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Title: Proton Radiography at Los Alamos

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Proton Radiography at Los Alamos

Alexander Saunders

(for the PRAD Team)

TTU, 3/1/17

The proton radiography (pRad) facility at Los Alamos National Lab uses high energy protons to acquire multiple frame flash radiographic sequences at megahertz speeds: that is, it can make movies of the inside of explosions as they happen. The facility is primarily used to study the damage to and failure of metals subjected to the shock forces of high explosives as well as to study the detonation of the explosives themselves. Applications include improving our understanding of the underlying physical processes that drive the performance of the nuclear weapons in the United States stockpile and developing novel armor technologies in collaboration with the Army Research Lab. The principle and techniques of pRad will be described, and examples of some recent results will be shown.

Outline of the talk

- What is proton radiography and how does it work?
- The Los Alamos pRad Facility
- Some unclassified examples of the uses of pRad for DoE and DoD research

Common Radiographic Tools

X-rays and neutrons have no electric charge and their trajectories cannot be manipulated easily.
The transmission through matter of areal density *X* have the forms

X-Rays

$$T_{X-Rays}(X) = e^{-\frac{X}{X_0}}$$

X_0 is the radiation length
Resolution limitations are due spot size and Compton scattering

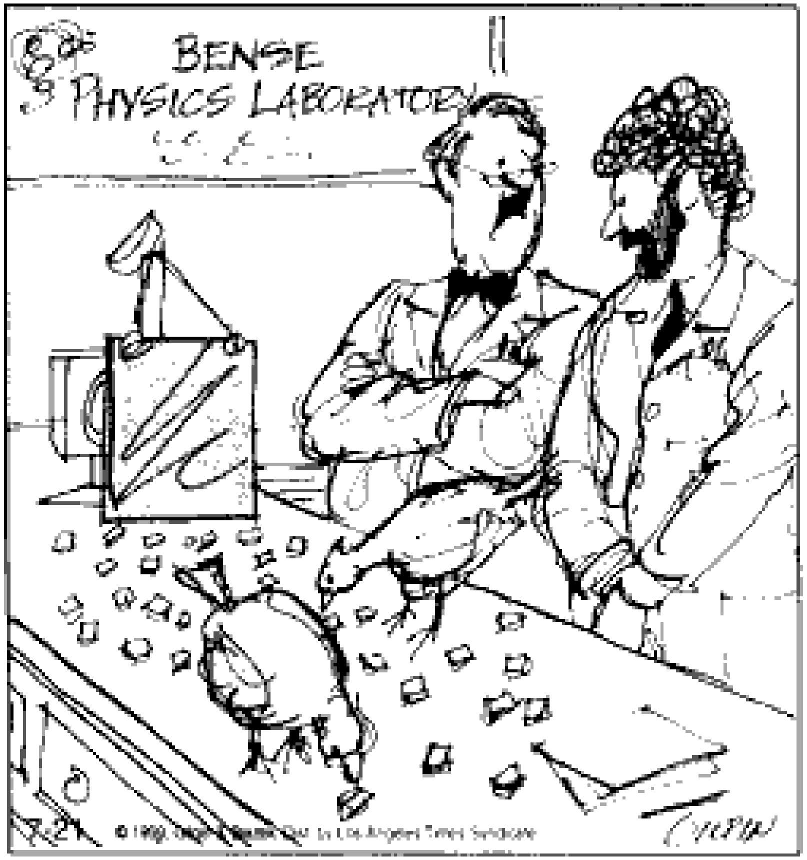
Neutrons

$$T_{Neutrons}(X) = e^{-\frac{X}{\lambda_{Nuclear}}}$$

$\lambda_{Nuclear}$ is the nuclear collision length
Resolution limited by nuclear scattering and to a lesser extent collimation of neutron beam

$\lambda_{Nuclear}$ is greater than X_0 for all elements Z>6 ➔ neutrons are good for radiographing higher-Z materials.
In addition to attenuation and energy loss, both X-rays and neutrons scatter.
The scattering can result in poor resolution unless the image sensor or converter is close to the object.
It is effectively impossible to make many rapid pulses of intense flash X-rays or neutrons.

The origins of PRAD



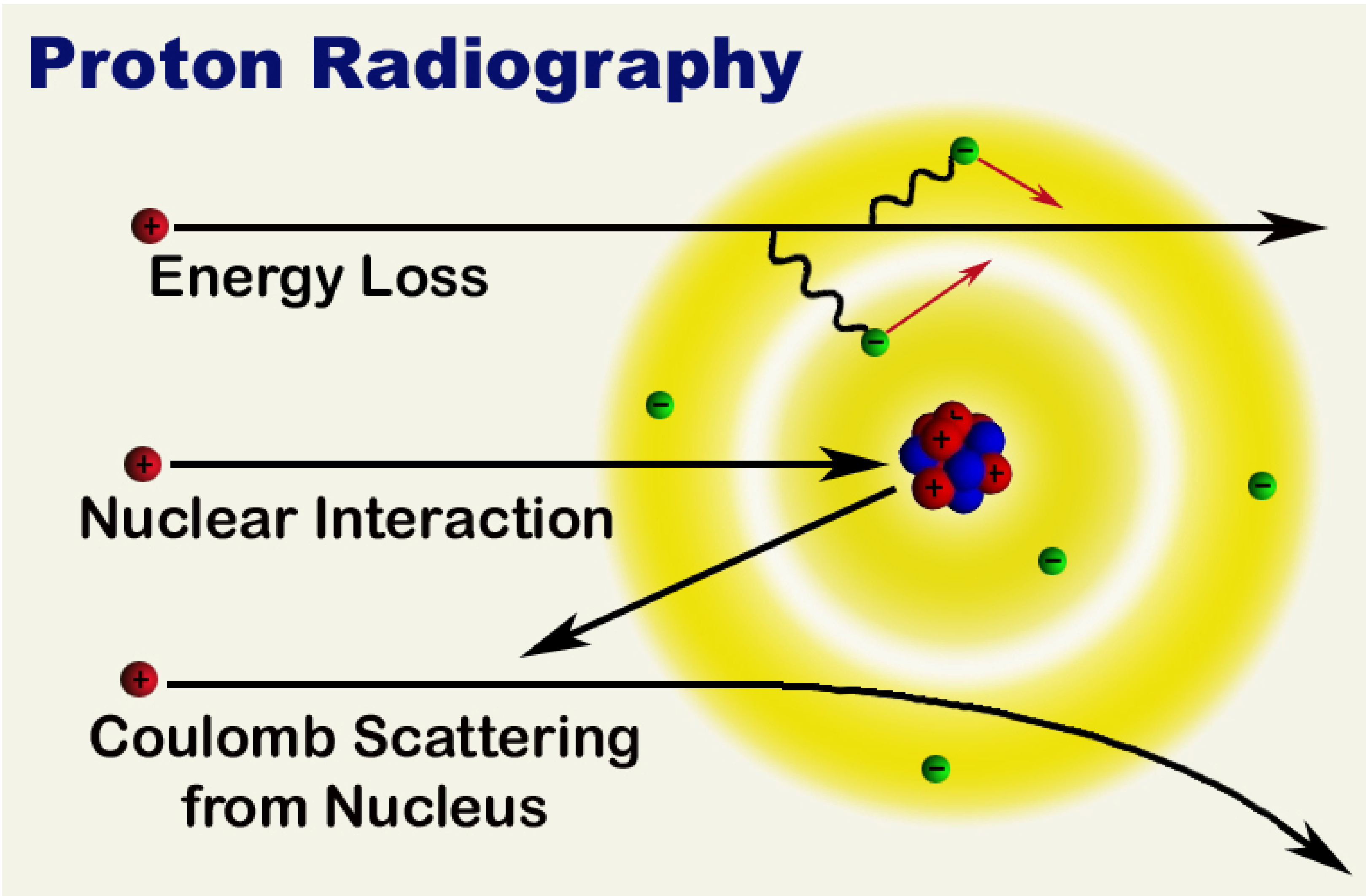
"Okay. Now that we know bombarding the sample with *croutons* isn't the answer, what say we try protons."

Protons have two key advantages over neutral particles:

1) They can be transported away from the object and focused
2) Many intense pulses can be generated

Proton Interactions

(everything you need to know about nuclear physics to be a radiographer)



Early Proton Radiography

A. M. Koehler, *et al.* *Science* **160**, 303 (1968)

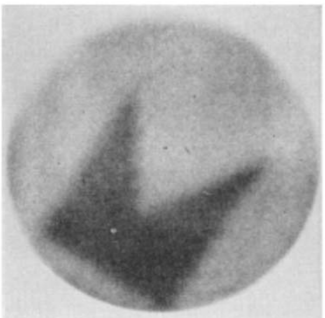


Fig. 1. Proton radiograph of aluminum absorber 7 cm in diameter and 18 g/cm² thick, with an additional thickness of 0.035-g/cm² aluminum foil, cut in the shape of a pennant, inserted at a depth of 9 g/cm². The addition of 0.2 percent to the total thickness produces a substantially darker area on the film.

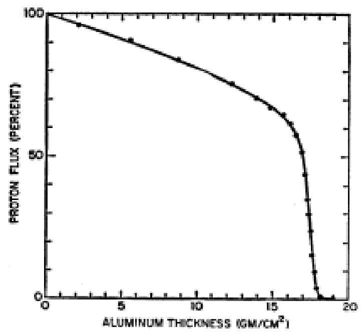


Fig. 2. Proton flux as a function of depth in aluminum. The steeply falling portion of the curve near 18 g/cm² is used to obtain the high contrast of Fig. 1.

<u>Marginal Range Radiography</u>

- Reduce proton beam energy to near end of range.
- Use steep portion of transmission curve to enhance sensitivity to areal density variations.
- Coulomb scattering at low energy results in poor resolution >1.5 mm.
- Contrast generated through proton absorption.

J. A. Cookson Naturwissenschaften 61, 184—191 (1974)

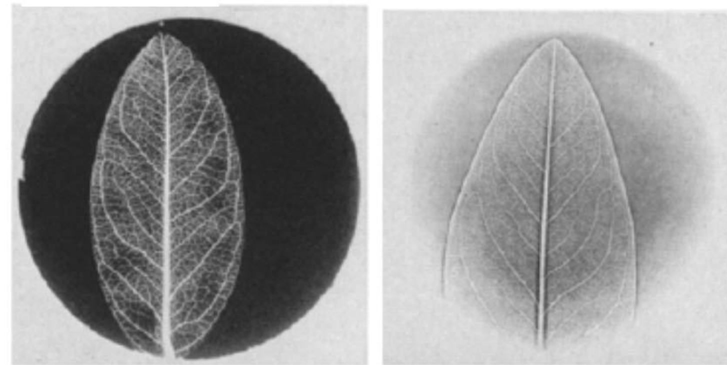


Fig. 6a and b. Radiographs of leaves by a) marginal range radiography with 196 mg/cm² of extra Al absorber, and b) scattering radiography with leaf sandwiched between two 6.9 mg/cm² Al layers and 14 mm from the film

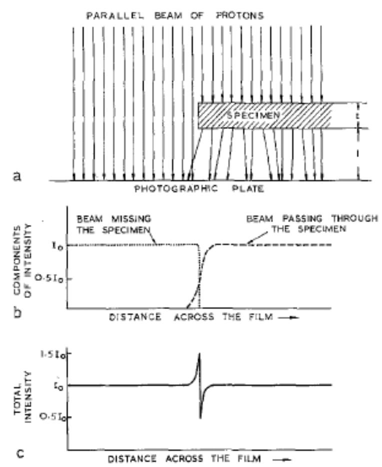


Fig. 7. Illustration of how multiple scattering produces its characteristic edge pattern

<u>Scattering Radiography</u>

- Edge detection only
- Limited to thin objects
- Contrast generated through position dependent scattering

LANL Transmission Radiography (1995)

188 MeV secondary proton beamline at LANSCE

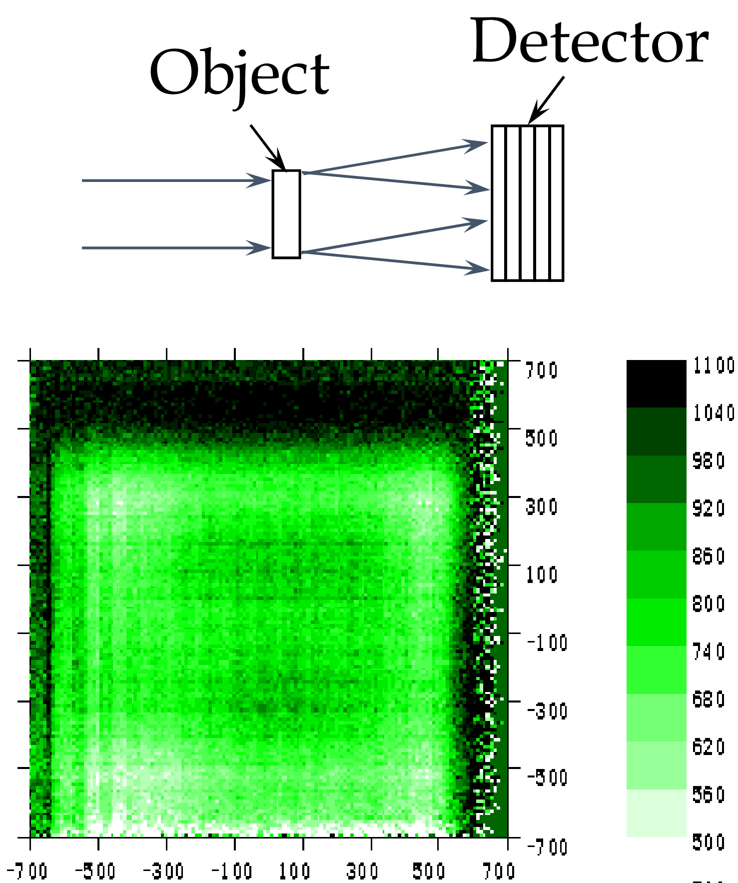
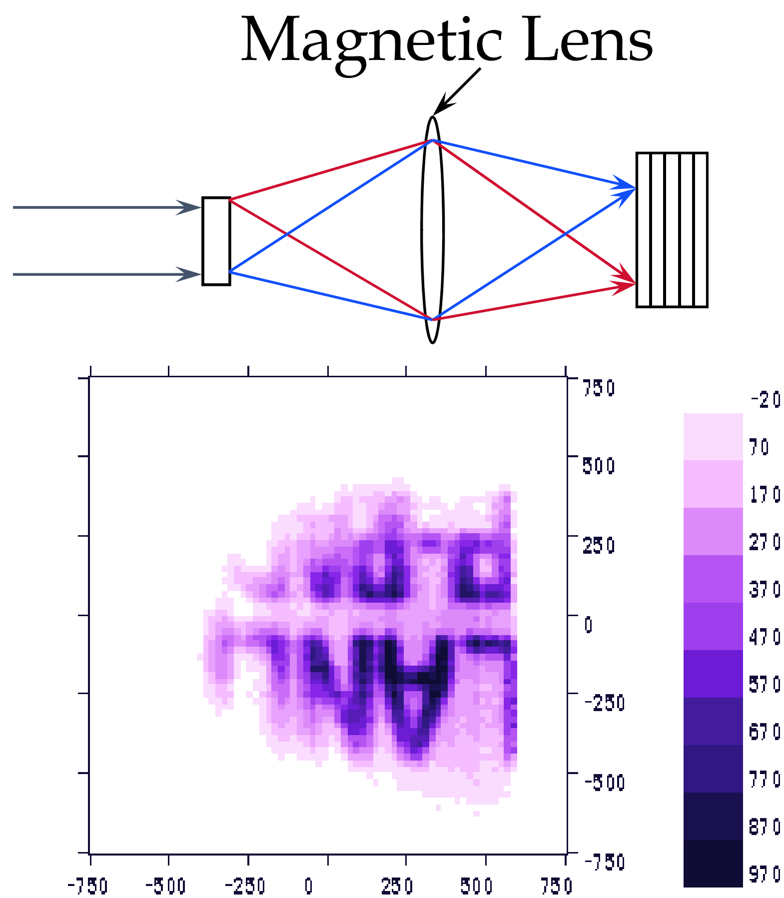


