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Title: Looking Inside Explosions and Other Stuff (with new kinds of Radiology)

Author(s): Christopher Morris, P-25
Subatomic Physics

Intended for: The Frontiers in Science Public Lecture Series
August 25, James A. Little Theater, Santa Fe, NM
August 27, 2009 Duane W. Smith Auditorium
Los Alamos, NM
Sept. 1, 2009 NM Museum of Natural History & Science,
Albuquerque, NM

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Form 836 (7/06)

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The Los Alamos National Laboratory Fellows Present:
The *Frontiers in Science* Public Lecture Series

Free Admission (Bring a friend!)

Looking Inside Explosions (and Other Things)

Dr. Christopher Morris
Subatomic Physics Group
Los Alamos National Laboratory

The ability to see within objects advances science, medicine, and even provides a better understanding of the forces unleased by high explosives during detonation. During his presentation, Dr. Morris will talk about the history and science of radiography and how x-rays, protons, and naturally-occurring cosmic rays can be used to see through opaque objects. From assisting surgeons with pictures of what's inside a human body to helping border agents find nuclear contraband inside freight containers, a wide range of applications will be discussed.

Tuesday, August 25 at 7 p.m.
James A. Little Theater, New Mexico School for the Deaf
1060 Cerrillos Road, Santa Fe

Thursday, August 27 at 7 p.m.
Duane W. Smith Auditorium
Los Alamos High School, Los Alamos

Tuesday, September 1 at 7 p.m.
New Mexico Museum of Natural History and Science
1801 Mountain Road NW, Albuquerque

Thursday, September 3 at 7 p.m.
Taos Convention Center
120 Civic Plaze Drive Coronado Hall, El Alcalde Room, Taos

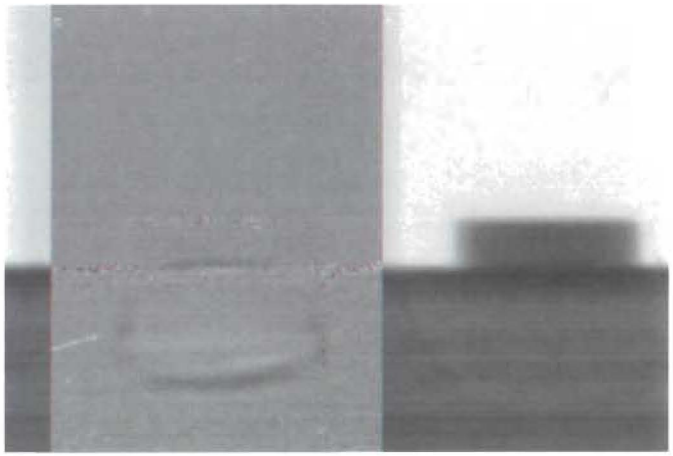
For more information, please contact the Community Programs Office at 665-4400 or (888) 841-8256 toll free.

Learn more about this series at the Los Alamos Fellows Frontiers in Science website

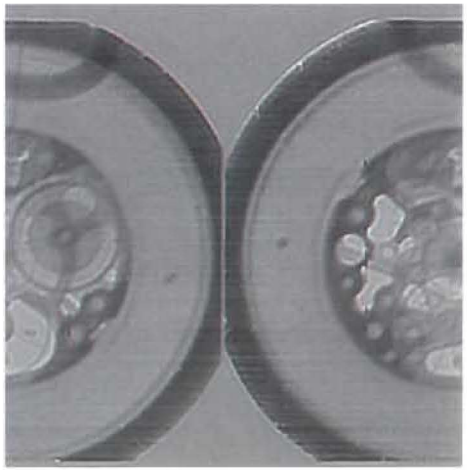
Looking inside explosions and other stuff (with new kinds of radiology)

Chris Morris
Physics
Los Alamos National Laboratory

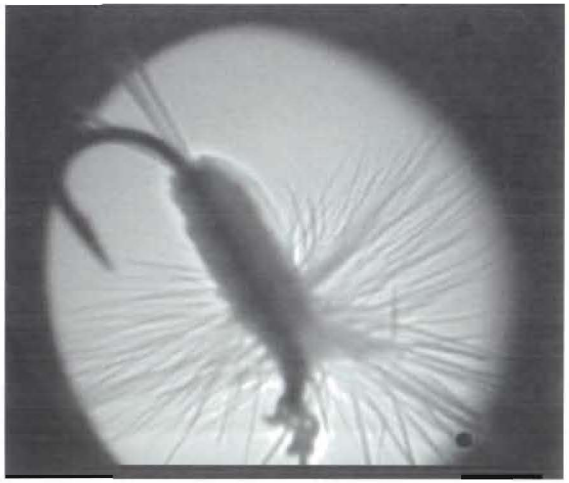
5×10^6 Hz
800 MeV p



2 Hz
800 MeV p



30 MeV e



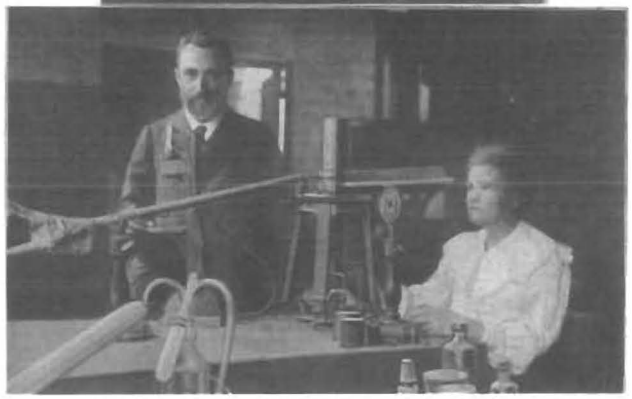
Los Alamos

Physics

Radioactivity, three discoveries-three Nobel prized

Wilhelm Conrad Roentgen
Discovered x-rays in 1895
First Nobel prize in physics 1901

Antoine Henri Becquerel
Discoveried Radioactivity in 1896 shared the Nobel prize in physics with **Pierre and Marie Curie**, 1903

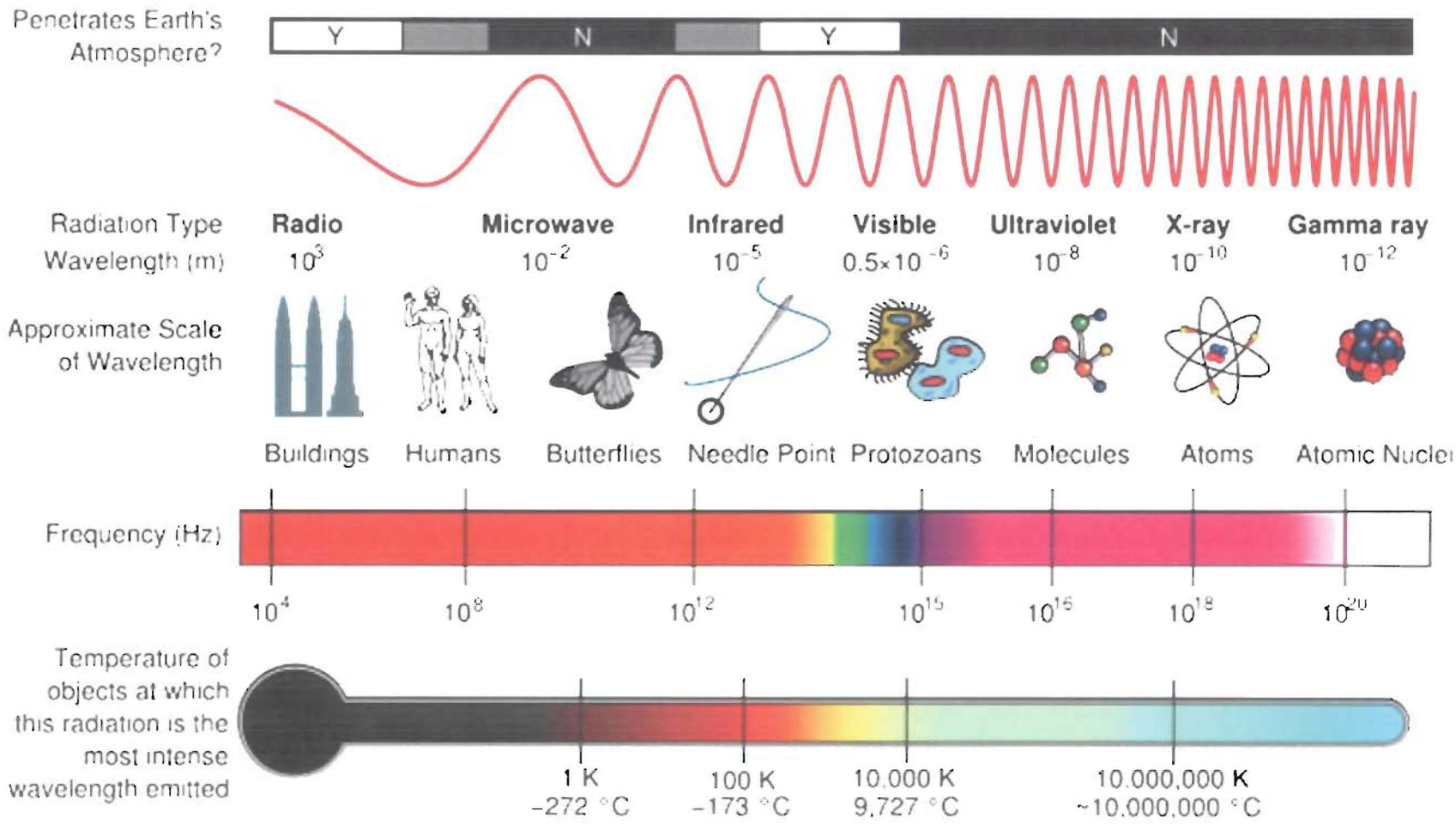


Victor Franz Hess
1910-1913 showed cosmic rays come from outside the solar system. Shared the Nobel prize in 1936 with C.D. Anderson

