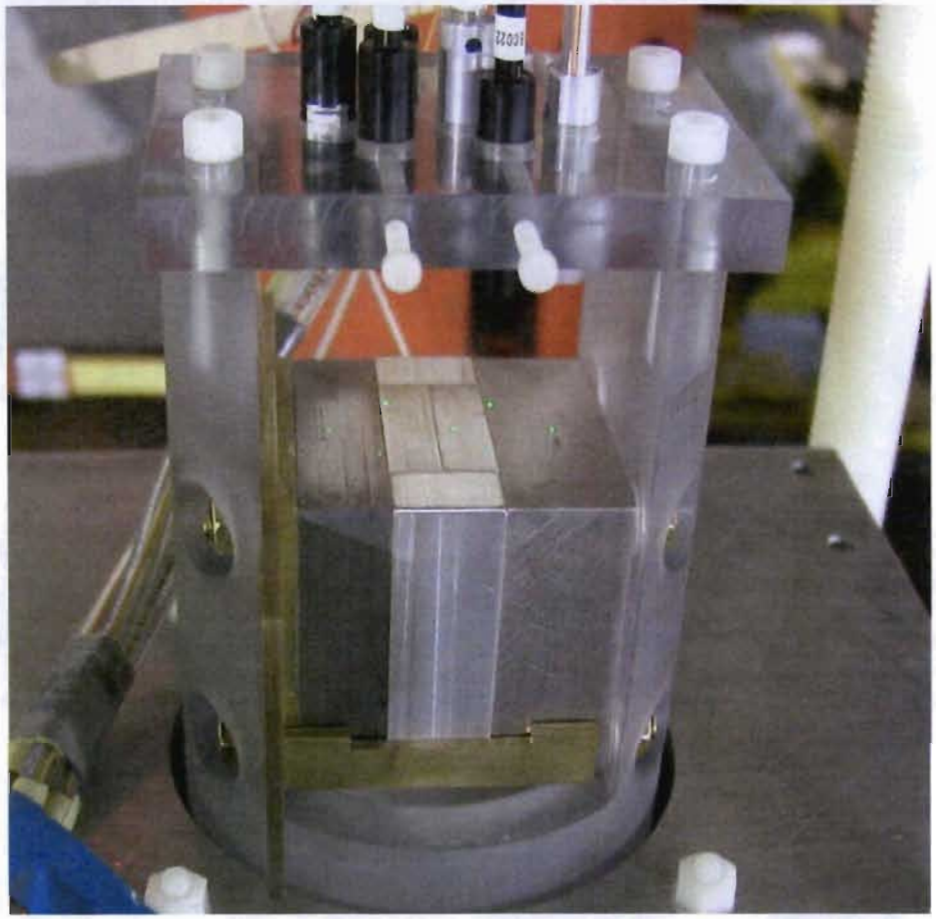
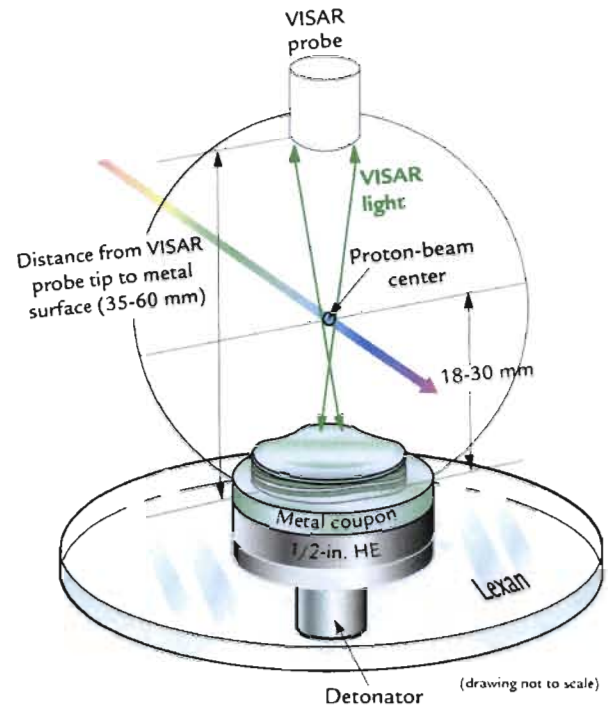
pRad
Velocimetry