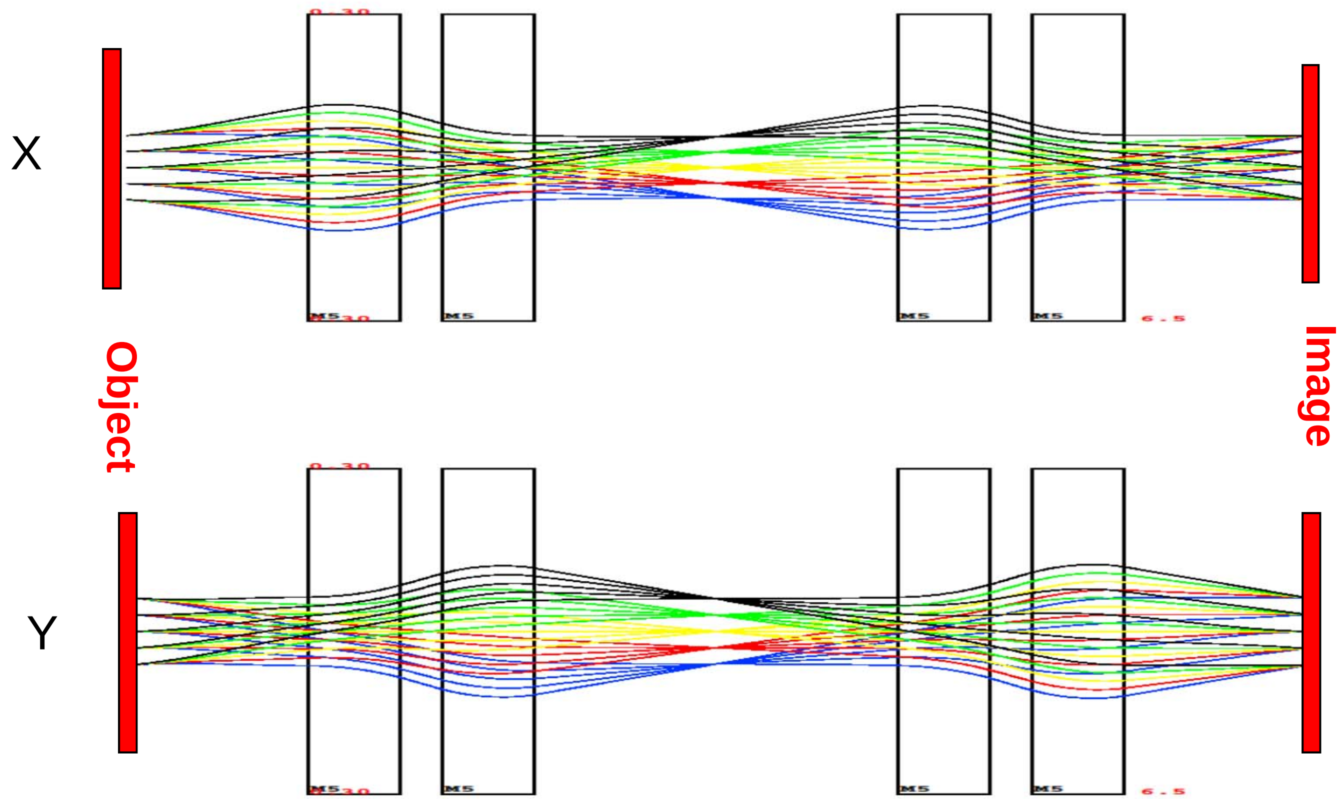
Image at the detector is substantially blurred.



Magnetic imaging lens preserves image with high resolution.

-I Magnetic Imaging Lens

A symmetric arrangement of four quadrupole magnets can be used to form a magnetic imaging lens in both x and y planes



Focal plane depends on the energy of the protons and setting of the quadrupole fields;

But Protons passing thru thicker parts of the object lose more energy than those passing thru thinner parts of the object

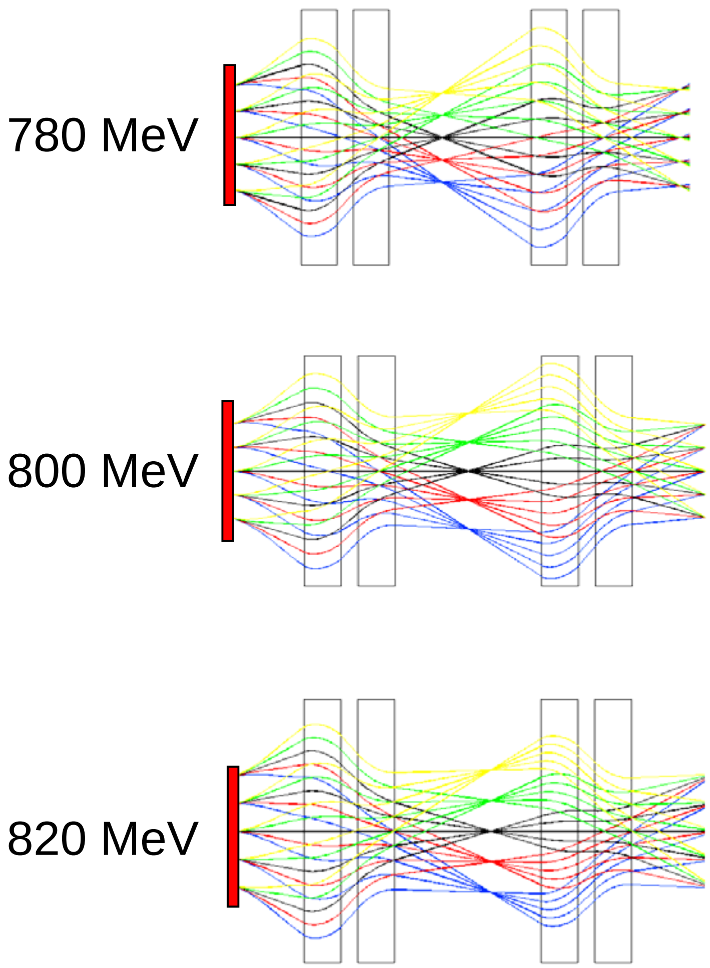
Therefore, the dominant source of blur is chromatic blur

Resolution

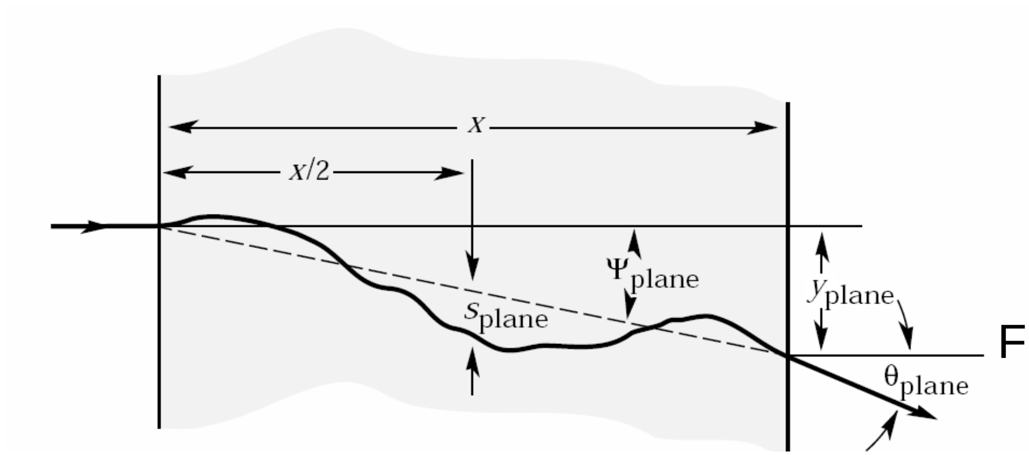
- Resolution dominated by second order chromatic effects

$$\partial x = T_{116} x\Delta + T_{126} x'\Delta$$
$$x' = wx + \phi$$
$$\partial x = (T_{116} + wT_{126}) x\Delta + T_{126}\phi\Delta$$
$$w = -T_{116} / T_{126}$$
$$\partial x = T_{126}\phi\Delta$$

- Resolution is object dependent
- Intrinsic resolution is ~150 μm (1-sigma RMS measured from an edge, Gaussian point-spread function)
- Scintillator and camera system contribute.
- Shot mitigation contributes.



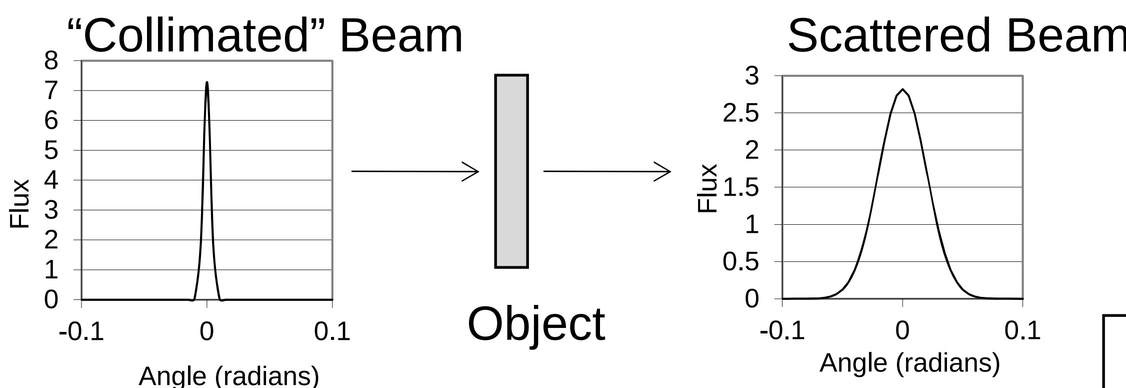
Multiple Coulomb Scattering



$$\theta_o = \frac{13.6MeV}{\beta p}\sqrt{x/X_o}\left[1+0.038\ln\left(x/X_o\right)\right] \; *$$

RMS Width

Full Width Half Maximum=2.35 θ_o

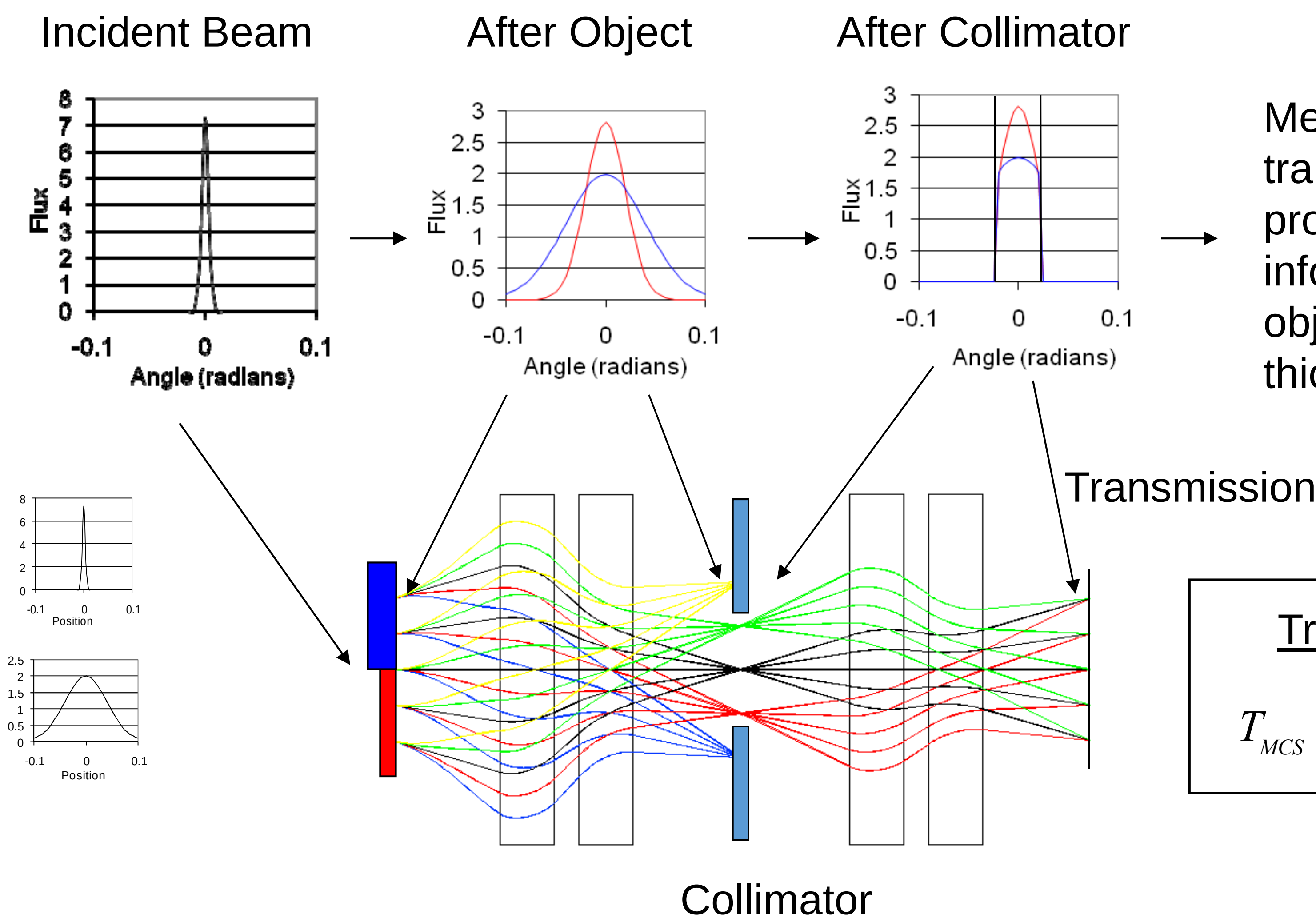


$$\theta_o = \frac{14.1MeV}{\beta p}\sqrt{x/X_o}$$

Typical LANL simplification

*C. Amsler et al., Physics Letters **B667**, 1 (2008)