Los Alamos

Physics

Visible light
x-rays

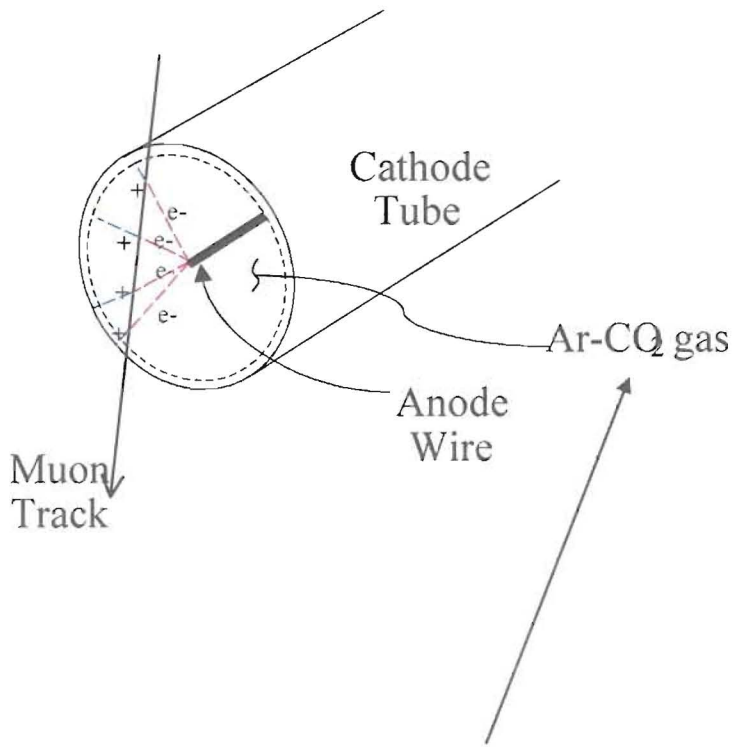


Los Alamos

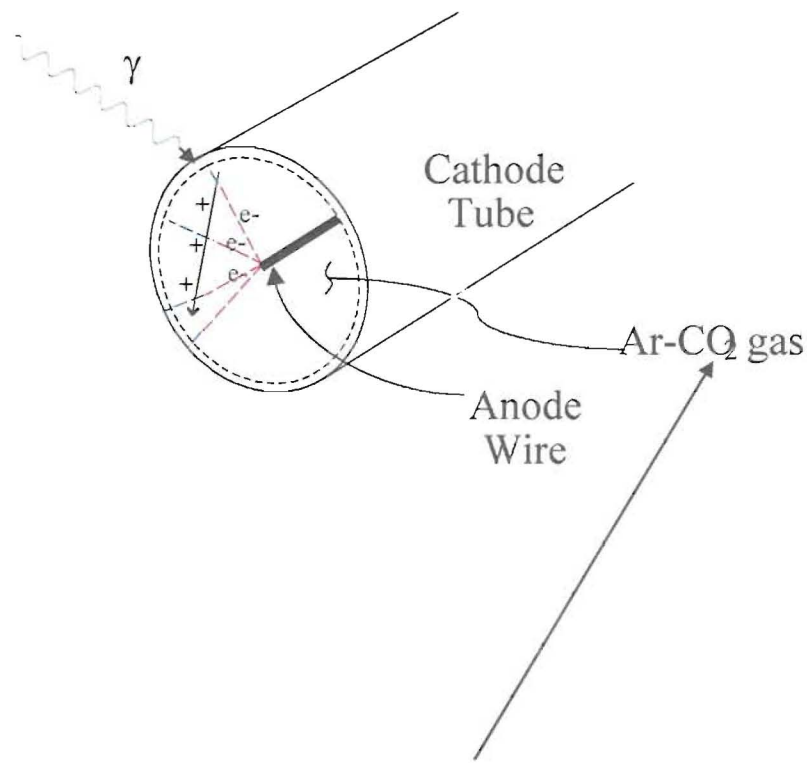
Physics

Demonstration of radiation

Energetic charged particles



Neutral particles



Los Alamos

Physics

1895-the beginnings of radiography

Burndy Library

Prof. Wilhelm Conrad Röntgen

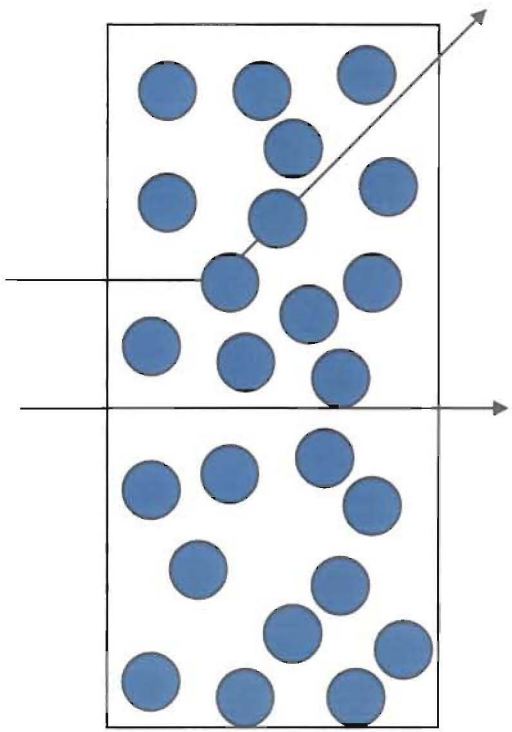
Burndy Library

Gunshot in the hand

Prof. Michael I. Pupin of Columbia University first heard of Röntgen's discovery directly from a German physicist friend. He immediately set up the equipment to perform X-ray experiments and, in the first days of February, 1896 was asked to radiograph the hand of a New York attorney accidentally shot. The above, signed by Pupin, is one of the earliest records of the aid to surgery made possible by the invisible rays.

[1] W. C. Röntgen, Nature **53** (1896) 274.

Cross section/mean free path-vocabulary, what Röntgen figured out



In 3 - d

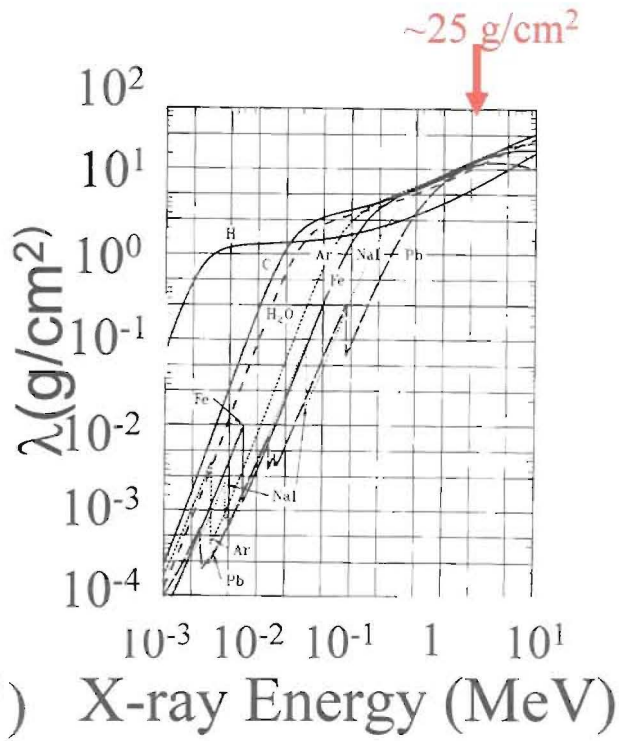
$$\sigma = \pi r^2$$

$$\lambda = \frac{1}{\sigma\rho}$$

λ is the mean free path

σ is the cross section

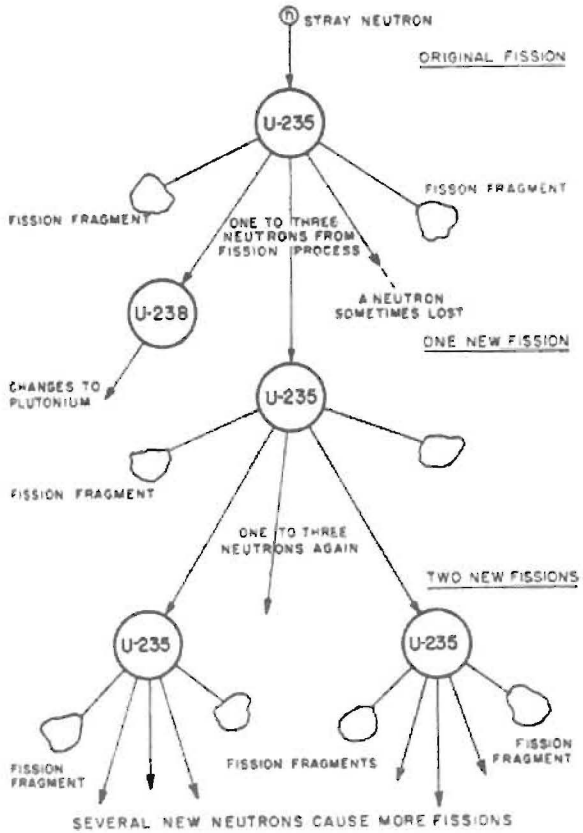
ρ is the density (atoms/cm^3)