Preparing velocimetry on a pRad shot





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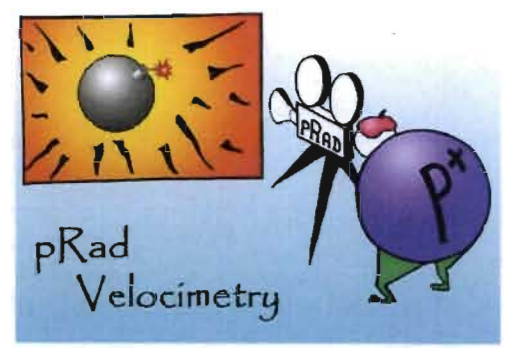

Placing the shot in the pRad vessel

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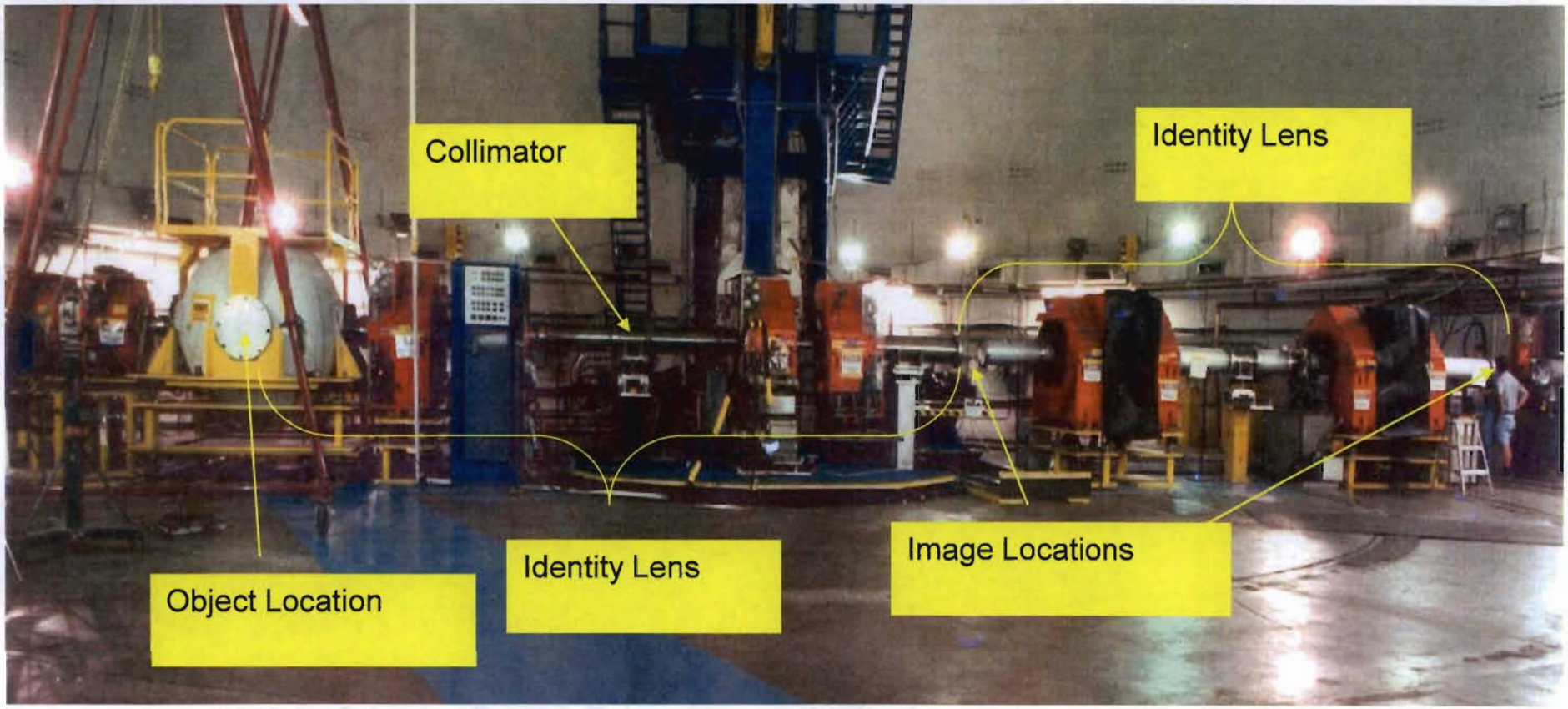
pRad
Velocimetry