Contrast from Multiple Coulomb Scattering



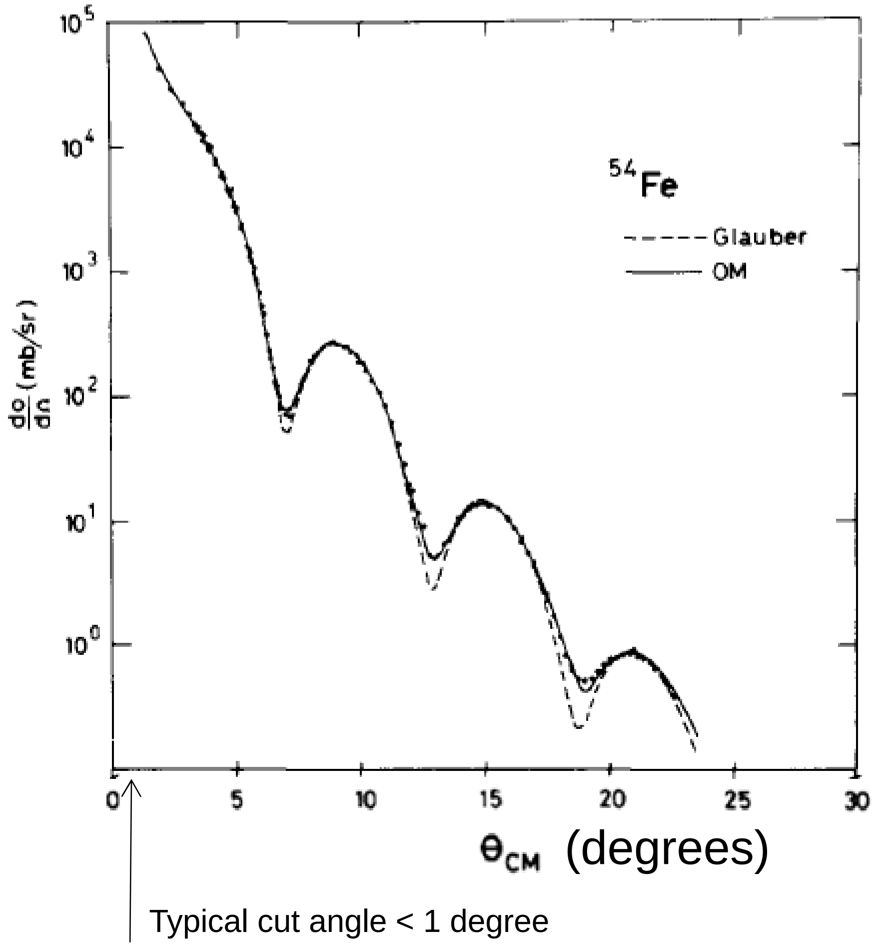
Measured transmission provides information of object thickness

Transmission

$$T_{MCS} = 1 - e^{-\theta_c^2 / 2\theta_o^2}$$

Nuclear Interactions

Angular distribution of 800 MeV proton nuclear elastic scattering from Iron.



<u>Simple Approximation for Modeling Proton Radiography</u>

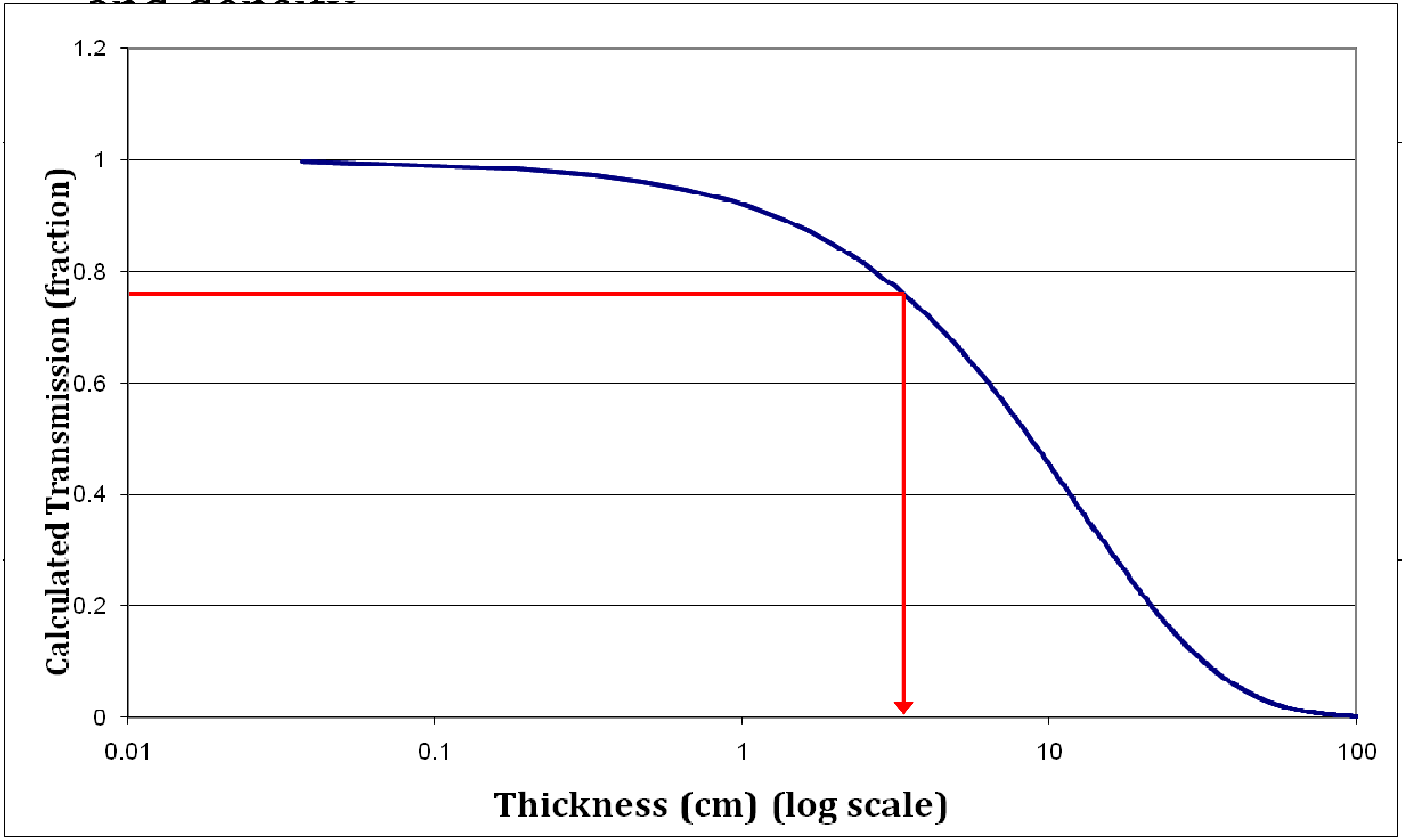
- Characteristic Nuclear Collision Length: λ_c
- Approximate that each interaction removes the proton from the acceptance of the imaging lens.
- Measure the collision Length at 800 MeV

The “true” nuclear interactions are more complicated than this simple assumption and these interactions are reasonably well understood. This can all be simulated, but it is typically not worth the effort for designing small scale experiments.

<u>Transmission</u>

$$T_{nuclear} = e^{-x/\lambda_c}$$

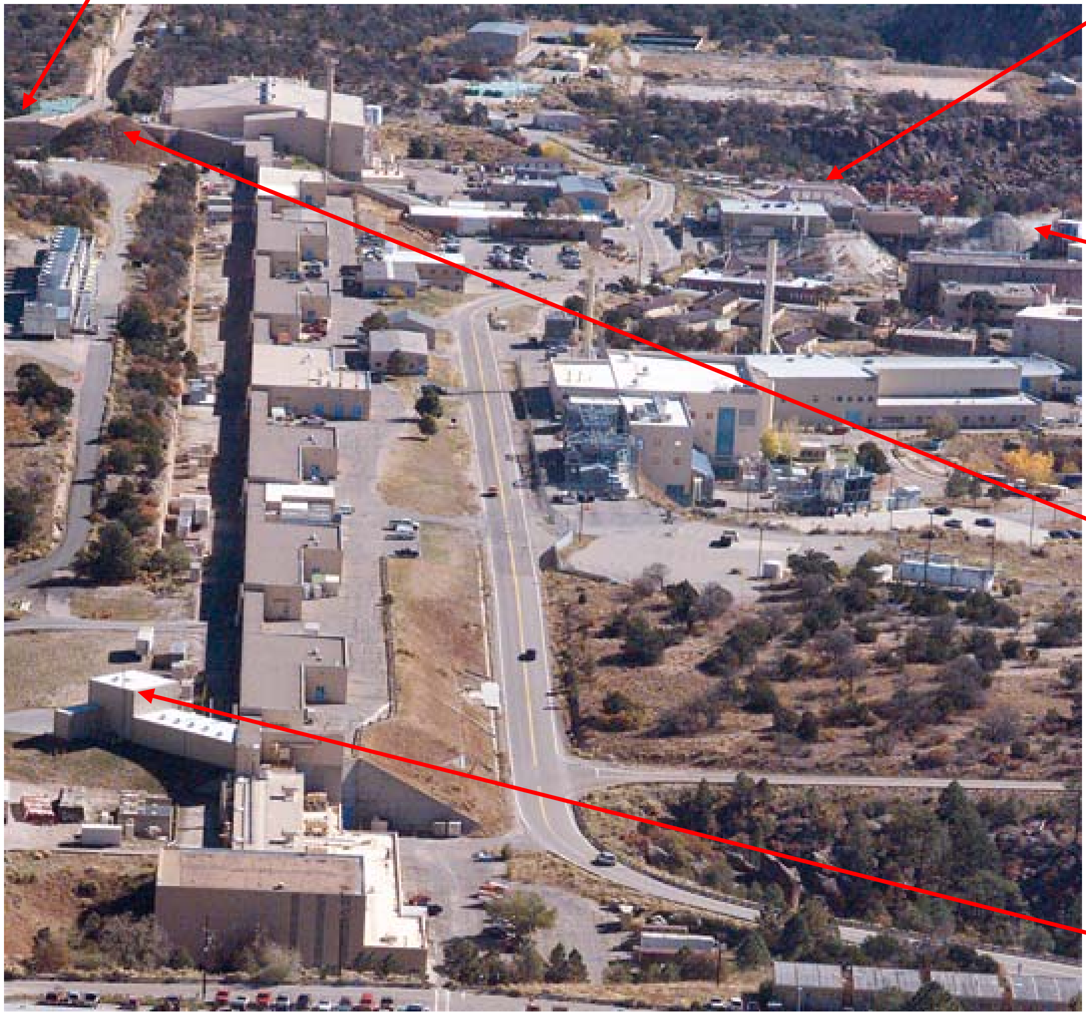
Areal Density Reconstruction: straightforward physics allows one-to-one matching of transmission and density