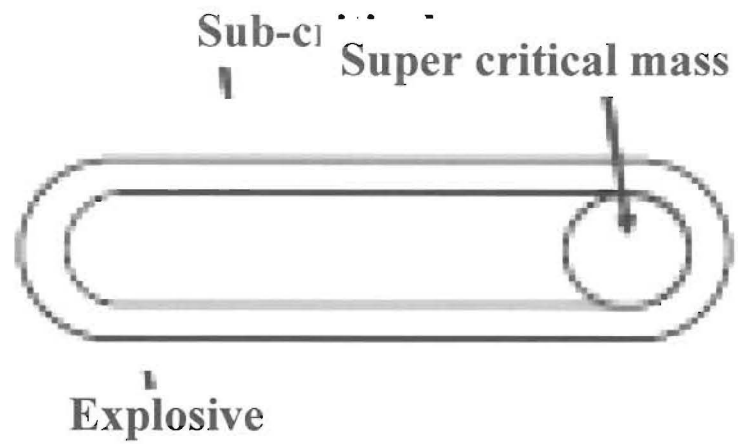


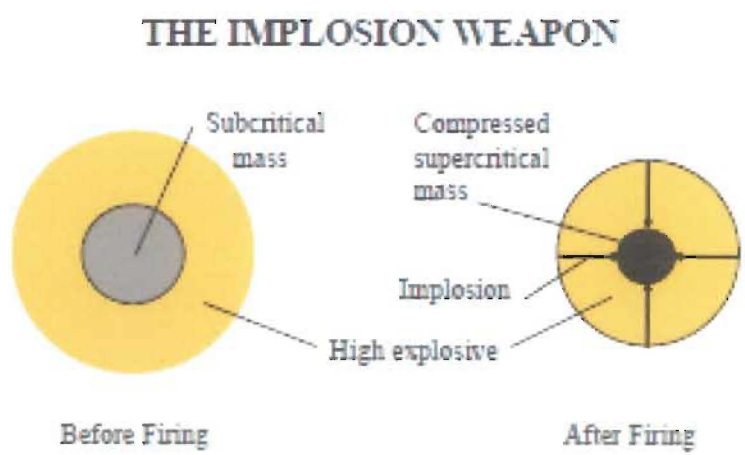
Los Alamos

Physics

Creating a nuclear explosion

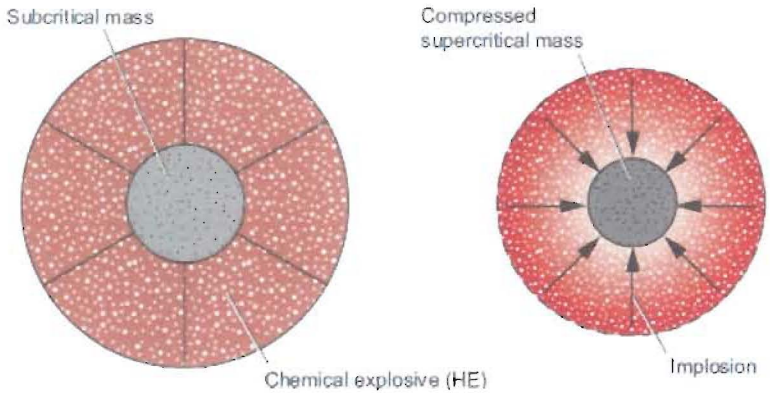


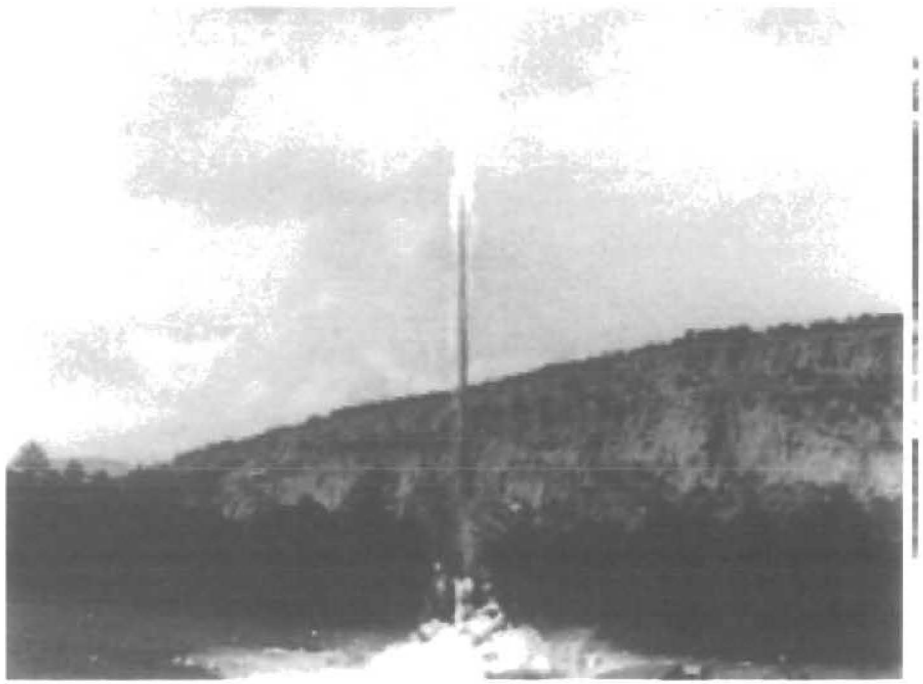


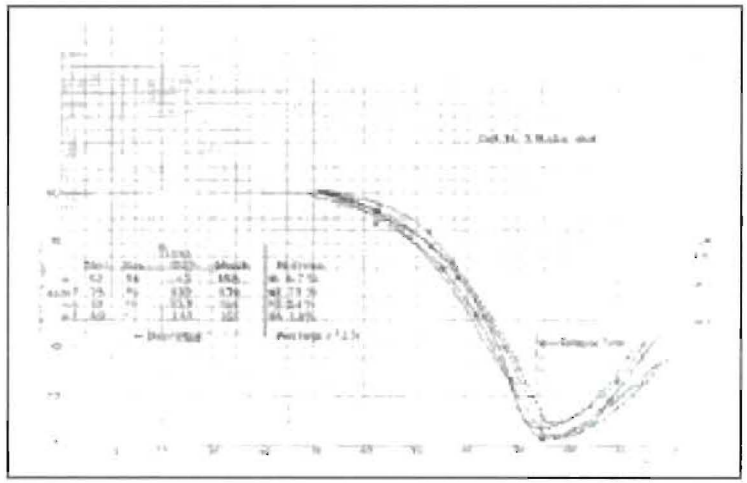


- High explosives
- Shock physics

RaLa experiments





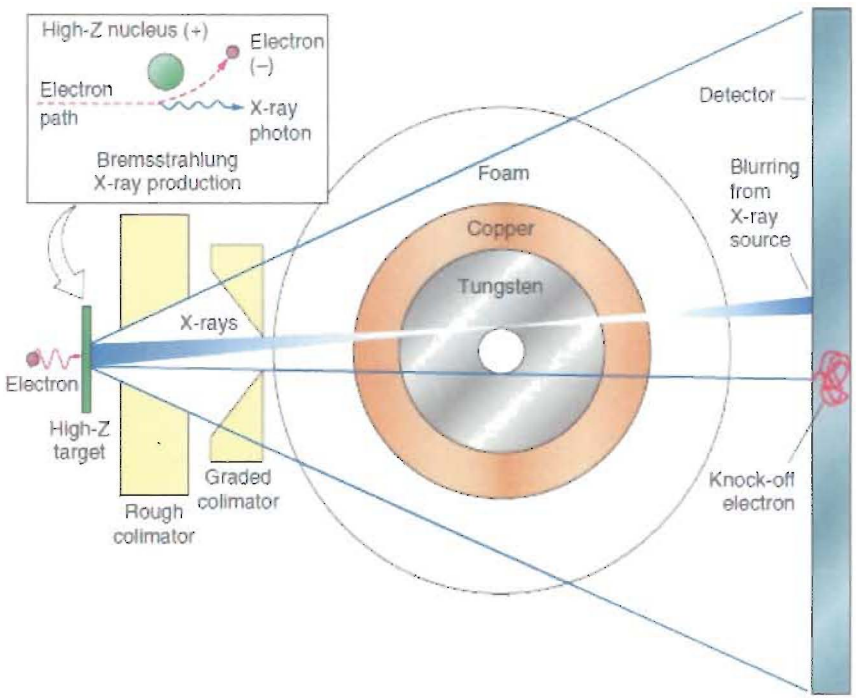


Robert Serber

Flash radiography of a surrogate material implosion (Manhattan project)

- 15 MeV betatron X-ray source
- 1 μsec long pulses
- Wilson cloud chamber detector

Flash Radiography



[1]Glen Seay (1952); Douglas Venable, "Phermex", Physics Today **17**, 19 (1964)

How do we take care of the nuclear stockpile without nuclear testing?

- Cold war stockpile
  - Remanufacture?
  - Science (back to WWII)?
  - Redesign?
  - Negotiated reductions?

- Implosions with surrogate materials coupled with modeling and simulation.
- Scientific understanding of shock waves and explosions

Beer's law*

Ideal radiography
- No background
- Mono-energetic

$$\frac{dN}{dz} = -\lambda N$$

$$N = N_0 e^{-\frac{z}{\lambda}} \; *$$

$$l = -\lambda \ln\left(\frac{N}{N_0}\right)$$

Error analysis
- Poisson statistics

$$\Delta l = \frac{\lambda}{\sqrt{N}}$$

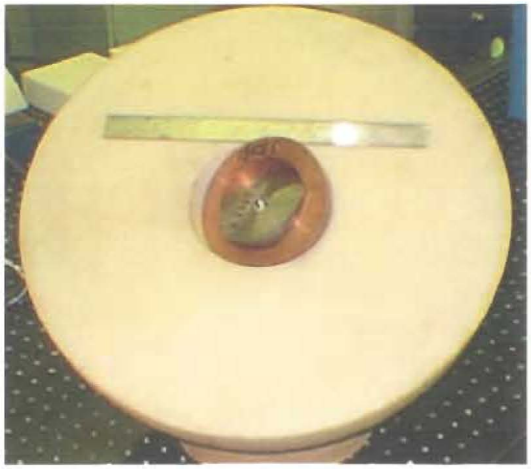
$$\frac{d(\Delta l)}{d\lambda} = 0$$

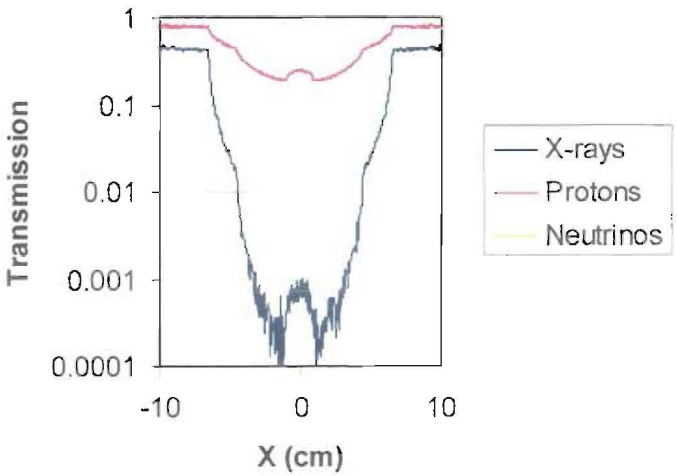
$$\Rightarrow \lambda = \frac{l}{2}$$

*A. Beer, *Ann. Physik. Chem.* **86** (1852) 78.

Different probes-10^9 incident particles.

French test object (FTO)

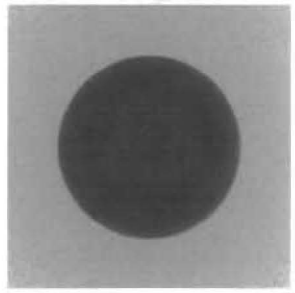


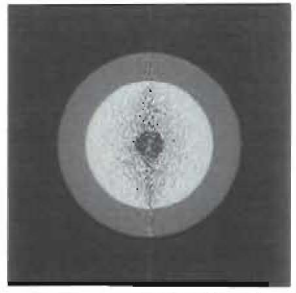


Simulated radiograph | Density reconstruction

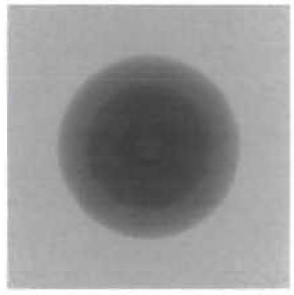
bb's
λ=0. g/cm^2

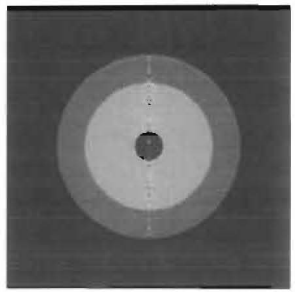
X-rays
λ=25. g/cm^2



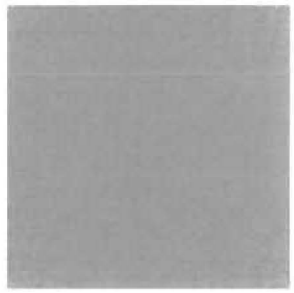


Protons
$\lambda \approx$185. g/cm^2





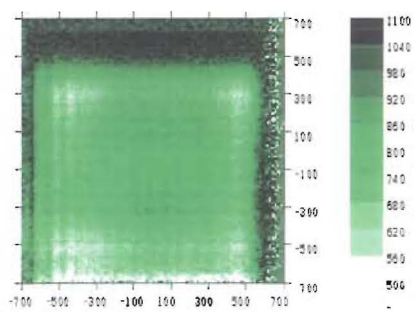
Neutrinos
$\lambda=\infty$ g/cm^2



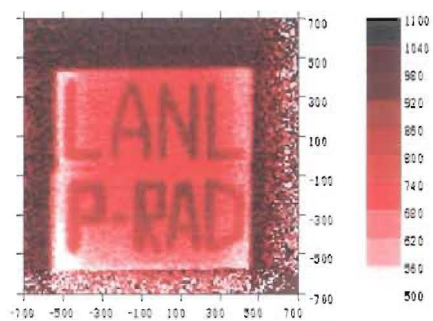
The idea-focus the transmitted protons with magnetic lenses