Placing the shot in the pRad vessel



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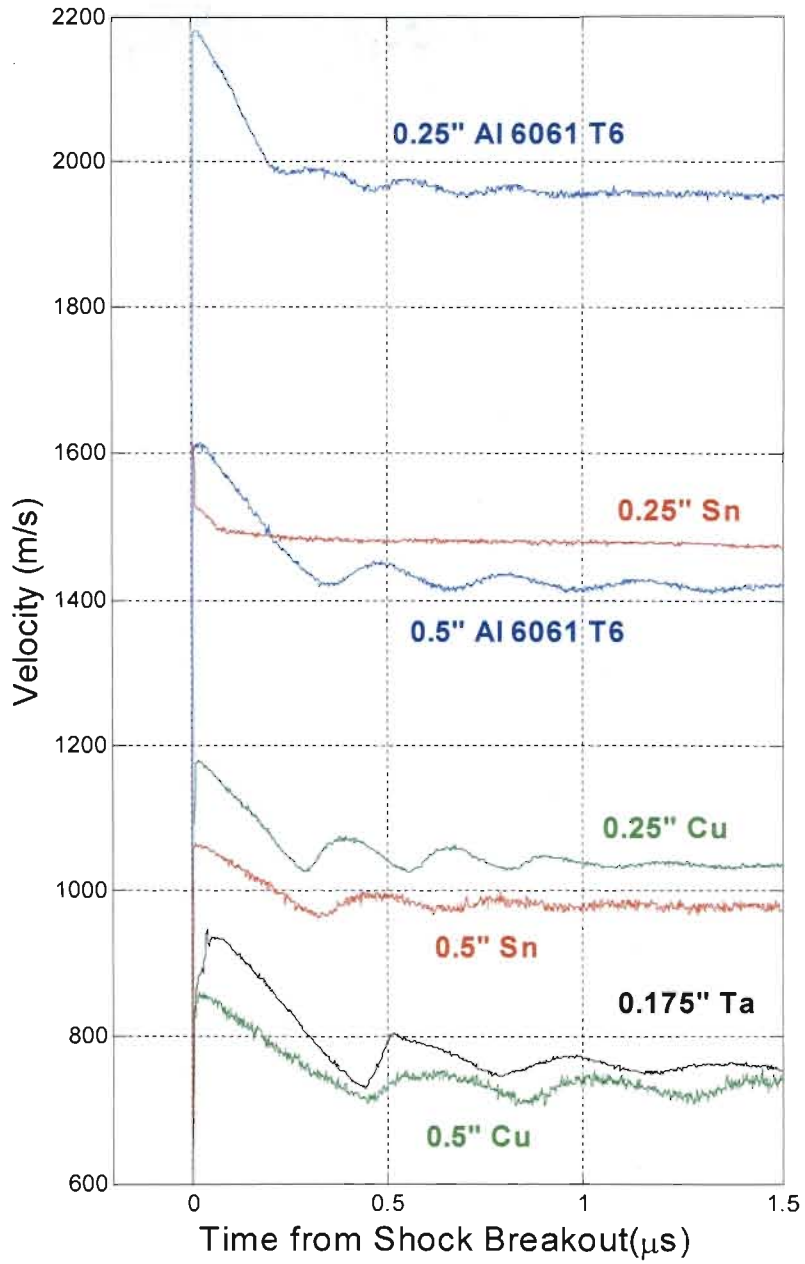
pRad
Velocimetry

Visar surface velocity measurements from several pRad experiments

differing thicknesses of:

aluminum
tin
copper
tantalum

data from experiments of D. Holtkamp



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PDV (Photon Doppler Velocimetry)

PDV: based on using "heterodyne," or looking at the beat frequency resulting from mixing the light reflected off a moving surface with the unshifted laser light

The beat frequency is

$$\Delta f = 2f\frac{v}{c} = 2\frac{v}{\lambda}$$

Which, for light of 1550nm and typical surface velocities of 100m/s, is 1.29 GHz

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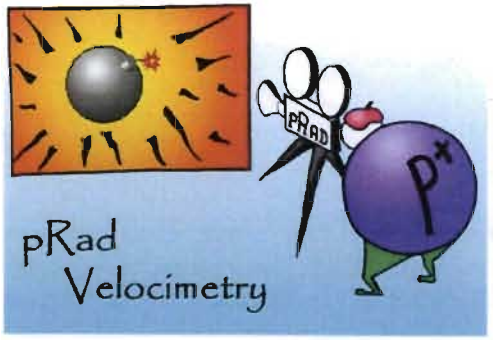

PDV (Photon Doppler Velocimetry)

PDV: based on using "heterodyne," or looking at the beat frequency resulting from mixing two beams