Los Alamos, New Mexico

LANSCE Experimental Areas

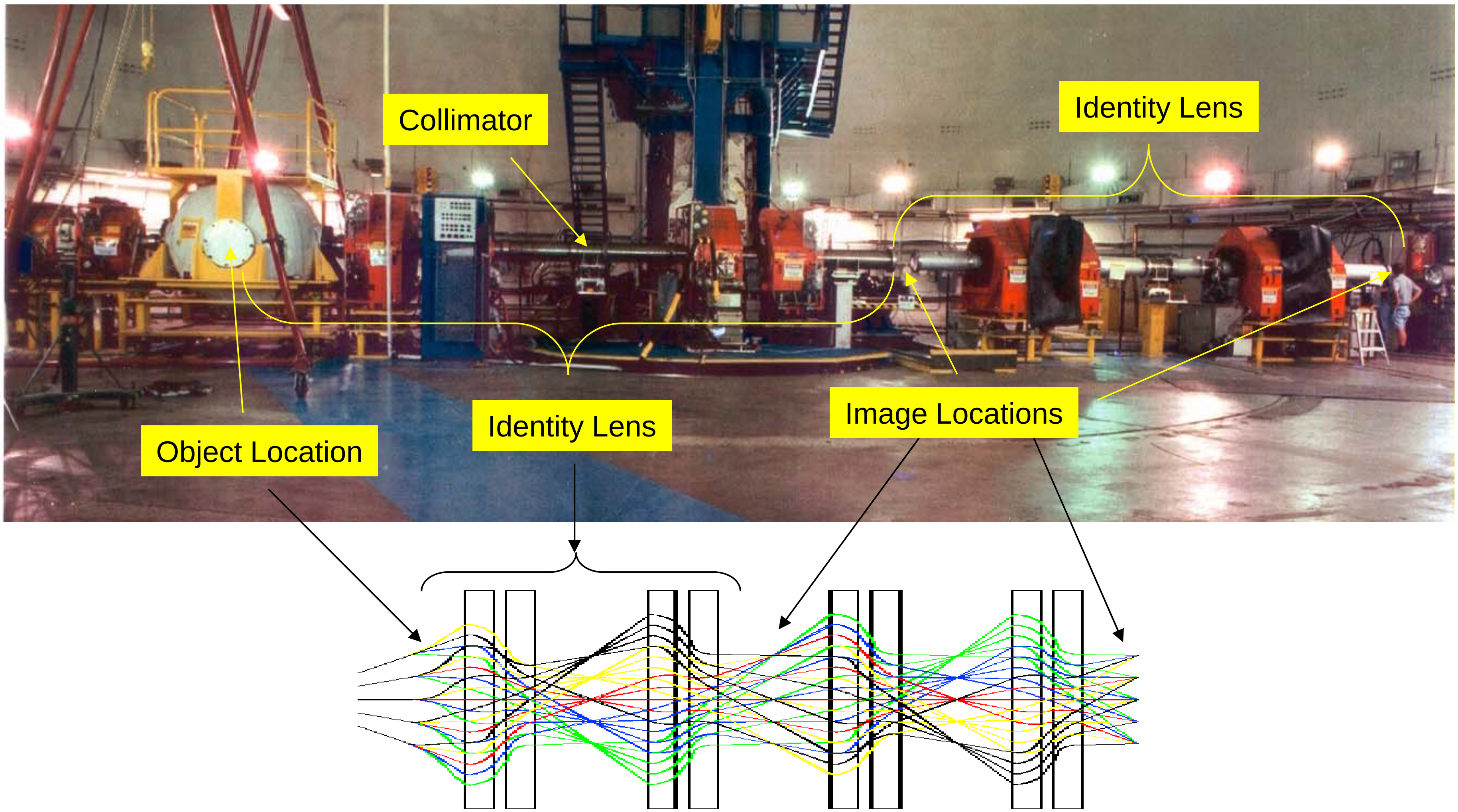
Ultra-cold neutrons



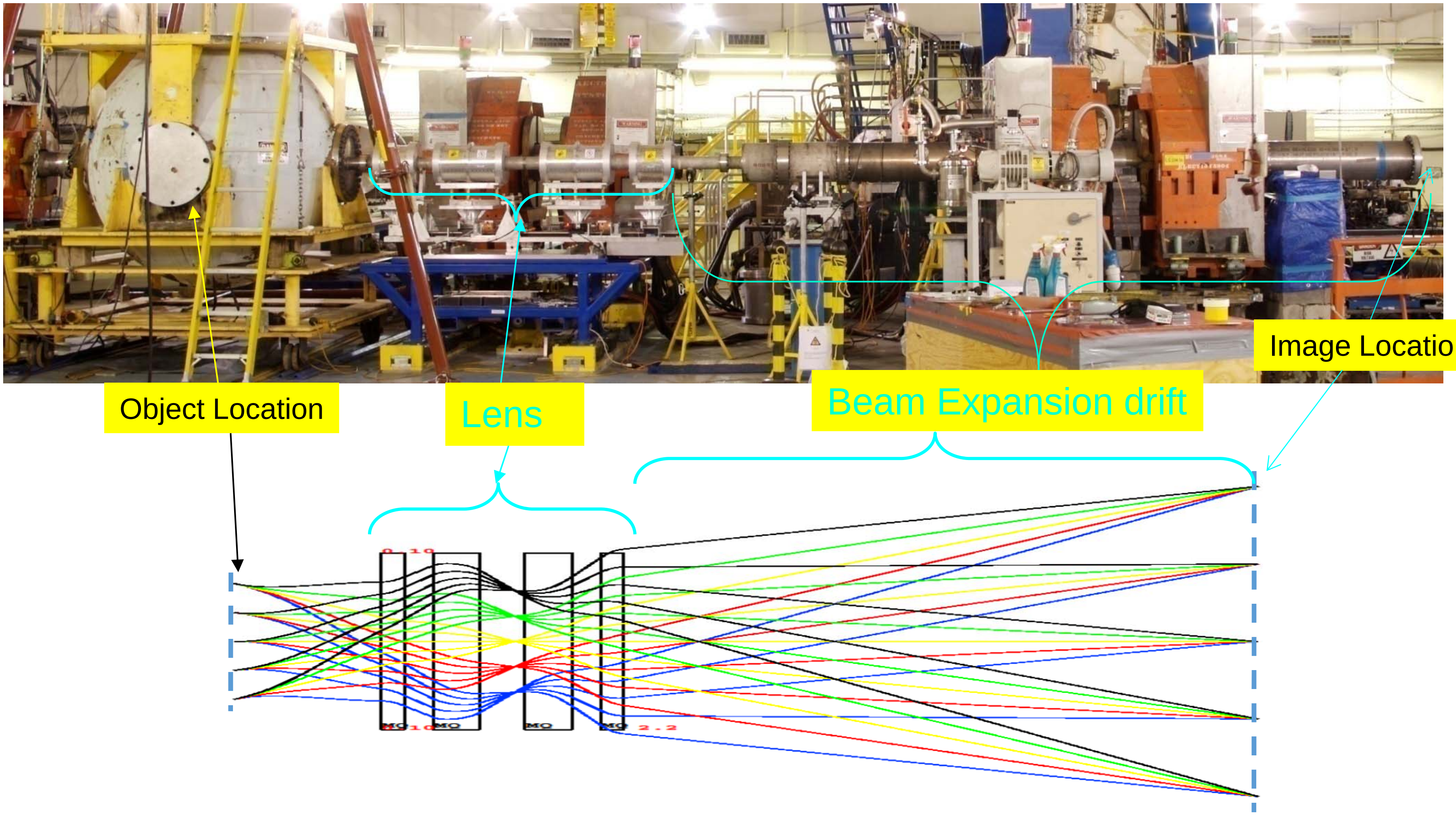
- Lujan Center
  - ***National security research***
  - ***Materials, bio-science, and nuclear physics***
  - ***National user facility***
- WNR
  - ***National security research***
  - ***Nuclear Physics***
  - ***Neutron Irradiation***
- Proton Radiography
  - ***National security research***
  - ***Dynamic Materials science,***
  - ***Hydrodynamics***
- Isotope Production Facility
  - ***Medical radioisotopes***

The pRad experimental area was inherited from the LAMPF Nuclear Physics program.

pRad Facility at LANSCE
-I Lens

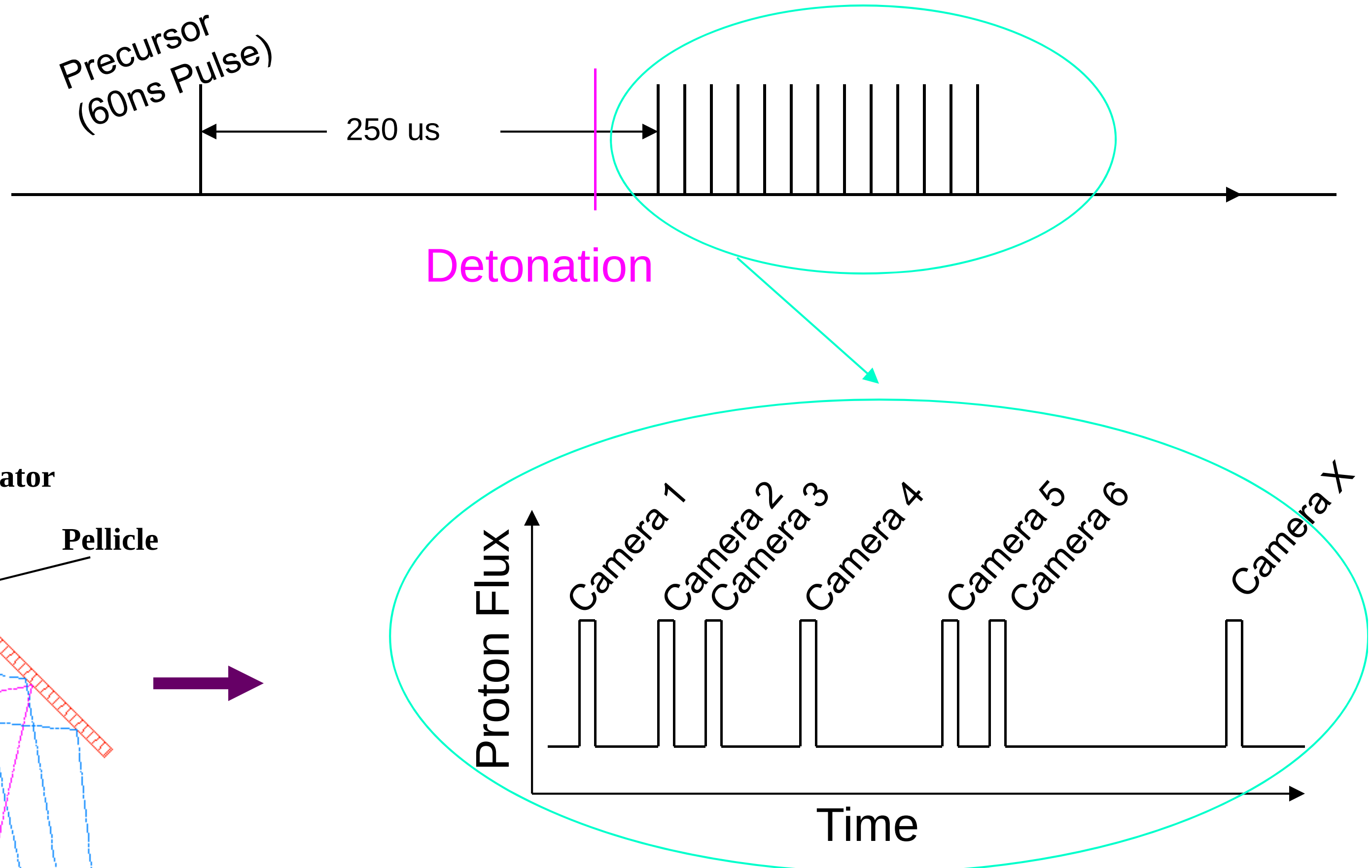


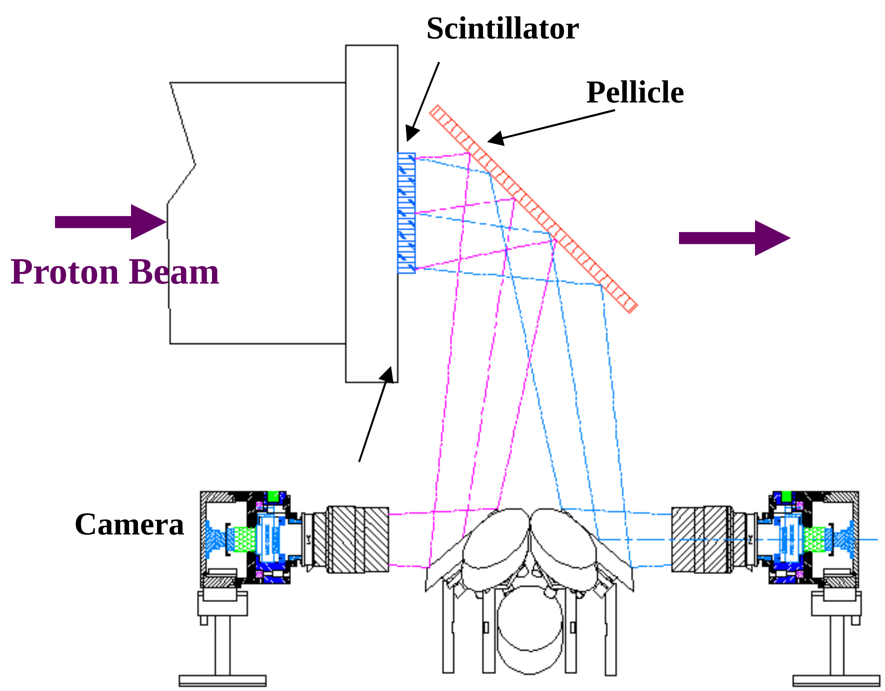
x3 Magnifier (PMQs)



Made up of four 4” bore permanent magnet quads.

Camera System and Standard Timing





- 19 images at first station (IL1)
- 22 images at second station (IL2)
- Typically 50 to 200 ns exposure times, approx. 1 us between frames

Typical Uses of pRad

pRad is especially well suited for studying very fast moving (explosively-driven) experiments. These fall into two categories:

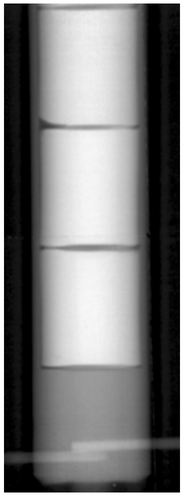
a)Studying the *behavior* of high explosives as they detonate

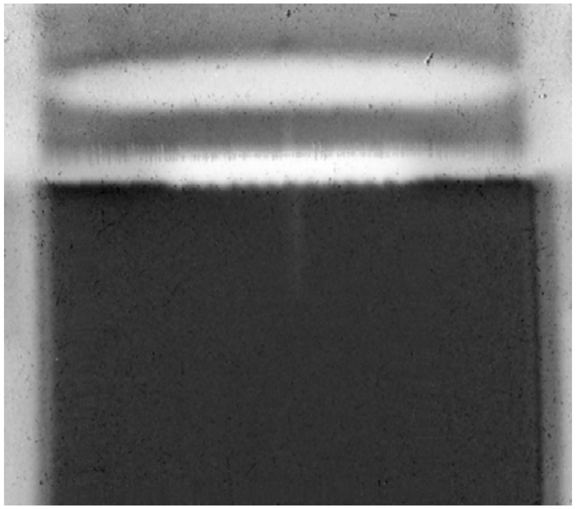
b)Studying the effects of high explosives on nearby materials

c)Radiographing objects that are themselves highly radioactive

This makes pRad extremely useful to the nation's nuclear weapons and nuclear energy programs!

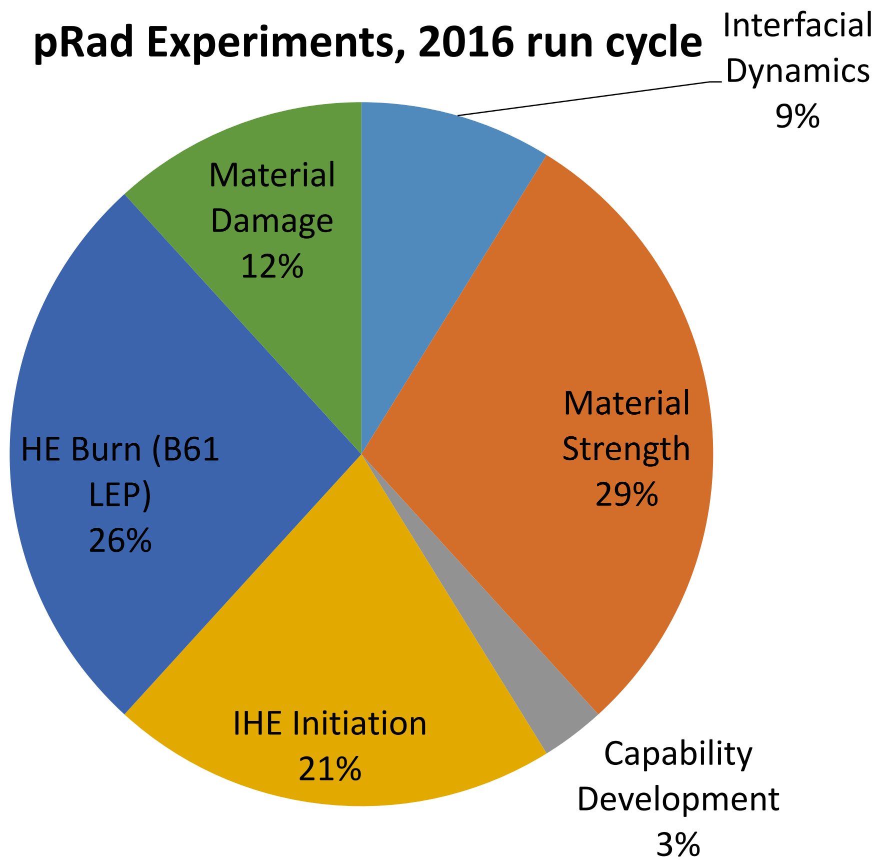
Nuclear reactor fuel pellets





Richtmyer-Meshkov Instability Studies

pRad fired 34 dynamic experiments in the LANSCE run cycle starting in September 2016



- 10 material strength
- 4 material damage
- 7 IHE Initiation
- 9 IHE Burn
- 3 Interfacial Dynamics
- 1 PG Development
- Plus many static experiments

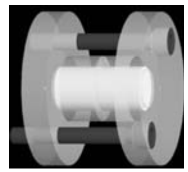
- All dynamic experiments in support of LANL weapons program
- 12 of 13 series in support of LANL weapons program
- 62 Users, 13 external to LANL (AWE, GSI)

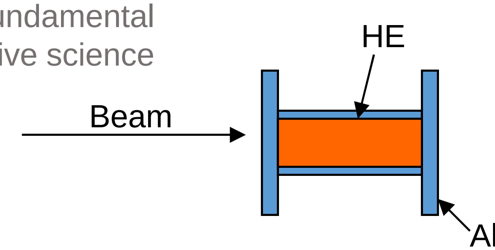
Understanding the processes of HE transitioning from deflagration to detonation is an important effort for weapons safety.