Transmission radiography FY95

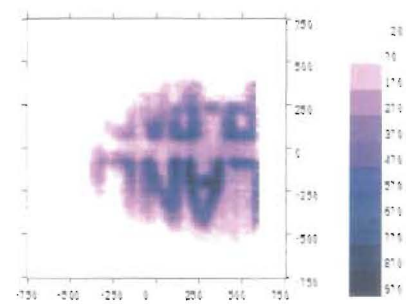
with 188 MeV protons



At the detector



Projected to the object



After a lens

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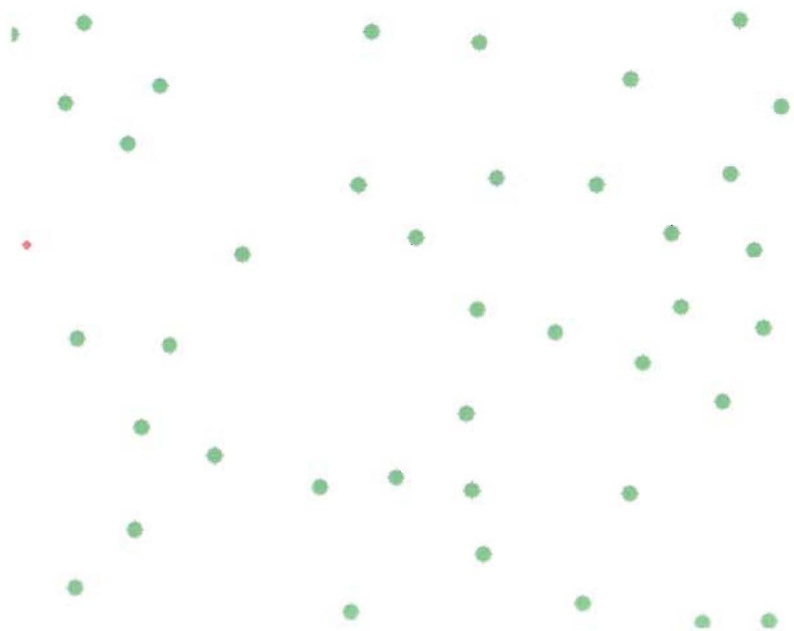
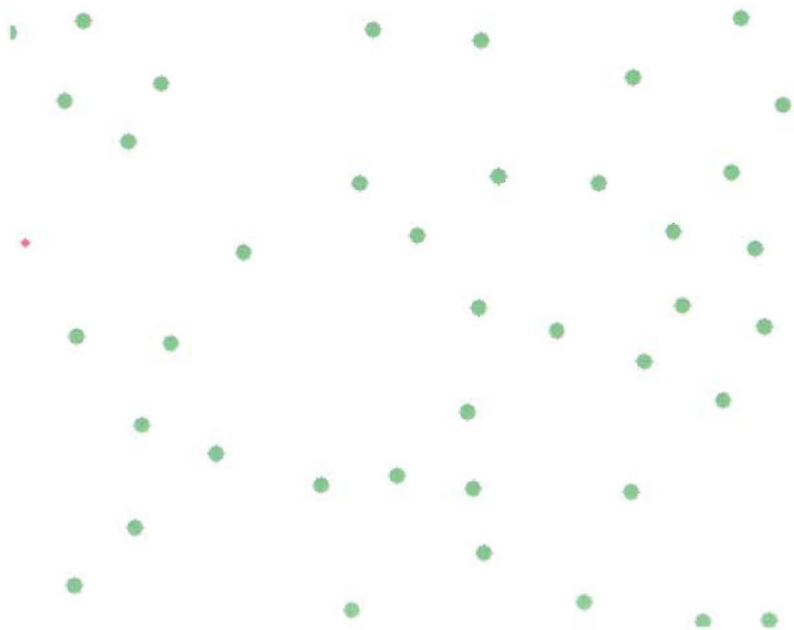
Physics

Two Interactions

The Coulomb interaction



The nuclear interaction



$$t = e^{-\frac{l}{\lambda_0}}\left(1 - e^{-\frac{\theta_c^2}{X + X_F}}\right)$$

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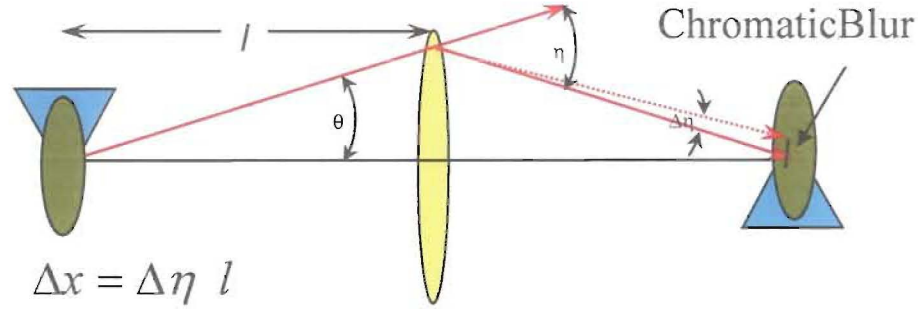
Physics

Proton radiography- angle matching



The leading aberations are chromatic :

$$x_{image} = x_{object} + (x \mid \theta\delta)\theta\delta + (x \mid x\delta)x\delta + \cdots$$

Setting :

$(x \mid \theta\delta)\theta\delta = -(x \mid x\delta)x\delta$ gives :

$$\theta = \frac{-(x \mid x\delta)}{(x \mid \theta\delta)} x$$

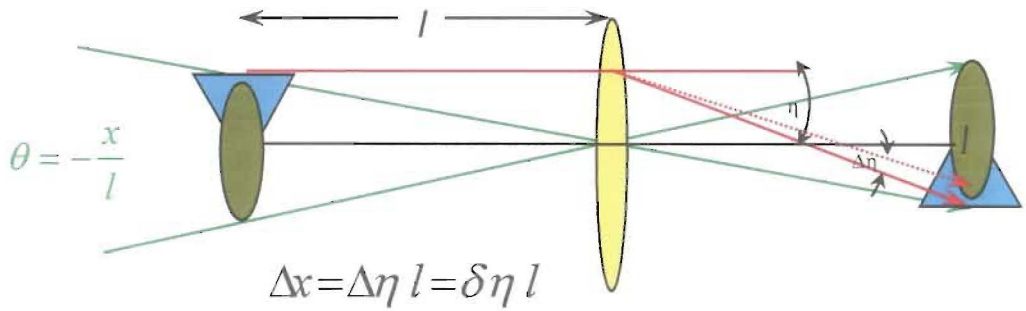
- **Uniform acceptance**
  - **analysis simple**
- **Reduced aberrations**
  - **pin hole camera**

$$\Delta x = \Delta\eta \; l$$

$$\delta = \frac{p - p_0}{p_0}, \eta = 2\theta, \Delta\eta = -\delta \, 2\theta, \text{so}$$

$$\Delta x = \delta 2\theta \, l$$

$$(x \mid \theta\delta) = 2l$$



$$\Delta x = \Delta\eta \, l = \delta\eta \, l$$

$$\eta = \frac{2x}{l}, \text{so}$$

$$(x|x\delta) = 2$$

$$(x|\theta\delta) = 7.8m$$

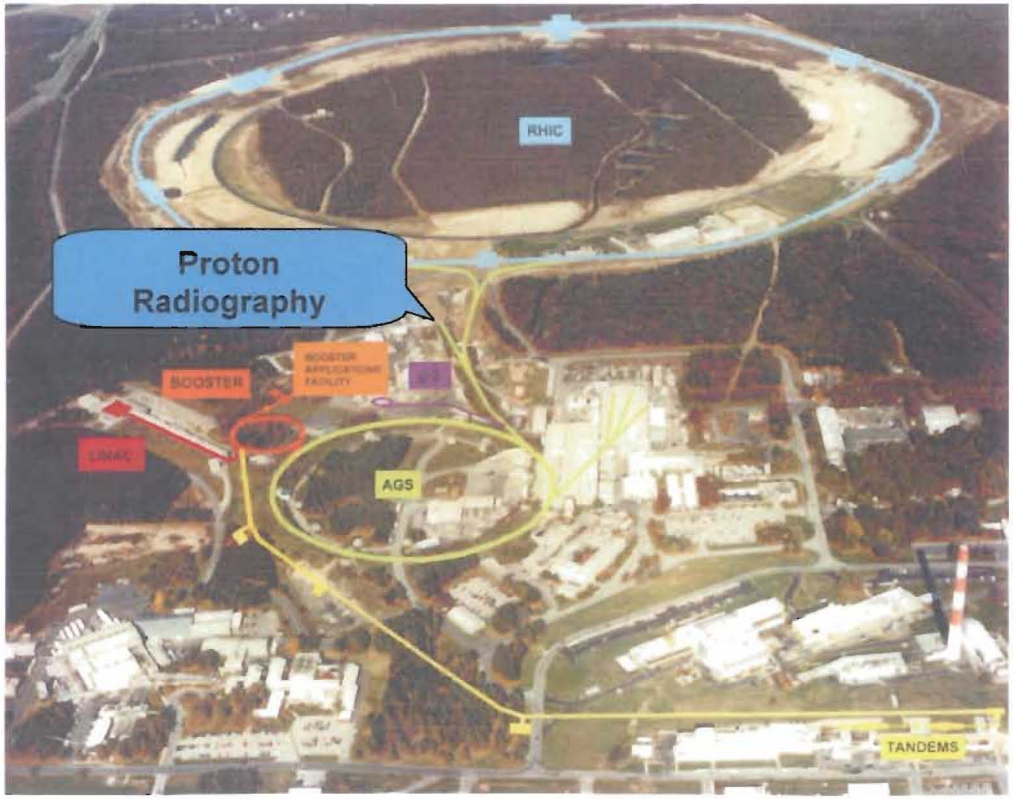
$$\langle\theta\rangle = 0.01 \text{ radians}$$

$$\langle\delta\rangle = 0.001$$

$$\langle x\rangle = 80 \; \mu\text{m}$$

Line U at the Alternating gradient accelerator

AGS accelerator



Line U

- 24 GeV/c protons
- 30 ns long pulses
- 2×10^{11} protons per pulse

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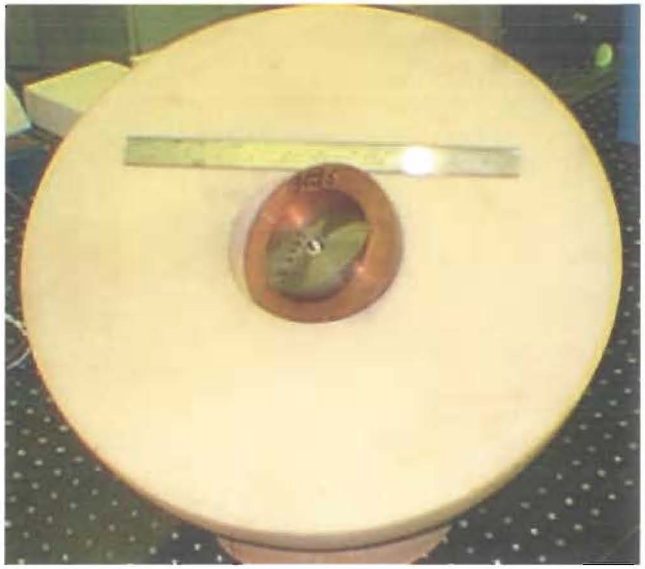
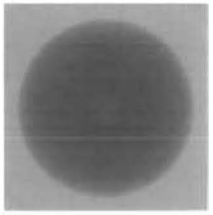
Physics

Precision Radiographic Density measurement

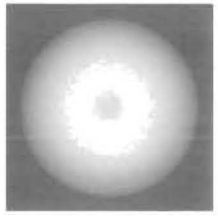


Run	Mass *gm*
6450	6976.5
6452	6960.5
6453	6976.5
6455	7004.5
Actual	6903
Average	6979.5
Average/actual	1.011
Stdev/Average	0.0026