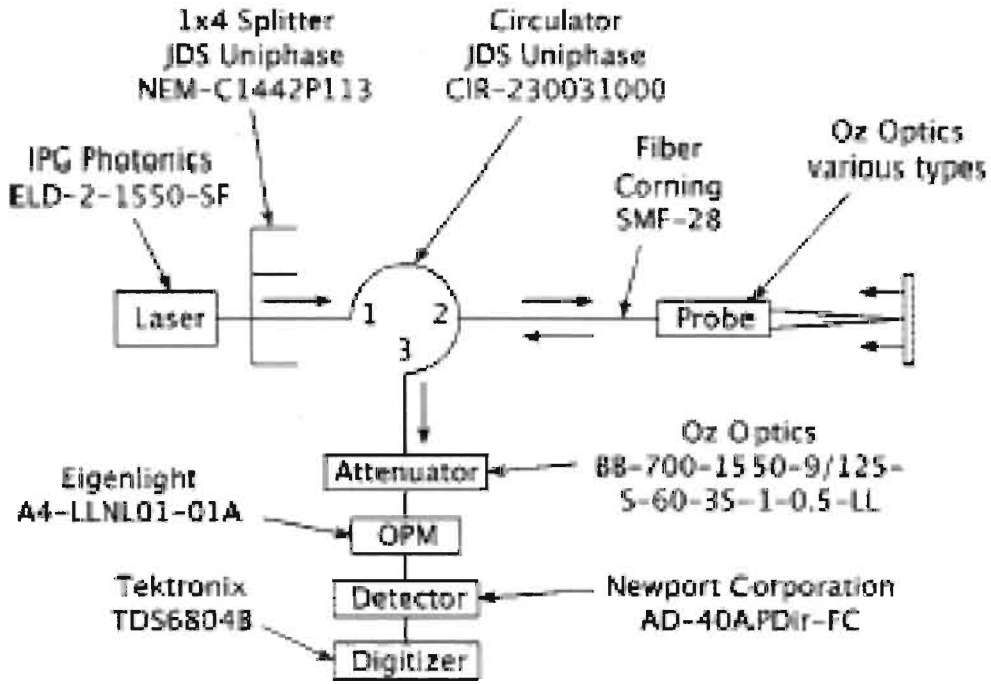

Diagram from Ted Strand, et al. Review of Scientific Instruments, 2006

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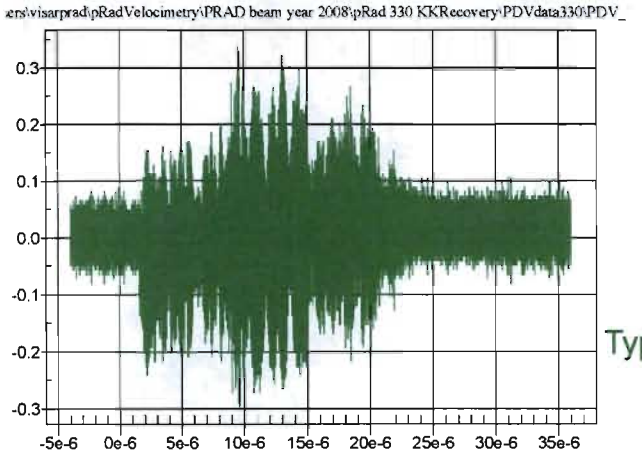
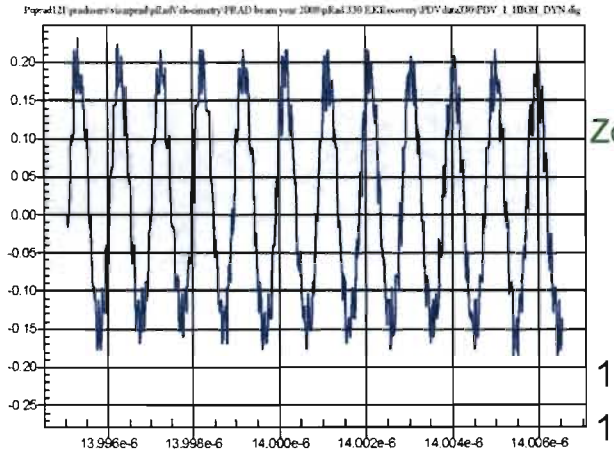
pRad
Velocimetry