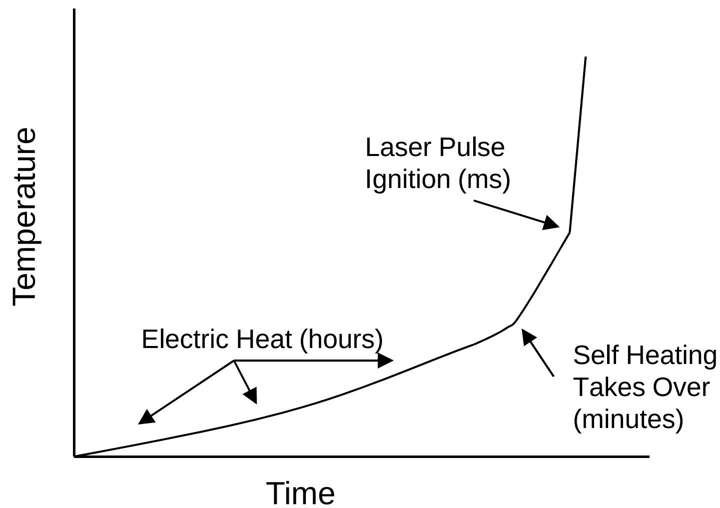
USS Enterprise, 1/1969:
28 dead, 314 injured

MK-32 Zuni rocket loaded on a parked F-4 Phantom exploded due to ordnance cook off after being overheated by an aircraft start unit mounted to a tow tractor. The explosion set off fires and additional explosions across the flight deck.

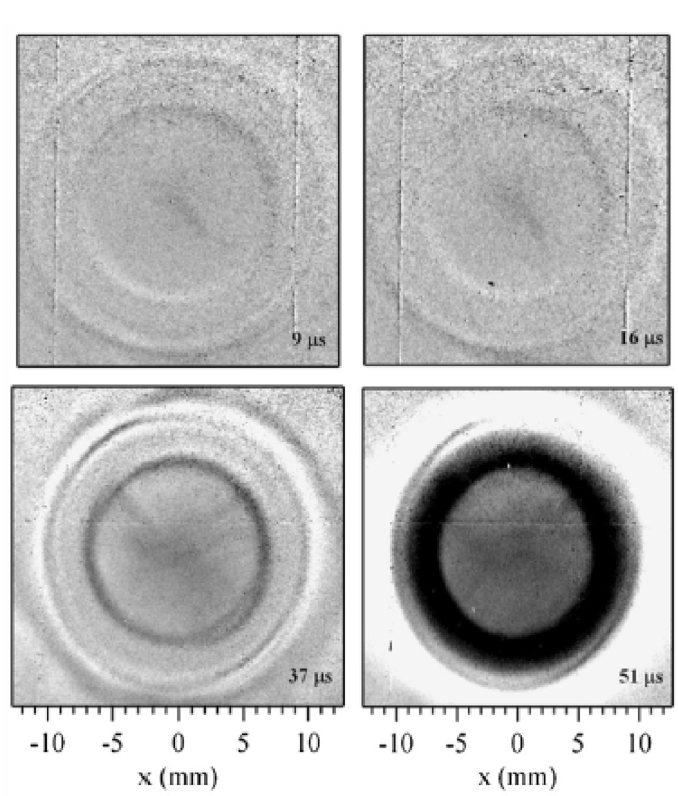
Small well diagnosed cook-off experiments aid in the fundamental understanding of explosive science



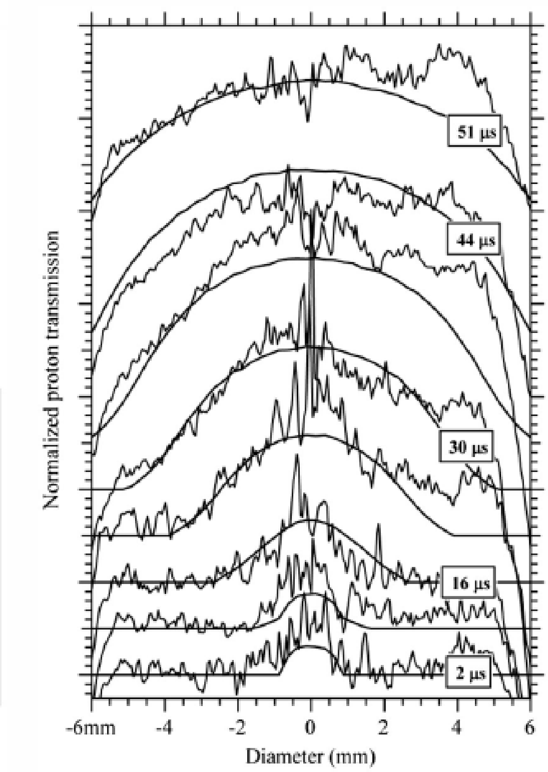




Cookoff Experiments

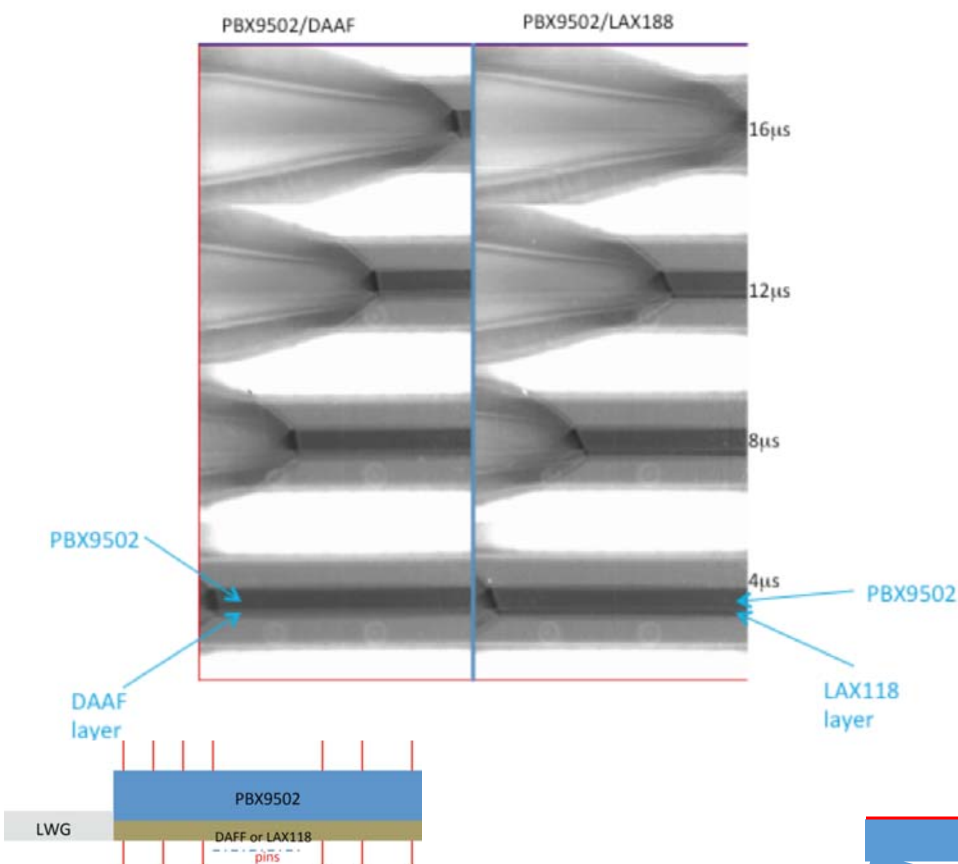


Crack formation from pressurization
Convective ignition
Conductive consumption

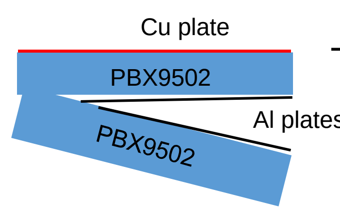


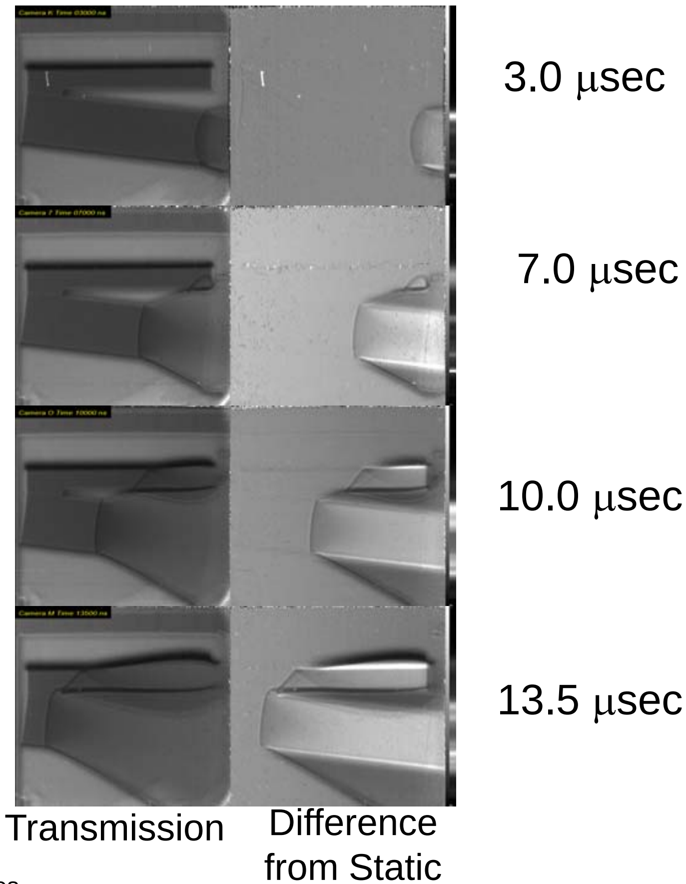
Model of convective ignition and conductive burning matches well with proton radiography data.

pRad is supporting high explosive science, design, and assessment: experiments test and validate HE models



High Explosive Sandwiches for the Advanced Certification Campaign





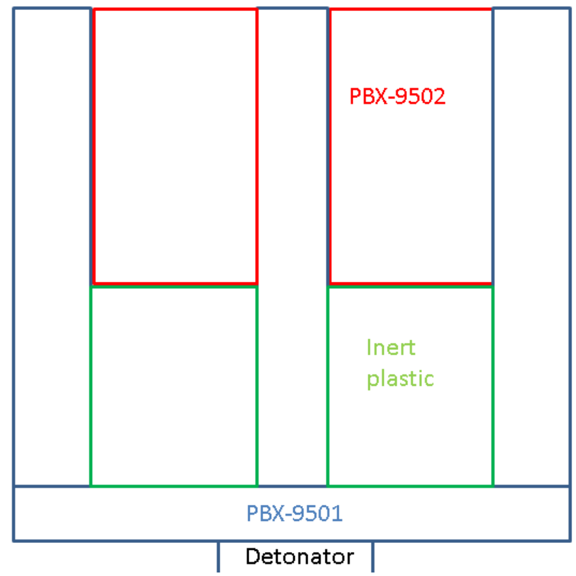
Wedge Relight for Campaign 1

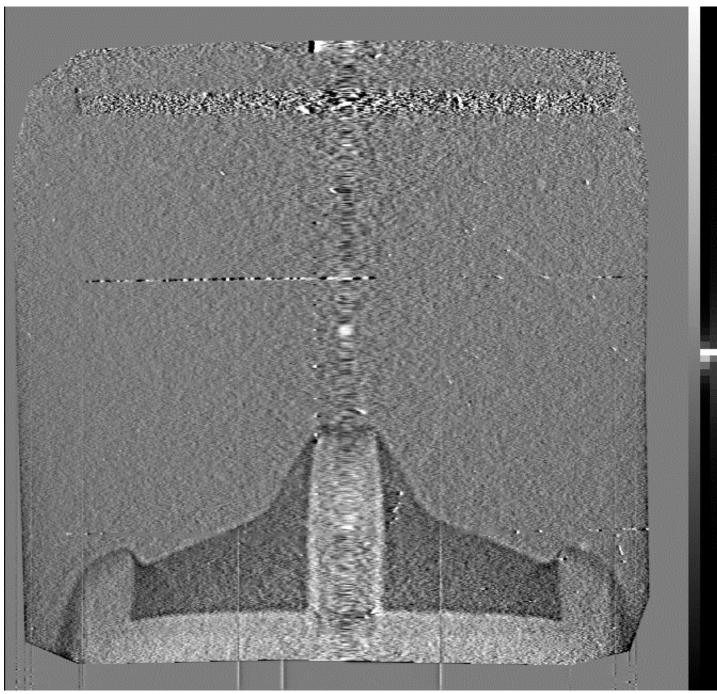
PRAD data is impacting present weapons assessment and certification decisions

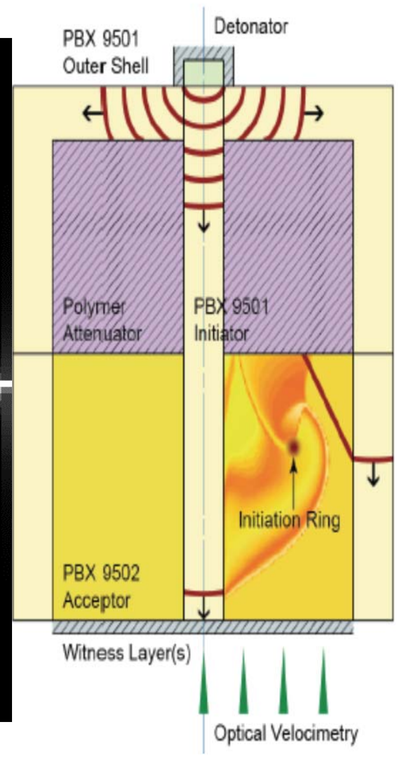
LT-63: B61 Life Extension Program (B61-LEP)

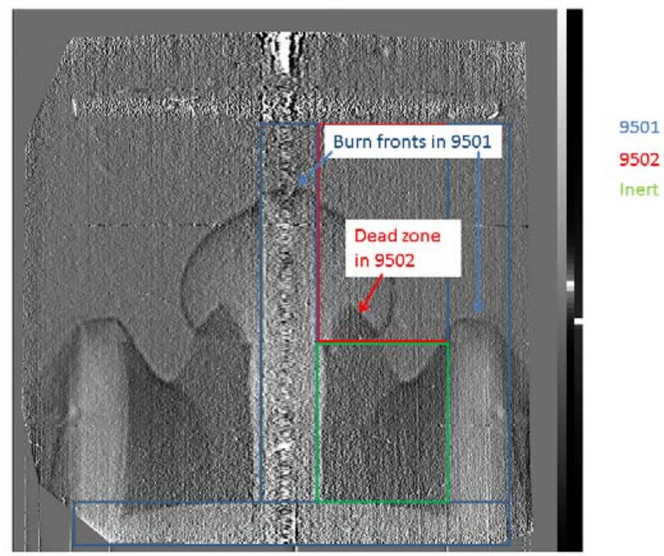
Terry Salyer (WX-9) and the pRad team fielded and executed four shots in support of the B61-LEP. These experiments were designed to help validate specific requirements for the use and function, as well as test reliability requirements in the LANL subsytem.