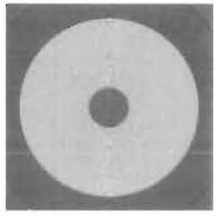
Transmission

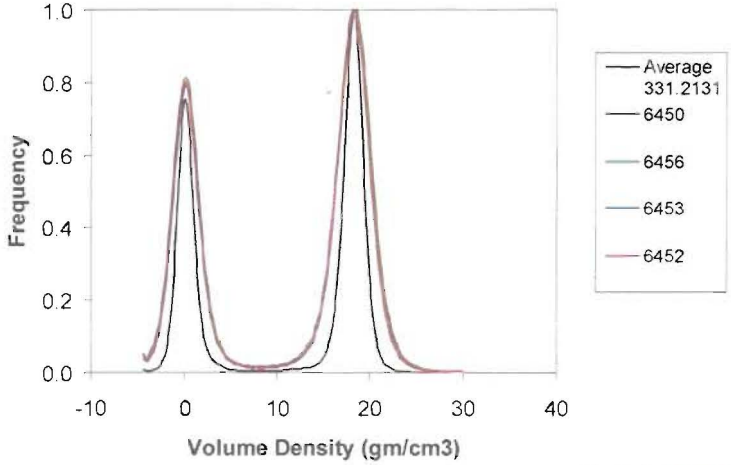


Areal density



Volume density





Los Alamos

Physics

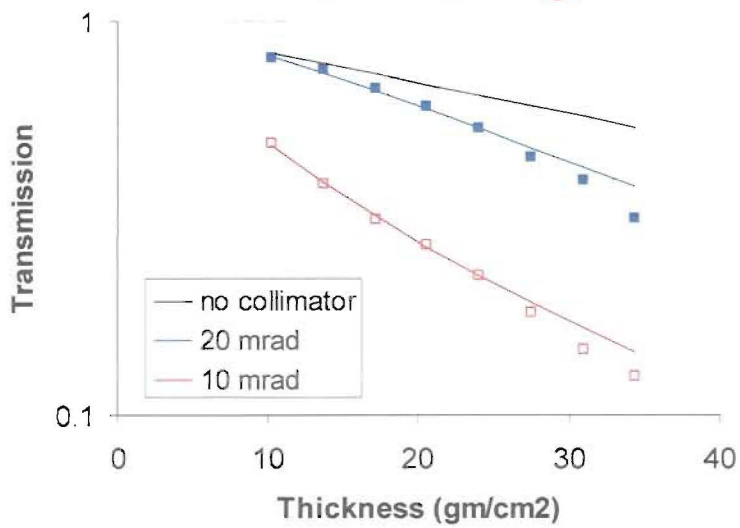
LANSCE

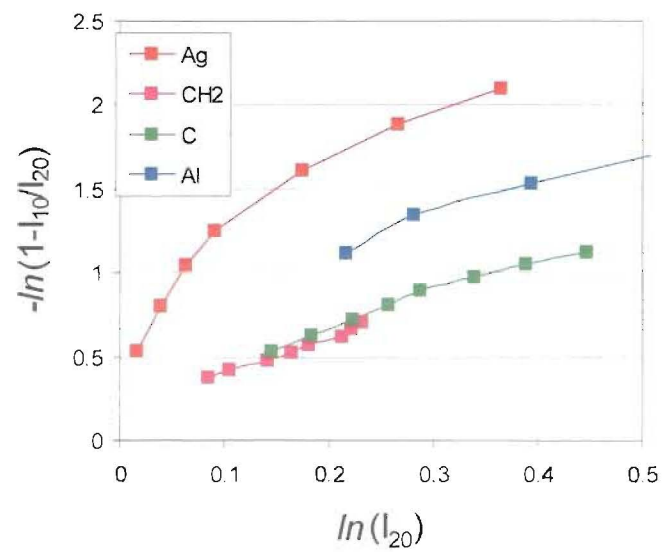
Los Alamos

Physics

LANSCE 800 MeV proton radiography facility

$$t = e^{-\frac{l}{\lambda_2}}\left(1 - e^{-\frac{\theta_c^2}{X}}\right)$$



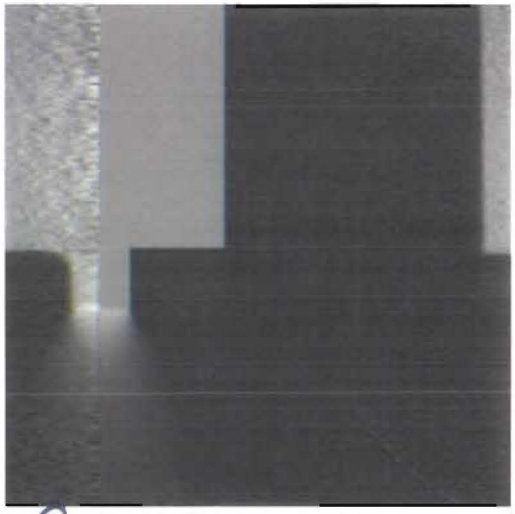


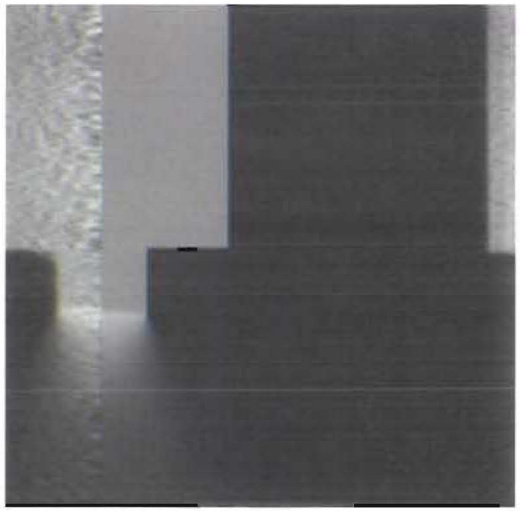
pRad allows unique studies of high explosive detonation and equation of state ()

- Corner Turner
- Rate Stick
- Colliding Detonation Waves
- Failure Cone

Measure the detonation and shock wave locations as a function of time.

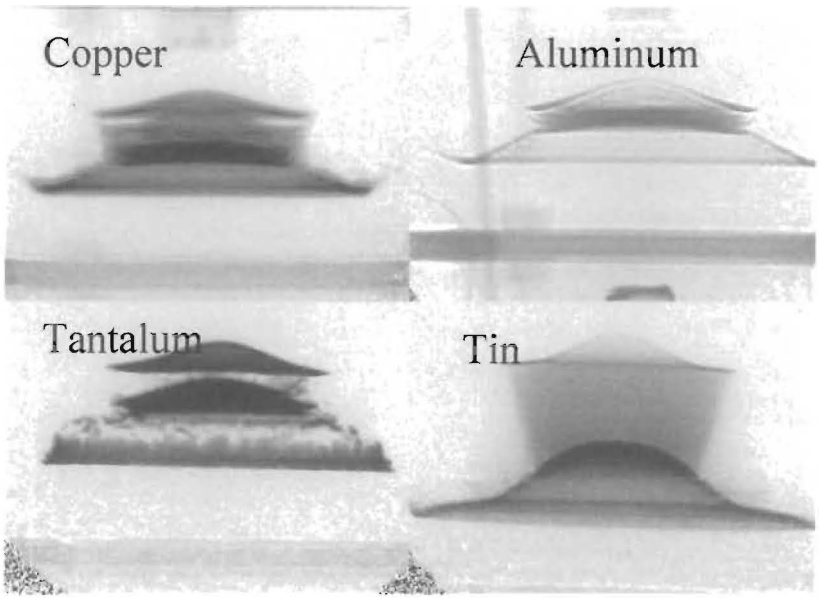
- EOS parameters
- HE detonation dynamics

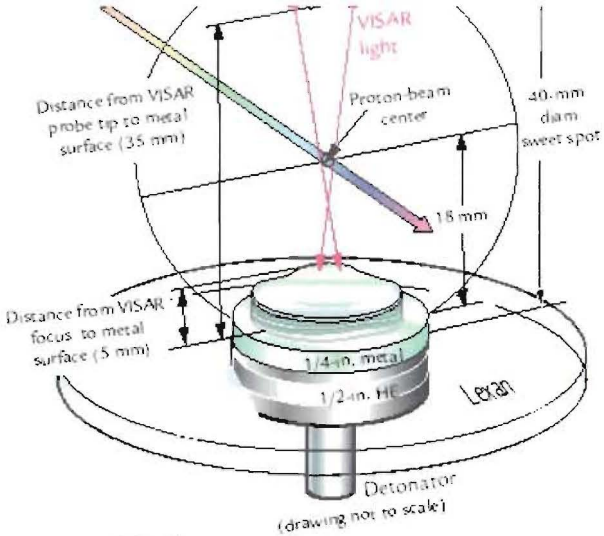




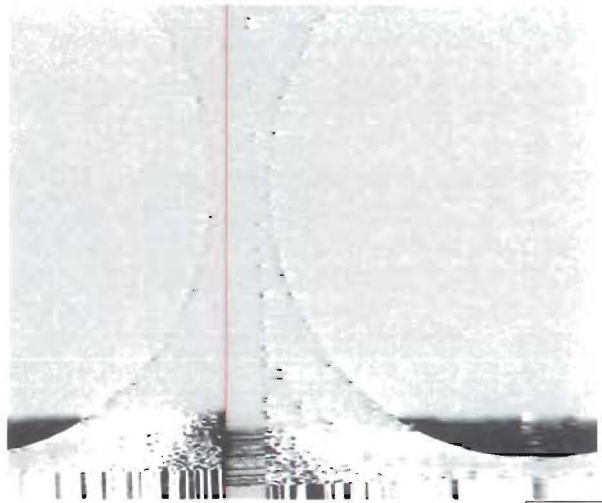
pRad has been used to study the failure of materials driven by point detonated high explosives (D. Holkamp)

A comparison of spall for different materials



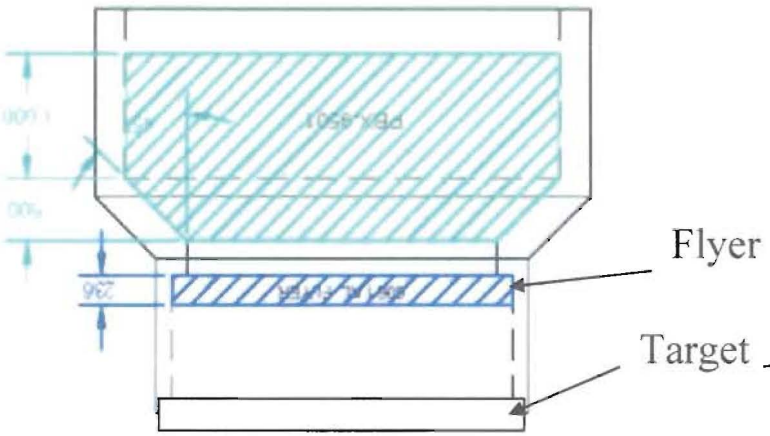


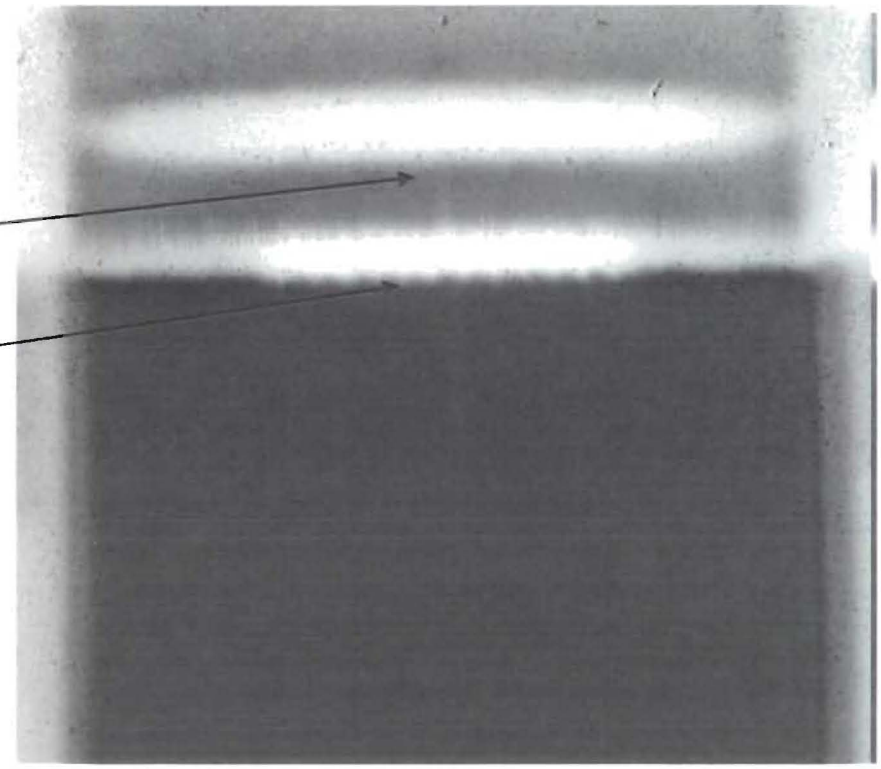
15 frame time sequence of the tin shot



- Experiments were aimed at extending VISAR measurements below the leading spall layer.
- Proton radiographs reveal that the deepest damage layers are not well defined.
- Multiple pRad experiments show that damage formation deep within the metal is "statistical" in nature and dependent on metal.