PDV data



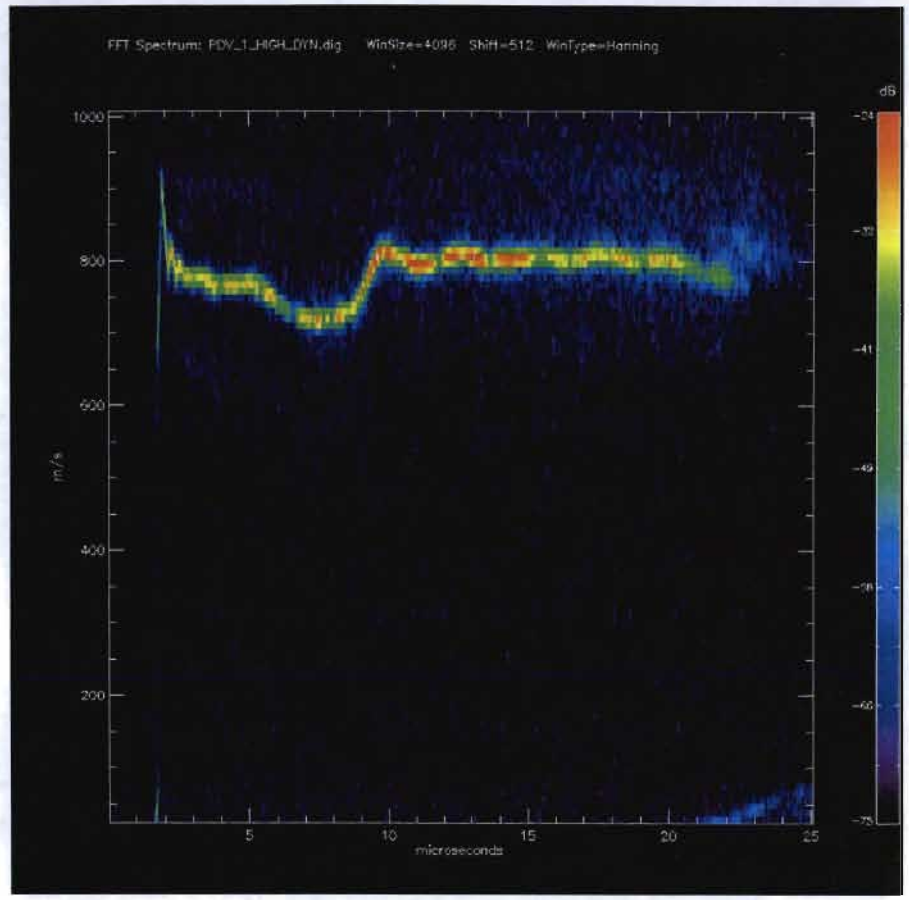
Typical raw data



Zoom in on data

11 cycles/10.6 ns = 1.04 GHz

1.04 GHz → 804.4 m/s



Out put from data analysis using Fourier transform algorithm

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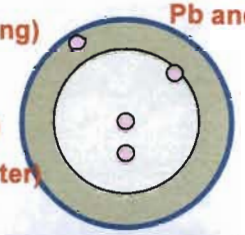
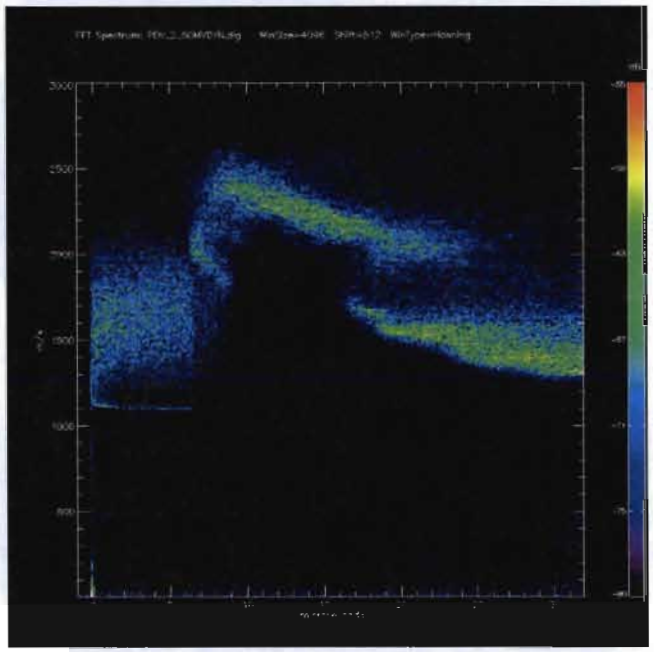
pRad Velocimetry