LT-63: studies of detonation and deadening in insensitive HE

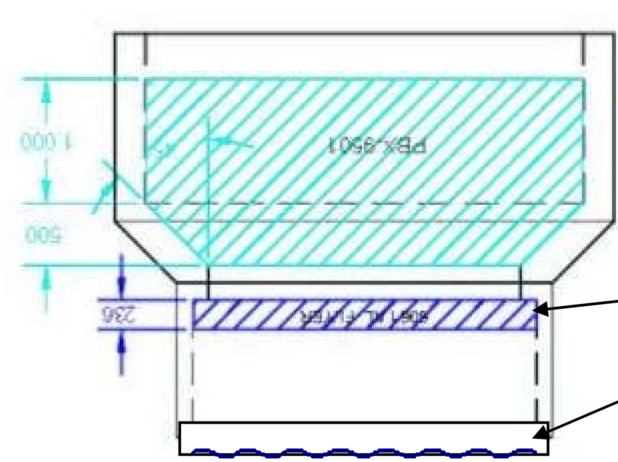


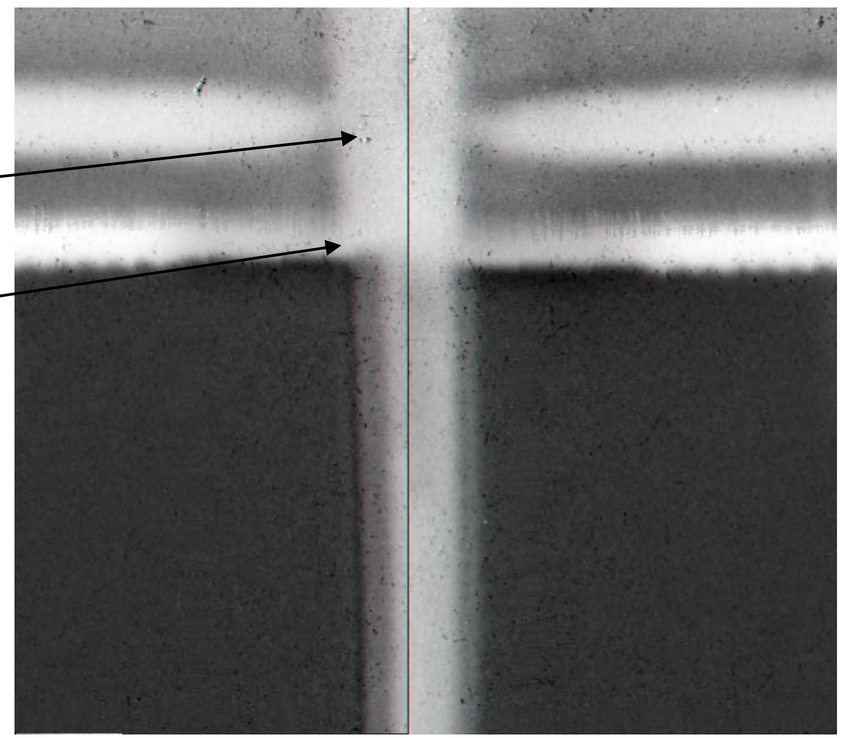






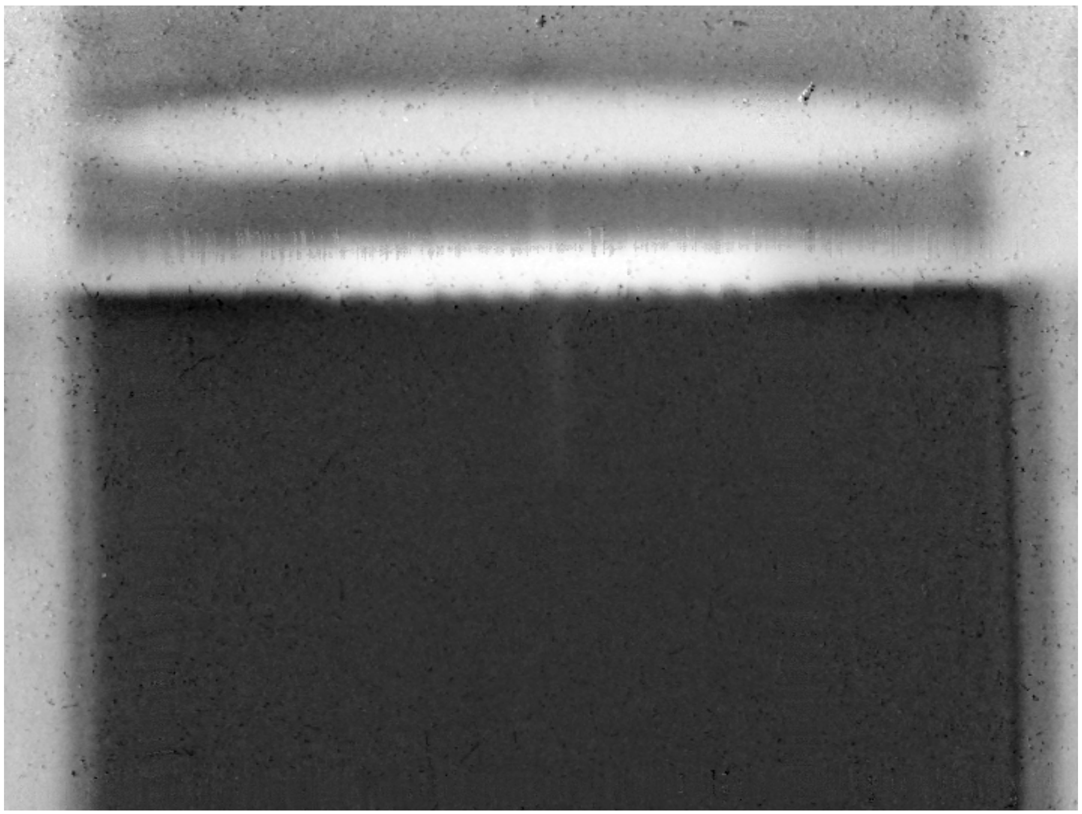
pRad has been used to make a movie of the development of a Richtmyer-Meshkov (RM) instability in solid tin (W. Buttler)

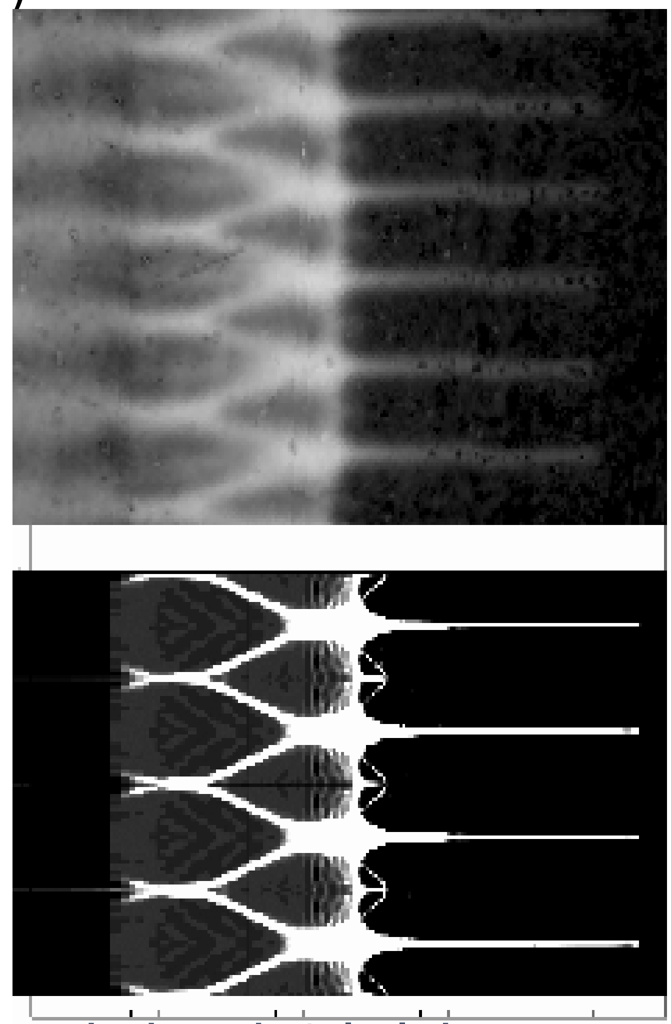




The target has a sine wave machined in its lower face

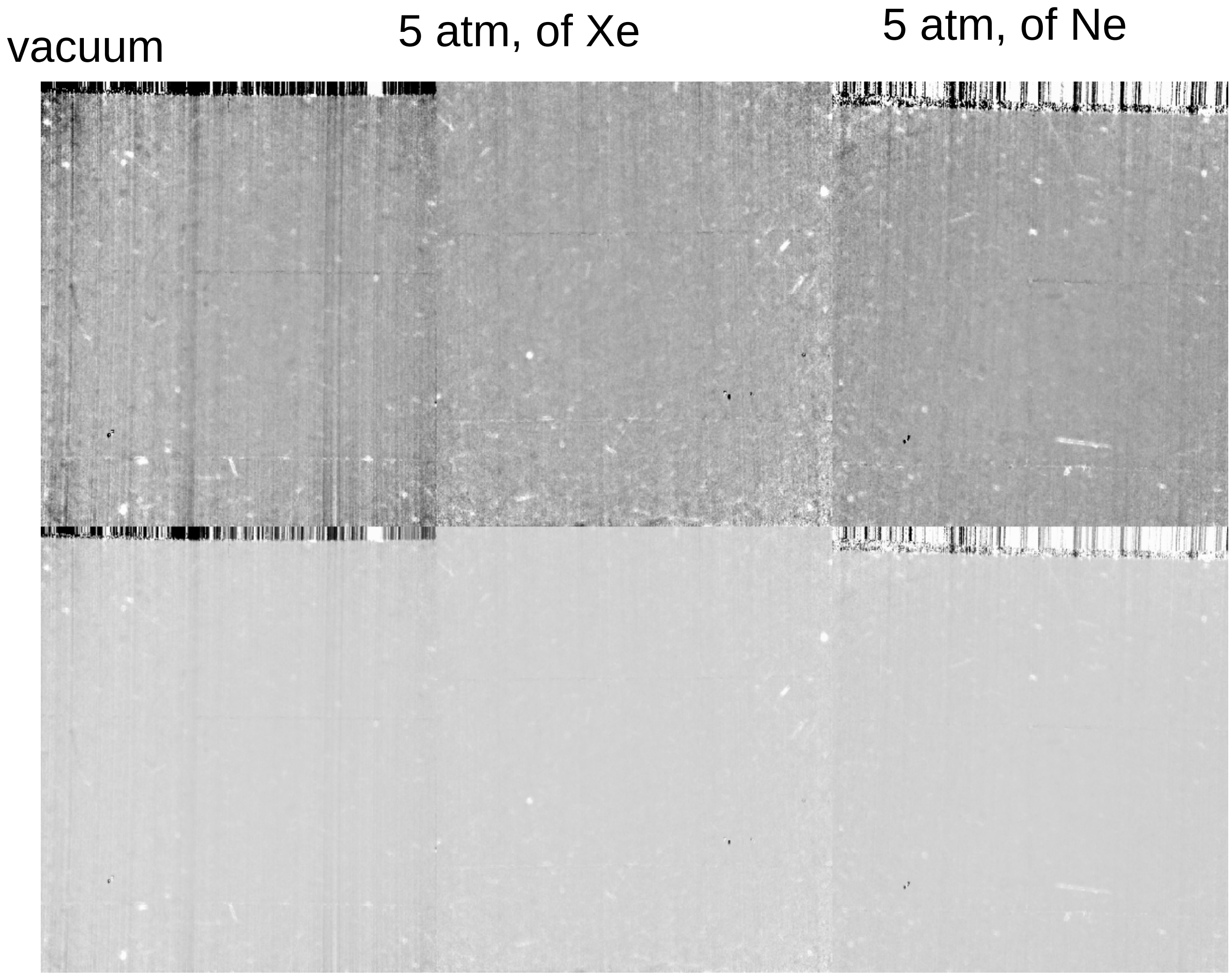
Richtmyer-Meshkov with uniform perturbation (RM) instability in molten tin (W. Buttler)



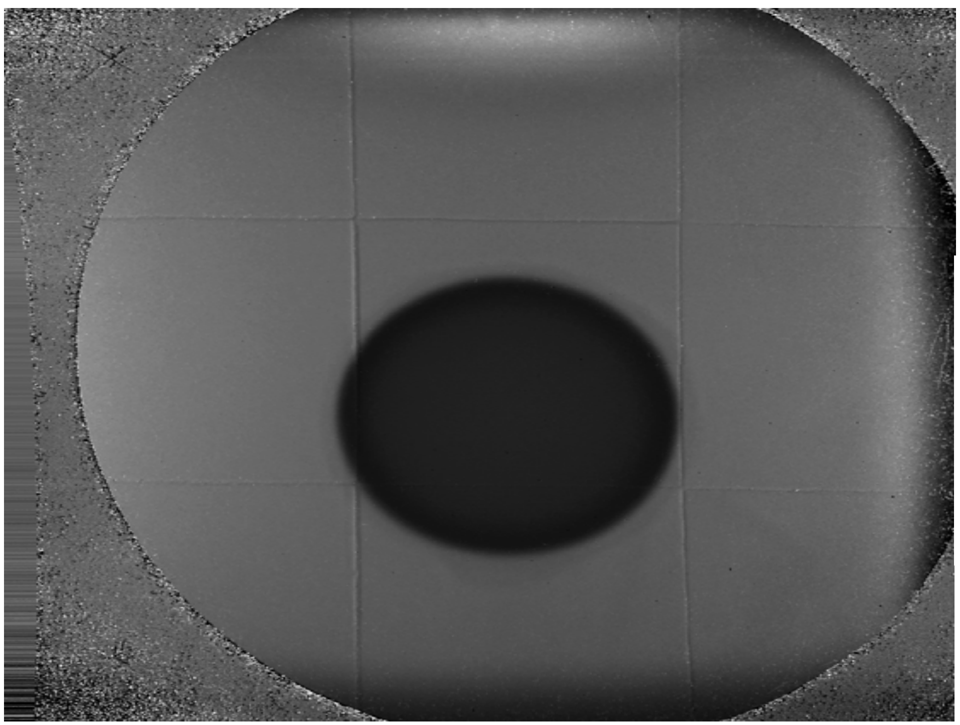


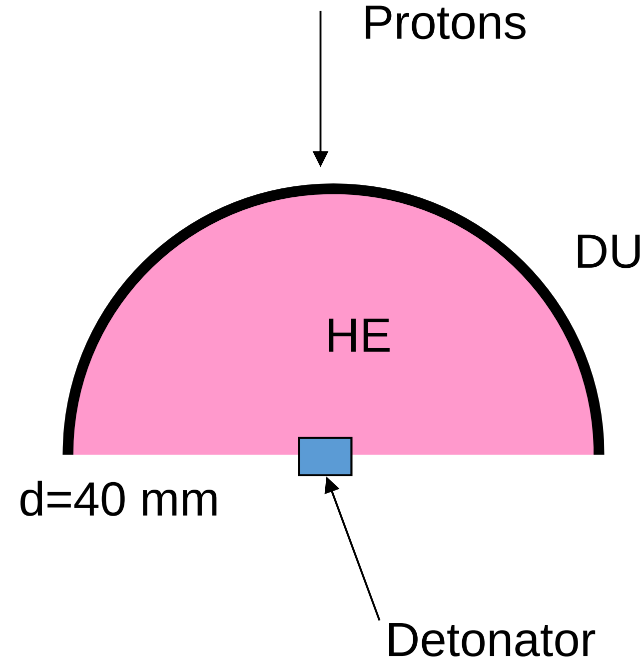
Hydrodynamic Calculations
(David Youngs et al.)