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





The target has a sin wave machined in its lower face

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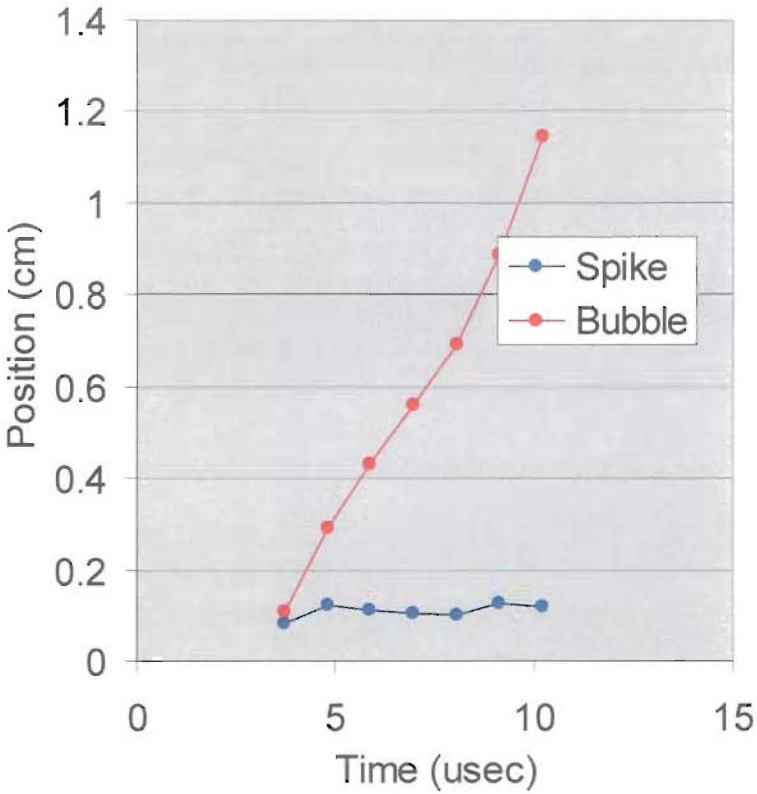
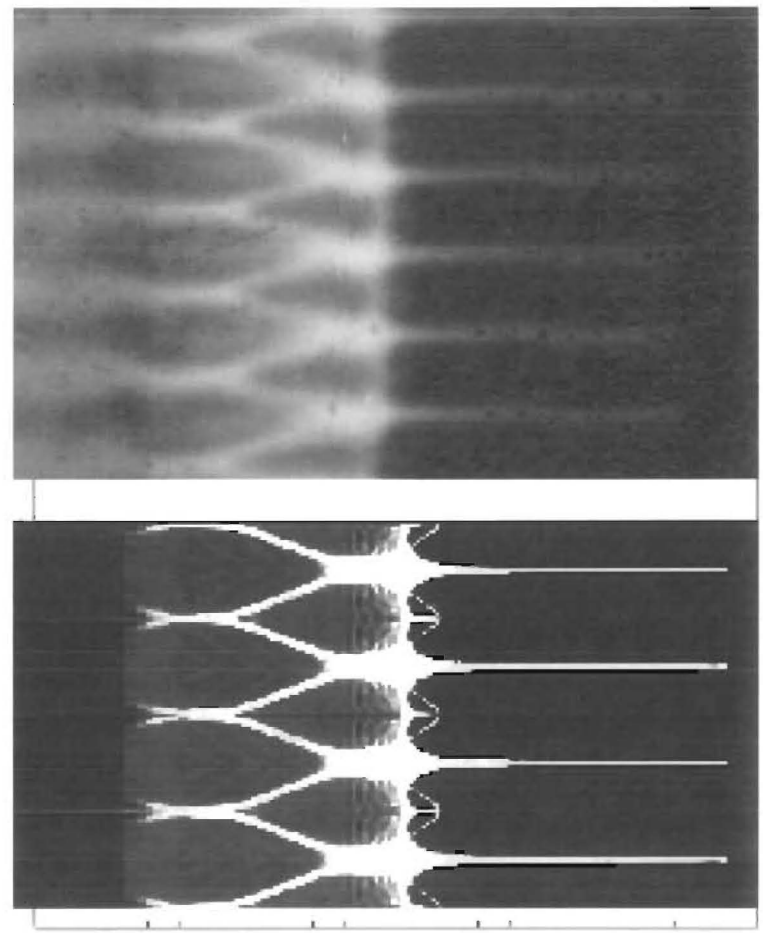
Physics

Hydrodynamic Calculations (David Youngs et al.)





$$\eta(t) = \eta_0 (1 + \frac{\Delta v A 2\pi}{\lambda} t)$$

where η_0 is the initial perturbation

λ is the wavelength

Δv is the velocity jump

A is the Atwood number

t is time

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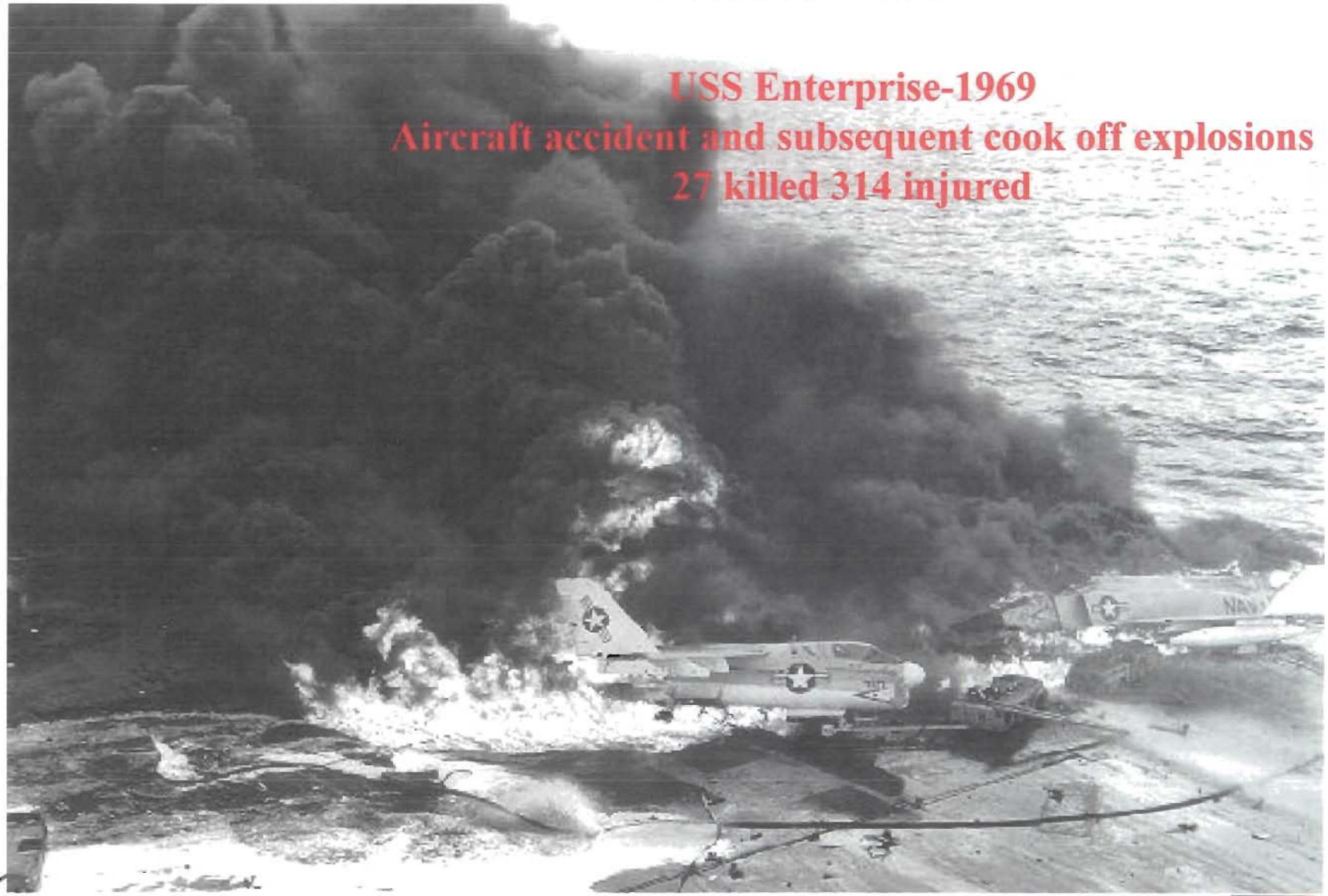
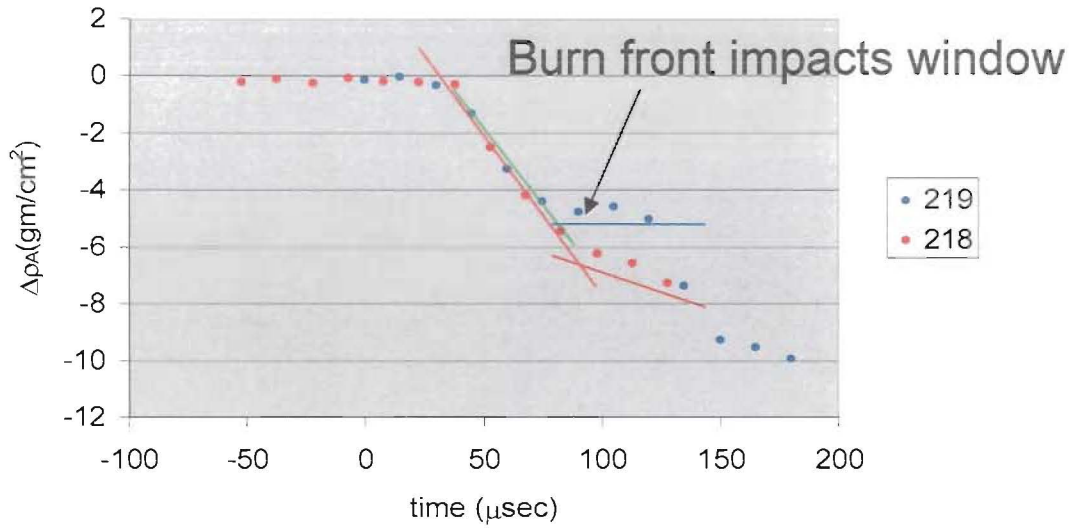
Physics