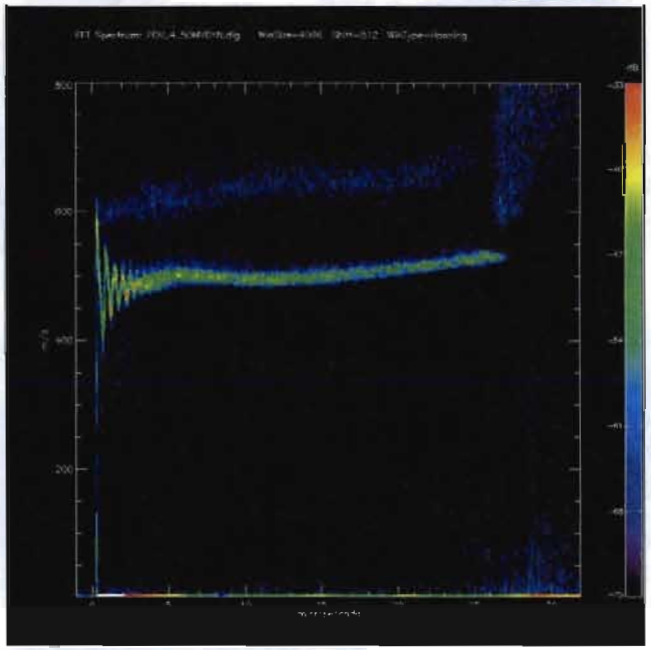
PDV - sample data from the Bacchus series pRad shot 365

Probe locations





Probe 2



Probe 4

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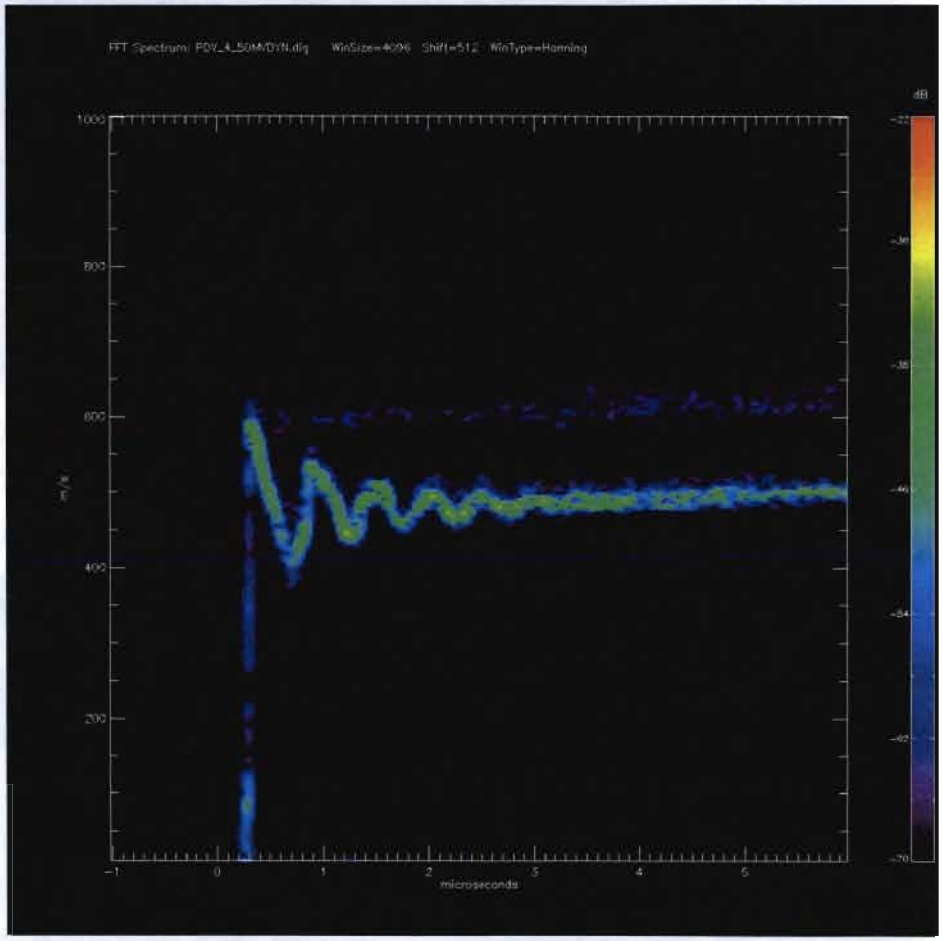
pRad Velocimetry