More RMI experiments: A group of three perturbations (W. Buttler)



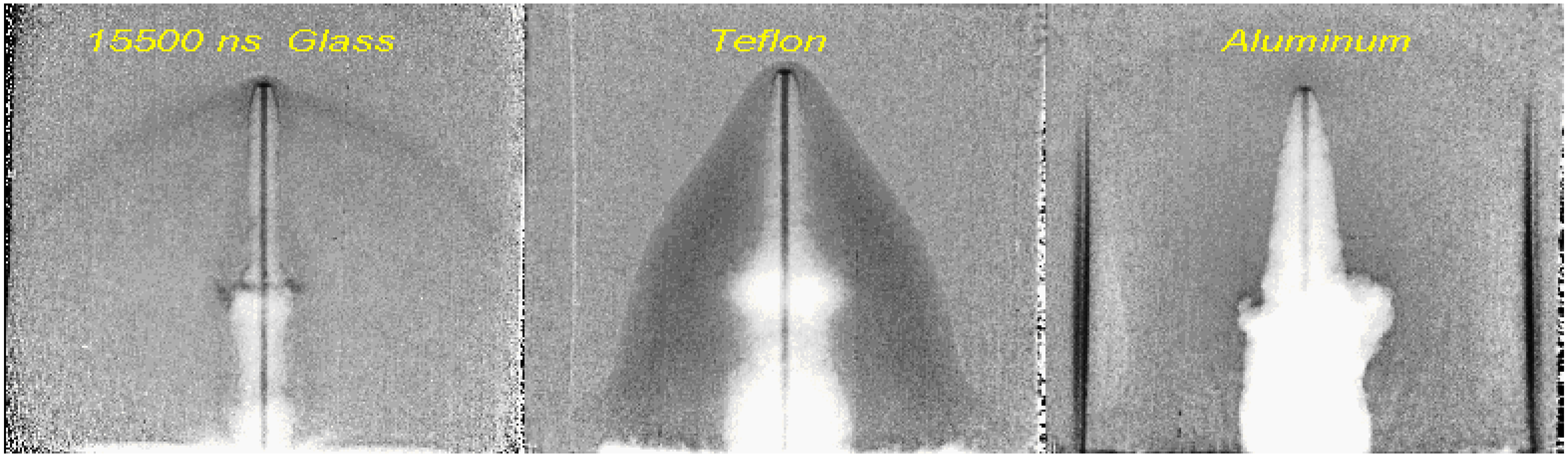
Expanding Uranium





What fraction of the area is DU vs empty?
How empty are the empty areas?

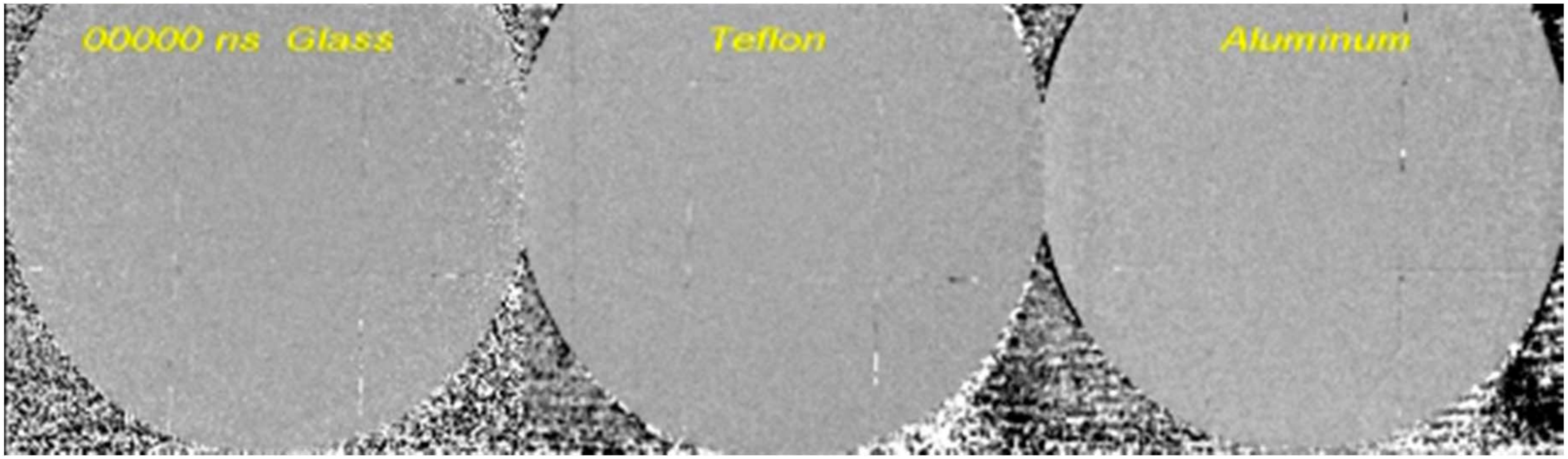
The Army Research Lab has studied shaped charge (viper) interactions with components of conventional armor materials with 800 MeV protons.

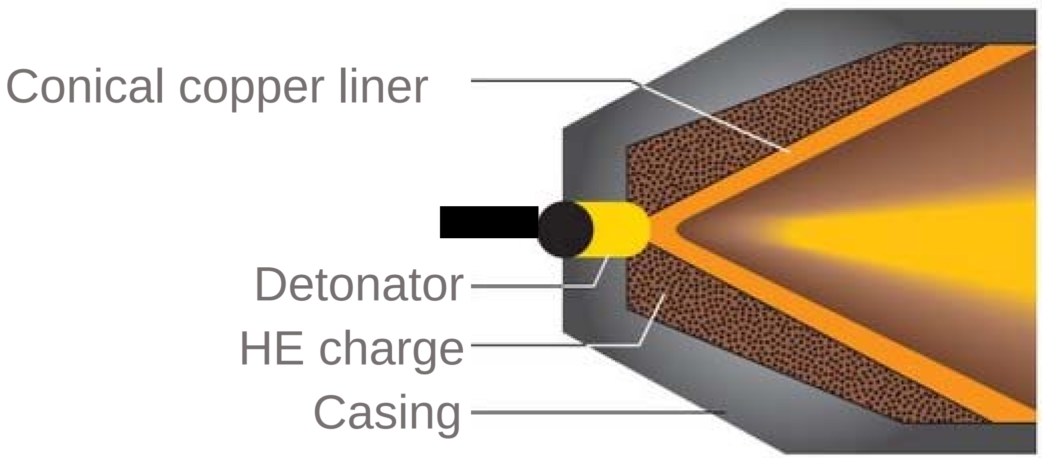


- Interest is growing from DOD laboratories to use proton radiography to address long standing dynamic materials issues.
- Previous armor development has been an empirical process. Thousands of dynamic experiments, directed through experience and intuition, would be performed to understand the most effective armor strategy for various threats.
- Recent proton radiography experiments are now revealing the underlying processes which are responsible for armor performance.
- These results are being incorporated into physics based models, which will provide the tools to quickly design new armor systems with confidence.

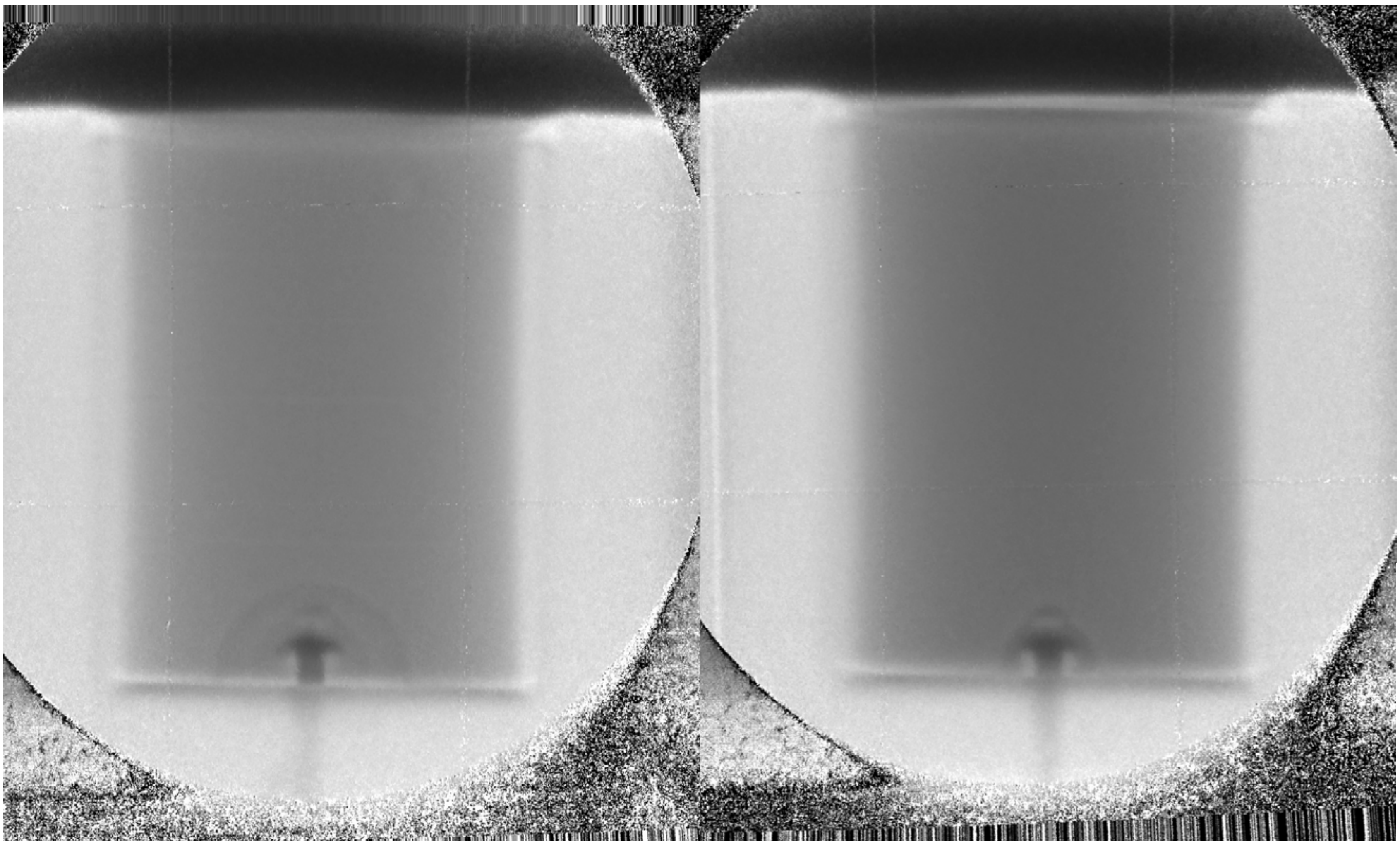
ARL has studied shape charge interactions with components of conventional armor

materials with 800 MeV protons. Proposals to look at realistic composite armor materials require penetration of 100 g/cm^2, which is beyond 800 MeV protons, but not 3 GeV.



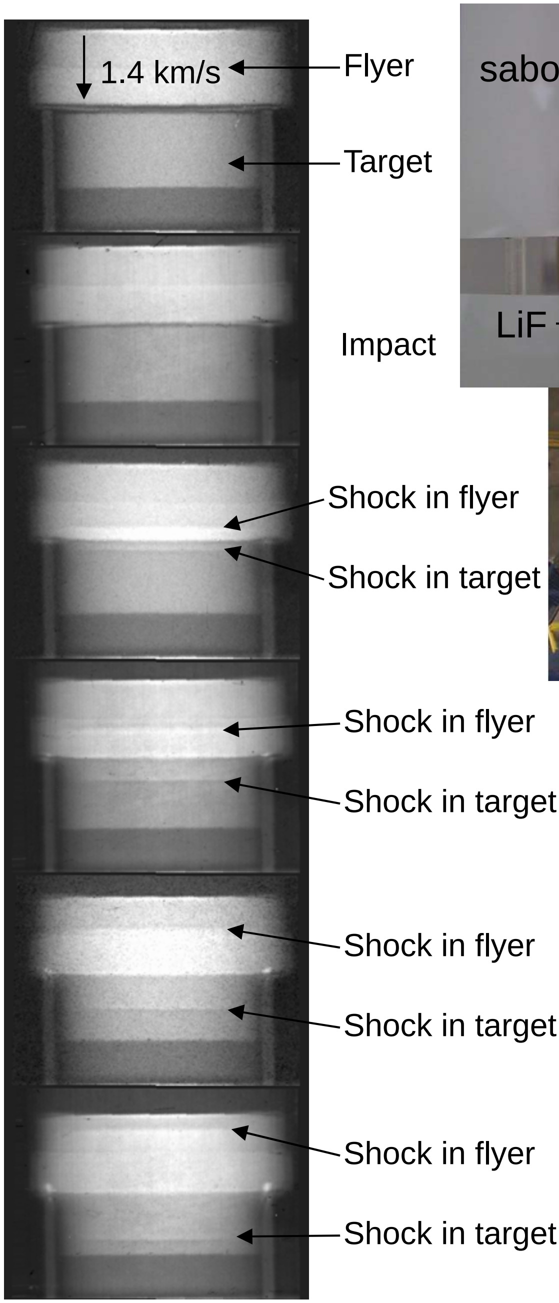


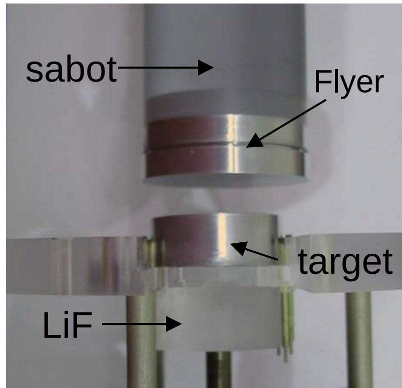
Reactive armor: using high explosives to break up jets before penetration