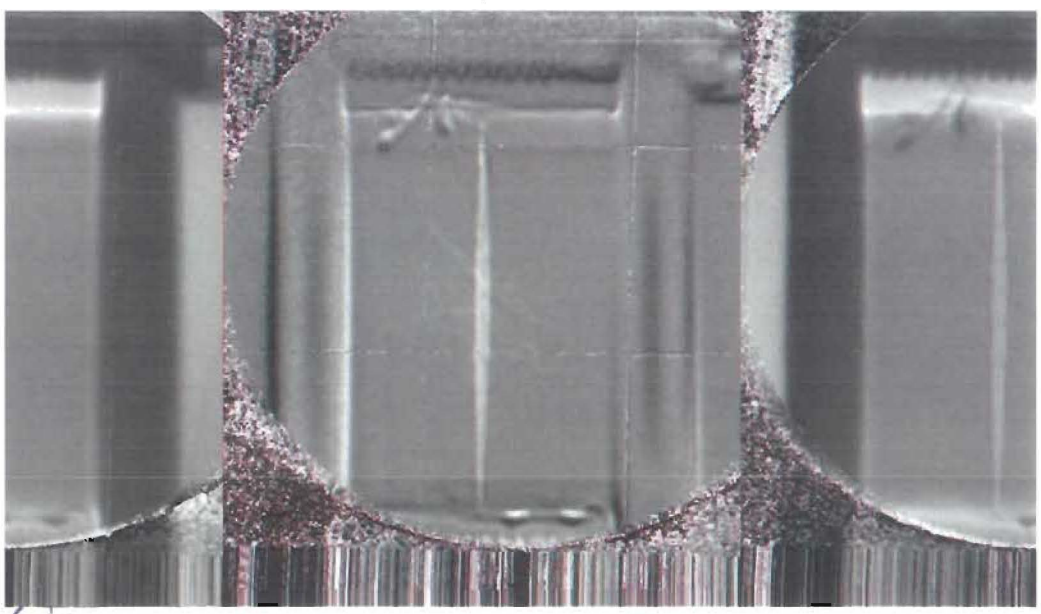
pRad has allowed the mechanism for high explosive cookoff to be better understood

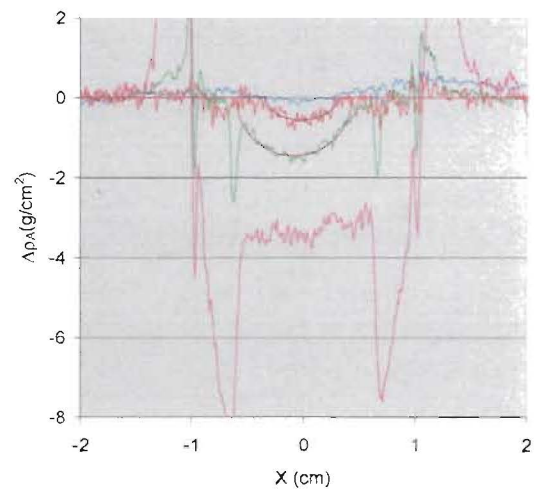
- 

A recent proton radiography movie shows features of the ignition mechanism

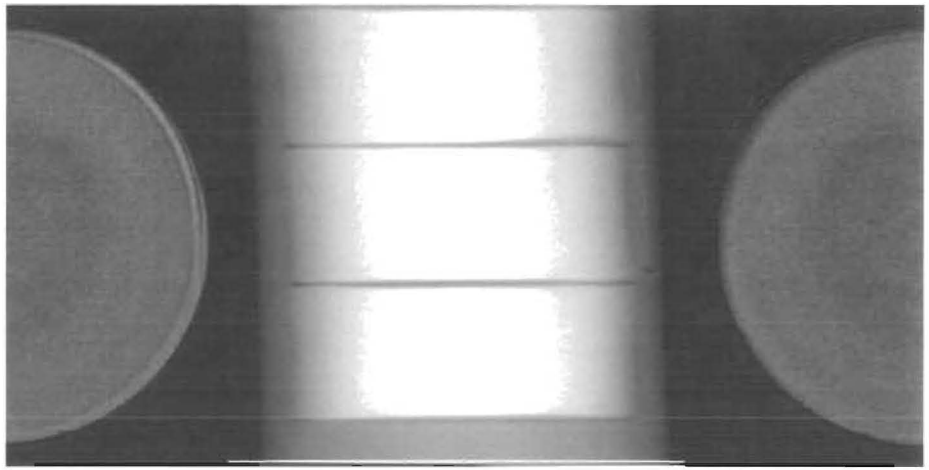


- Hot spot develops
- Ignition propagates along cracks
- Reaction burns remaining material





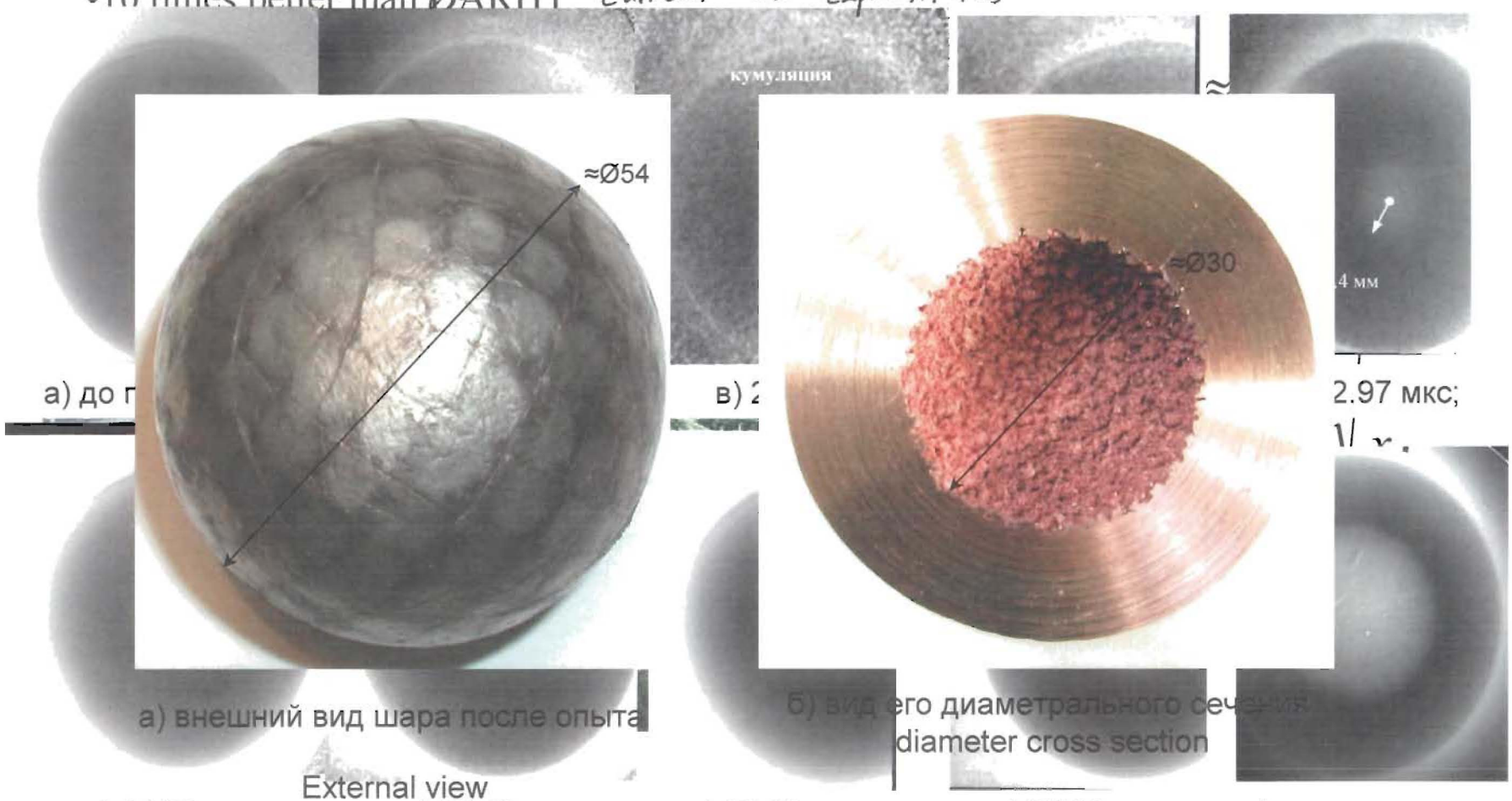
We have built a proton microscope and studied reactor control rod with it



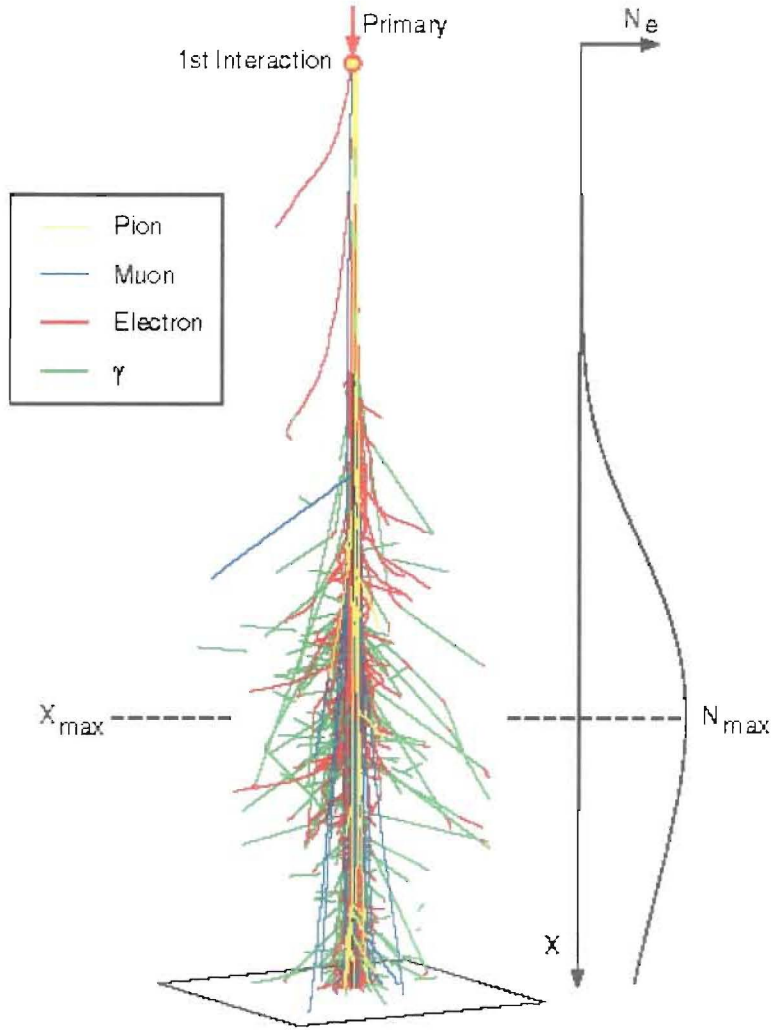
- ×3 magnification
- 40 μm position resolution
- ×2 reduction in chromatic length
- HfO_2 Fuel rod test (F. Mariam)

The future: A Premier Flash Radiography Facility?

- Full scale hydrotest experiment (60 GeV)
- 10 times better than ~~DARHT~~ current vs capabilities



Charged particle radiography with cosmic rays



- As primary cosmic rays strike our upper atmosphere, they interact, producing showers of particles including pions (τ=26 ns)(hadron) which decay into muons (τ=2.2 μsec) (lepton)

- Muons interact only through the Coulomb and weak force and thus have a large penetrating ability and are able to go through tens of meters of rock with low absorption.