PDV - sample data from the Bacchus series
pRad shot 365



Probe 4

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pRad
Velocimetry

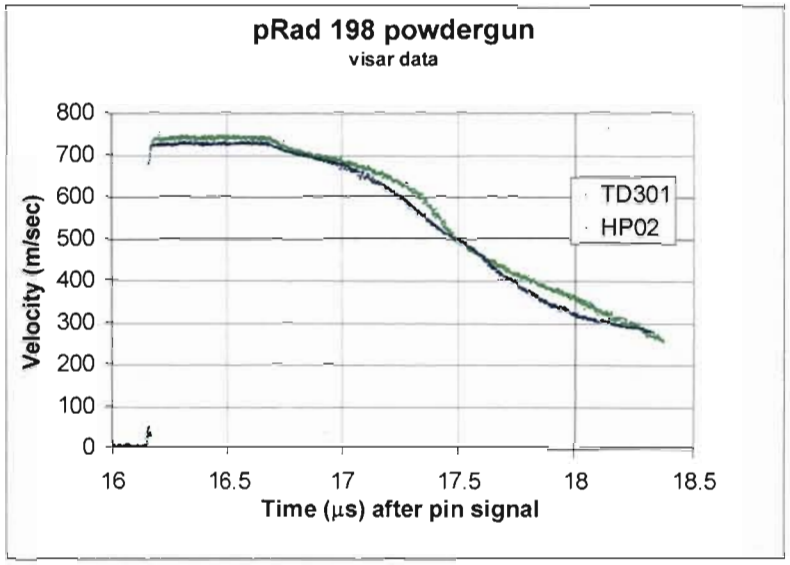
Velocimetry capabilities at pRad:

Visar

Up to 9 points of visar with single fringe constants

One single-point two-leg "mini-visar" (built by B. Marshall, NSTec Santa Barbara) ; upgradable to fast (450MHz) data recording

One seven-point single-leg homebuilt visar system



Above is a Visar velocity measurement of the surface of the Al Target piece from the powdergun experiment shown earlier.

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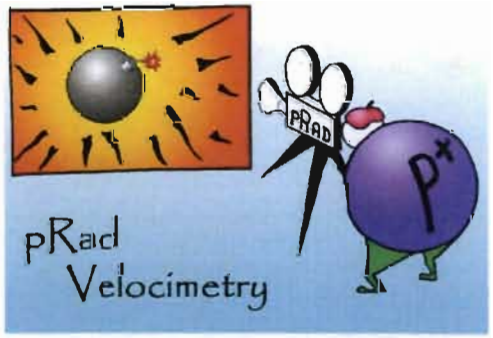


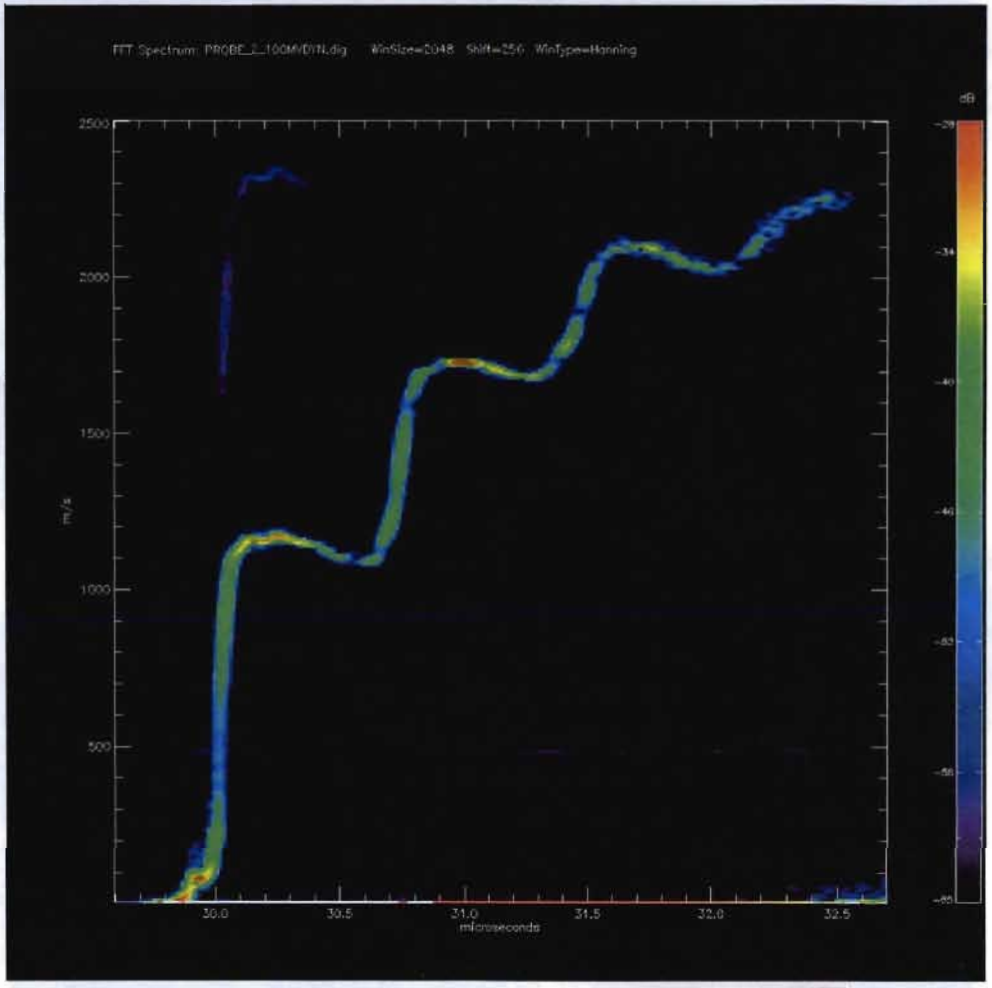
Velocimetry capabilities at pRad:

PDV

current capability of 6 PDV points, with an 8-point capacity using NSTec built 3U rack mount 13GHz modules

one 16GHz and three 8GHz Tektronix oscilloscopes, and two 5W 1550nm IPG lasers for experiments fielded at pRad

facility infrastructure could support fielding up to 48 points of PDV (if more equipment becomes available)



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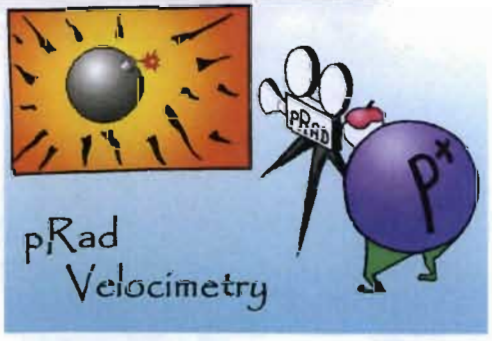

Future work at pRad

Proton Radiography, and a similar technique with electron radiography are slated to play an integral role in LANL's future MaRie. MaRIE, a facility to study Matter and Radiation Interactions in Extreme Conditions, will utilize charged particle radiography to diagnose material properties in dynamic conditions.

Student/Postdoc Opportunities Available

Contact Dale Tupa, tupa@lanl.gov

pRad User Program

A user program provides experimenters the opportunity to work at the 800 MeV LANL Proton Radiography facility at the Los Alamos Neutron Science Center. The facility can handle both unclassified and classified experiments. There is a yearly call for proposals for experiments. A Program Advisory Committee evaluates the proposals; beam time is allocated based on the recommendations of the committee.

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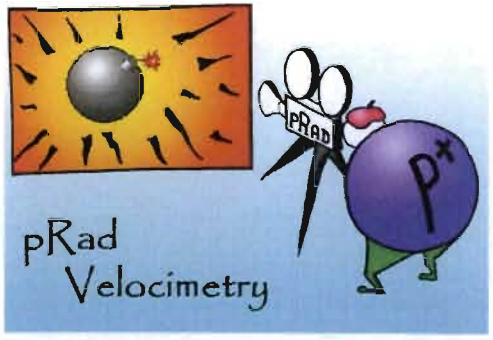
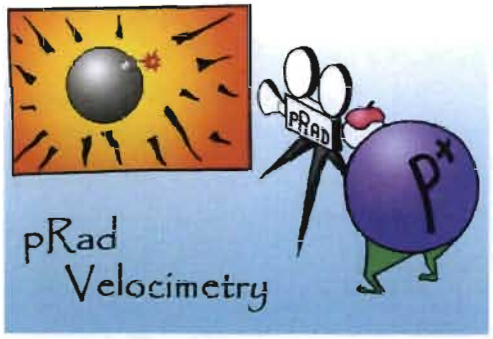


Summary:

The Los Alamos Proton Radiography facility is a tool to characterize materials and components under dynamic conditions.

Experiments at pRad have provided valuable data for nuclear stockpile stewardship, helping to avoid a return to underground testing.

At pRad, optical velocimetry measurements supplement the insight gained from proton radiographs.

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