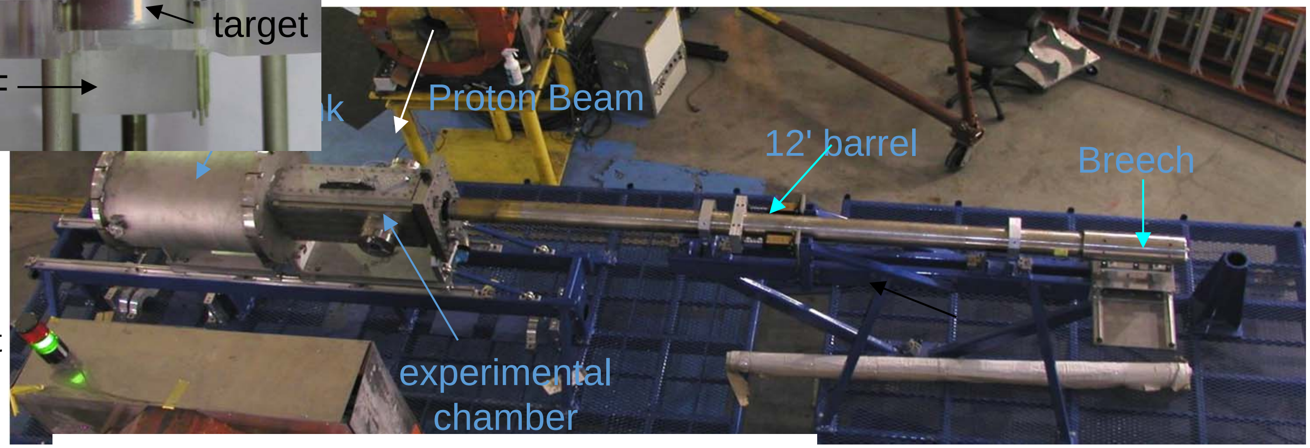


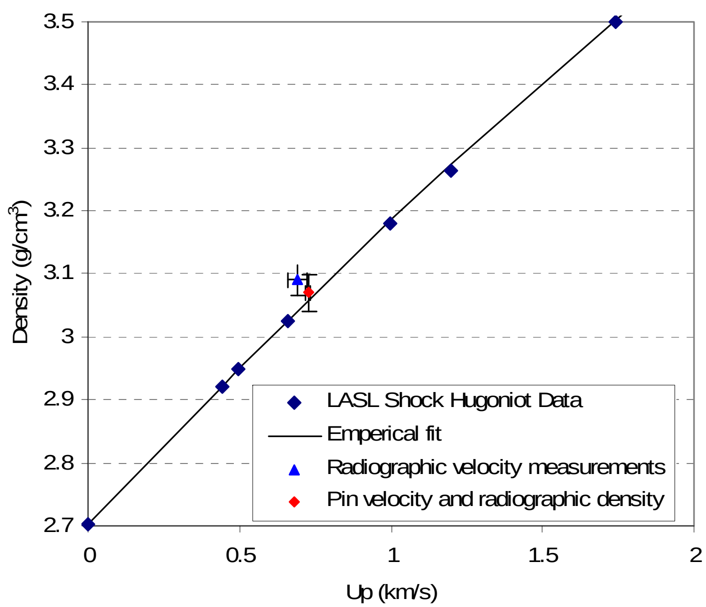
High explosive Teflon

Demonstration of new EOS measurement capability with proton Radiography









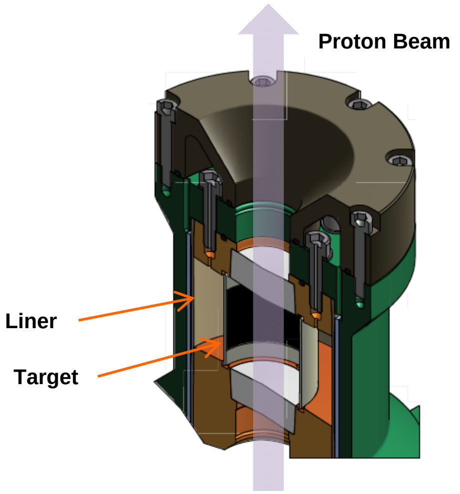
Two methods of measuring a point on shock Hugoniot per dynamic event:

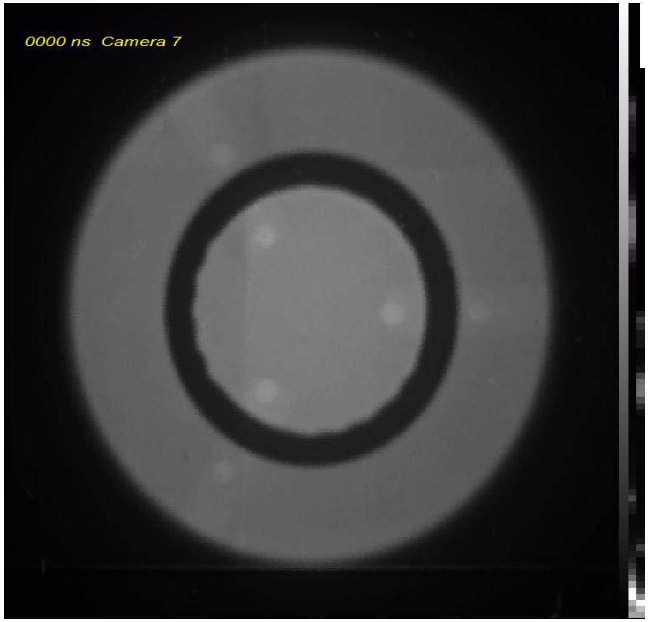
- Radiographic measurement of density behind shock front.
- Simultaineous measurement of particle and shock velocity

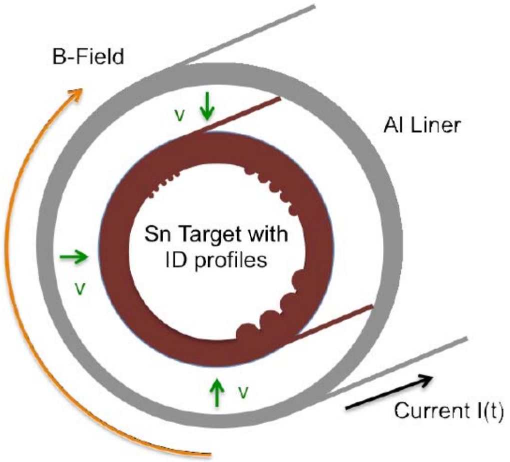
PHELIX Driven Dynamic Implosion Experiment Conducted at LANSCE Proton Radiography (pRad) Facility

- Pulsed-power driven covergent experiment conducted at pRad on Dec 9, 2015.
- PHELIX (Precision High Energy-density Liner Implosion eXperiment) portable capacitor bank (300 kJ) delivered 3.7 MA peak, 10 µs pulse to the load via cable coupled transformer.
- Cylindrical liner-on-target load configuration with perturbations on inner target surface. Self-confined experiment. No vessel.
- 100% data return (pRad, transverse X-Ray)
- 21 axial pRad images over 40 µs. Five time the imaging data in one experiment as flash X-ray.
- High spatial and temporal resolution of features of interest.

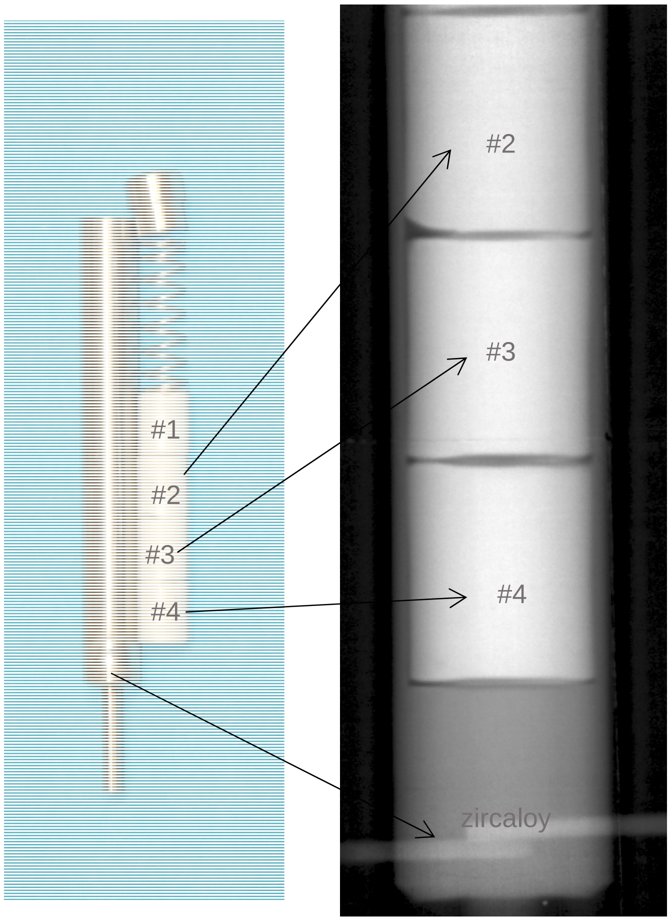
Cylindrical Liner-on-Target Load







Tomographic Studies of Nuclear Fuel Rods



Halfnium Oxide pellets

Developed the capability for tomographic reconstructions and demonstrated the new capability

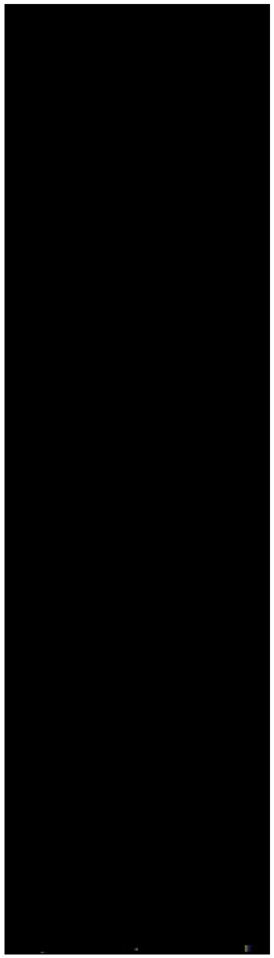
Tungsten particles

Tungsten wire transverse

Tungsten wire longitudinal

Tungsten wedge

Tungsten wedge



Tungsten wire

Tungsten wedge

Longitudinal void

Spherical voids

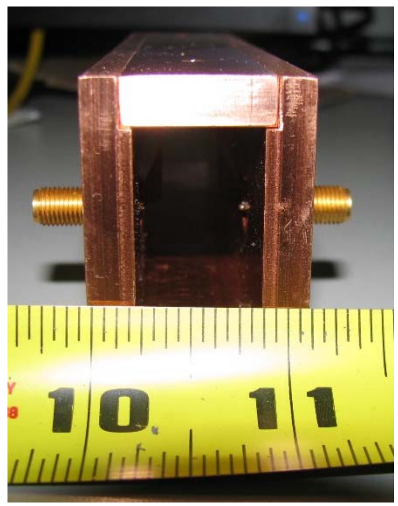
Transverse void

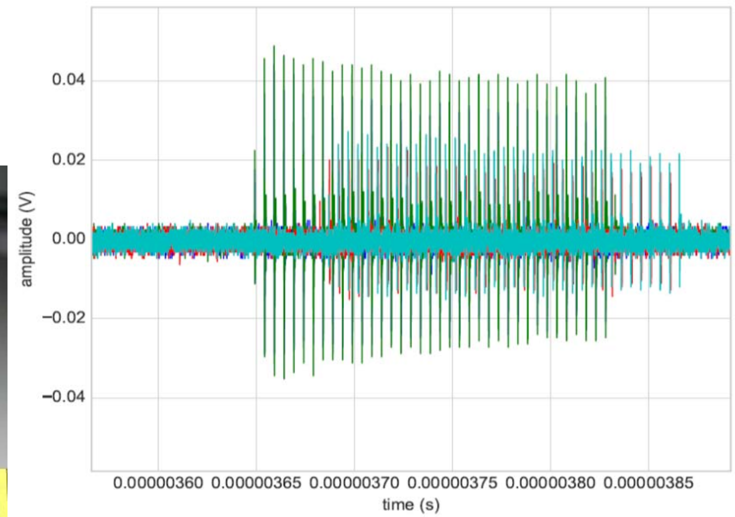
Longitudinal void

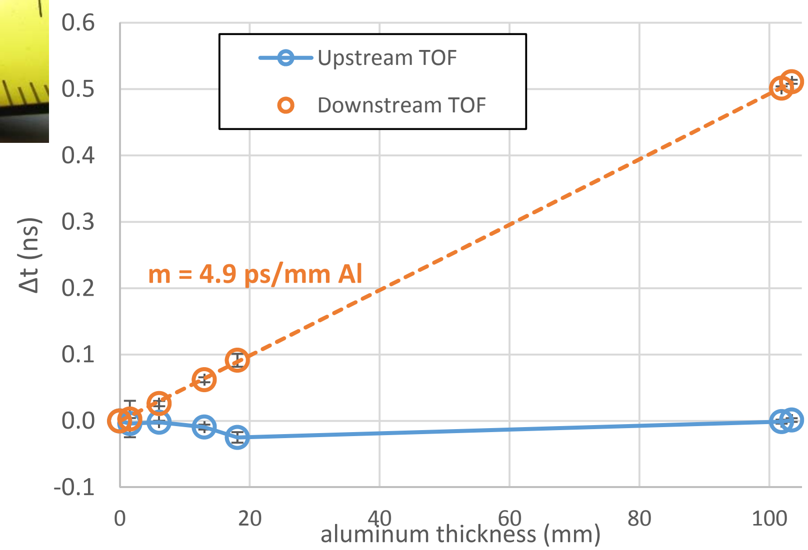
Tungsten pieces

Static Measurements Developing TOF Energy loss radiography for Hi_Phy series

- Energy loss radiography allows:
  - Precision (~1 %) measurement of density in single pixel of thick object
  - Measurements at 5 ns time spacing, up to 1 ms trace length
  - Sacrifices spatial resolution
- Results:
  - Demonstrated ~500 keV energy resolution
  - ~1% for 2.5 cm W object
  - Requires fast scopes, few picosecond time resolution, precision trigger







PRAD Core Team

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(Students)

Concluding Remarks:

Uses:

a) Study of HE detonation characteristics

b) Material strength and EOS studies with high explosive drive

Main Feature:

- Versatile timing possible due to flexibility in time patterns of the LANSCE proton beams
- Multiframe flash capability: up to 41 frames per dynamic event

Other Diagnostic Tools:

VISAR and PDV (laser velocimetry technologies) can also be deployed to measure velocities of HE driven surfaces

Pins can detect arrival of surfaces with precise timing

Other optical diagnostics