- Muons arrive at a rate of 10,000 per square meter per minute (1/cm^2/minute).

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Physics

Muons have been used to radiograph large structures

Fig. 1 (top right). The pyramids at Giza. From left to right, the Third Pyramid of Mycerinus, the Second Pyramid of Chephren, the Great Pyramid of Cheops. [© National Geographic Society]

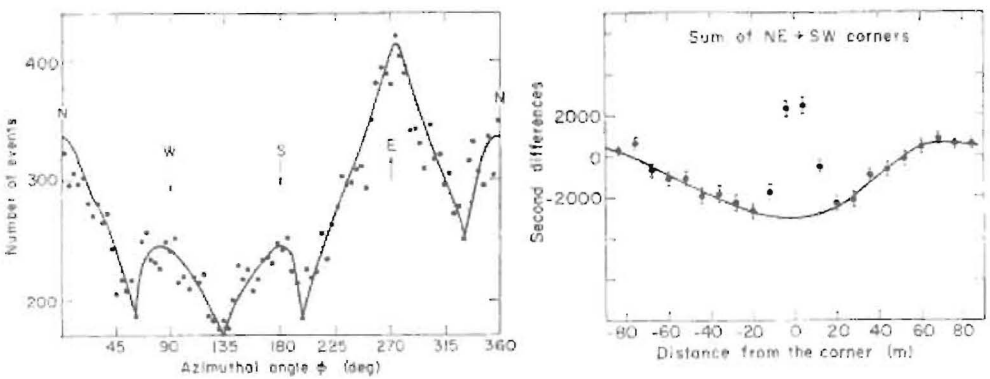

Fig. 3 (left). The initial measurement (with zenith angle of counts from 20 to 40 degrees) of the variation of cosmic-ray intensity with azimuthal angle, as observed from the Belzoni Chamber underneath the Second Pyramid of Chephren. Fig. 4 (right). Detection of the northeast and southwest corners of the pyramid obtained by plotting the second differences of the counting rate on the planes tangent to the corners as a function of distance from the corners.

$$\frac{1}{\lambda} = -\frac{1}{N}\frac{dN}{dl}$$

$$\Delta l = \frac{\lambda}{\sqrt{N}}$$

for a $10\ \mathrm{cm}^3$ volume of uranium

$\lambda \approx 100\ \mathrm{cm}$

$N \approx 100 / \mathrm{minute}$

$\Delta l \approx 10\ \mathrm{cm}$

Search for Hidden Chambers in the Pyramids, by Luis W. Alvarez, Jared A. Anderson, F. El Bedwei, James Burkhard, Ahmed Fakhry, Adib Girgis, Amr Goneid, Fikhry Hassan, Dennis Iverson, Gerald Lynch, Zenab Miligy, Ali Hilmy Moussa, Mohammed-Sharkawi, Lauren Yazolino

Science © 1970 American Association for the Advancement of Science

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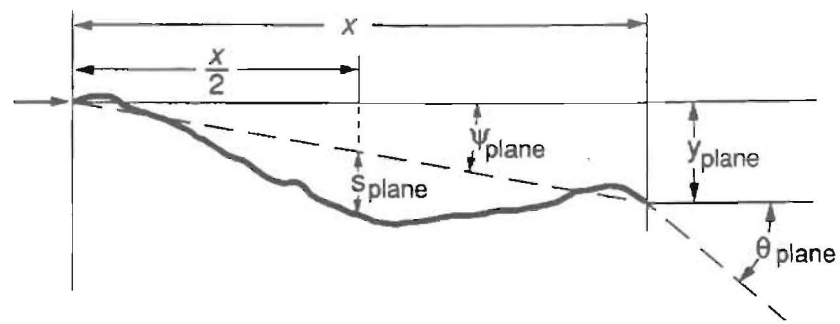
Physics

We are using multiple scattering radiography for homeland defense

- **Range**
  - Useful for pyramids
- **Energy loss**
  - Most sensitive but expensive
- **Multiple scattering**
  - Cost effective and simple



$$y_{\text{plane}} = z_1\, x\, \theta_0 (1-\rho_{y\theta}^2)^{1/2}/\sqrt{3} + z_2\, \rho_{y\theta}\, x\, \theta_0/\sqrt{3}$$

$$= z_1\, x\, \theta_0/\sqrt{12} + z_2\, x\, \theta_0/2\ ;$$

$$\theta_{\text{plane}} = z_2\, \theta_0\ .$$

Material	dE/ dx	χ
	MeV-cm²/gm	cm
H_2O	2.06	36
Fe	1.87	1.76
Pb	1.54	0.56

$$\frac{dN}{d\theta_x} = \frac{1}{\sqrt{2\pi}\theta_0} e^{-\frac{\theta_x^2}{2\theta_0^2}}$$

$$\theta_0 = \frac{13.5}{p\beta}\sqrt{\frac{l}{\chi}}$$

since each measurement of θ_x and θ_y measures θ_0

$$\frac{\Delta l}{l} = \sqrt{\frac{2}{N}}$$

where N is the number of detected muons

*Fermi and Rossi, 1940

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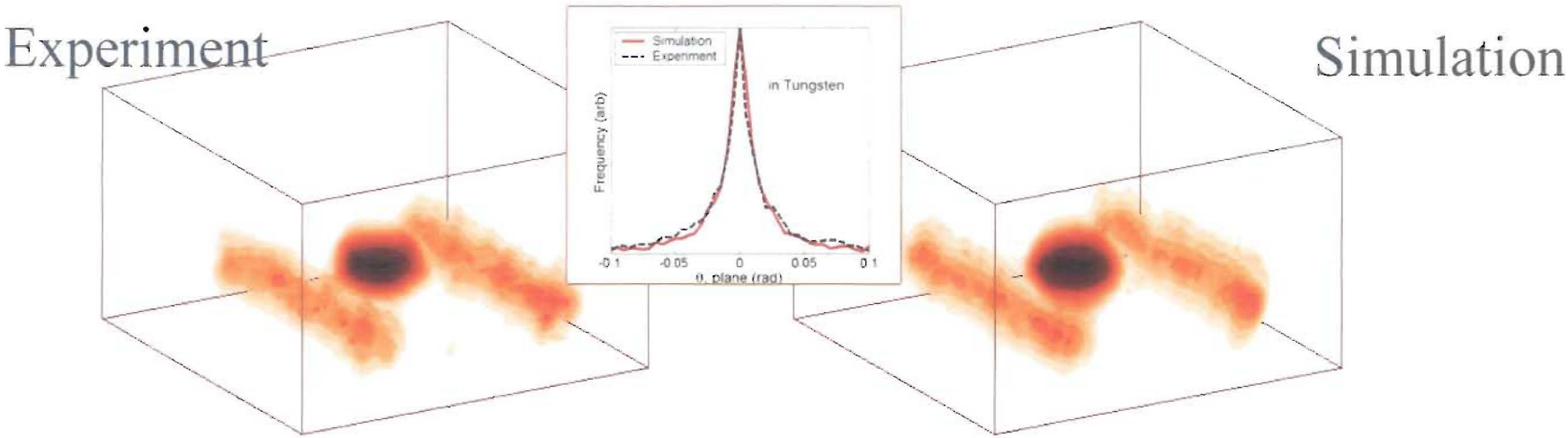
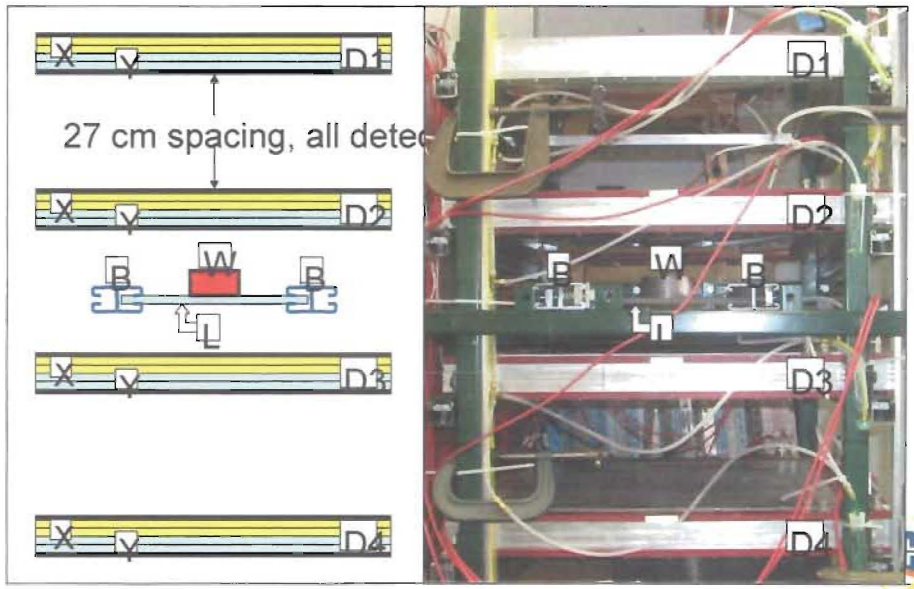
Physics

Tomography with cosmic ray muons has been shown to work



- Cosmic ray muon generator / multiple scattering simulation.
- Good agreement with experiment.
- Allows for extrapolation to larger, more complex scenes.



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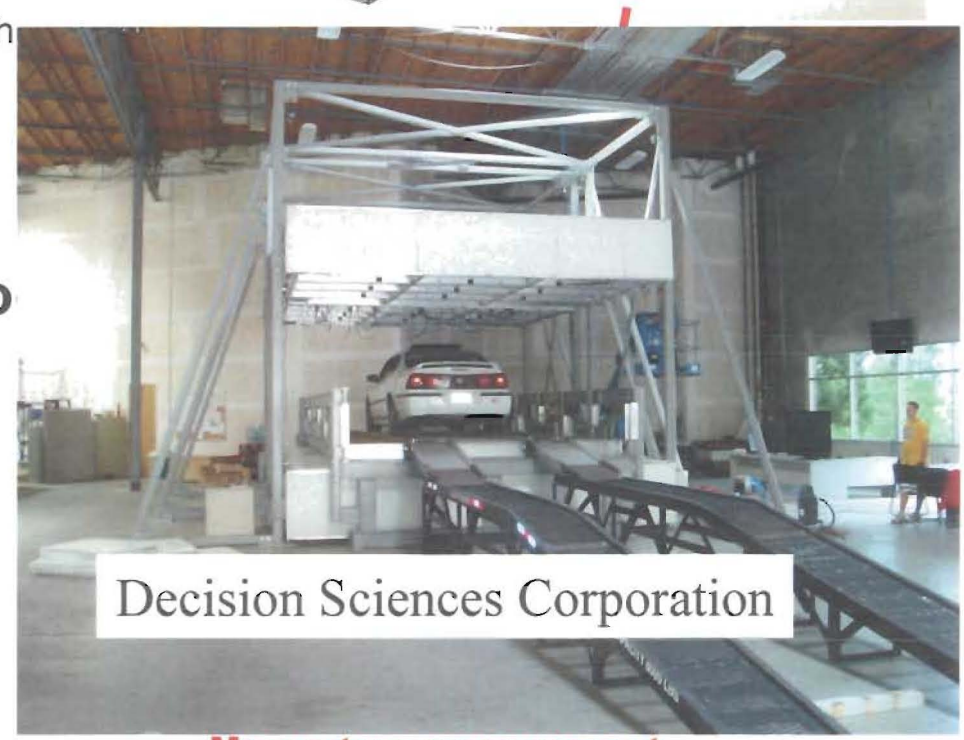
What does a scanner look like?

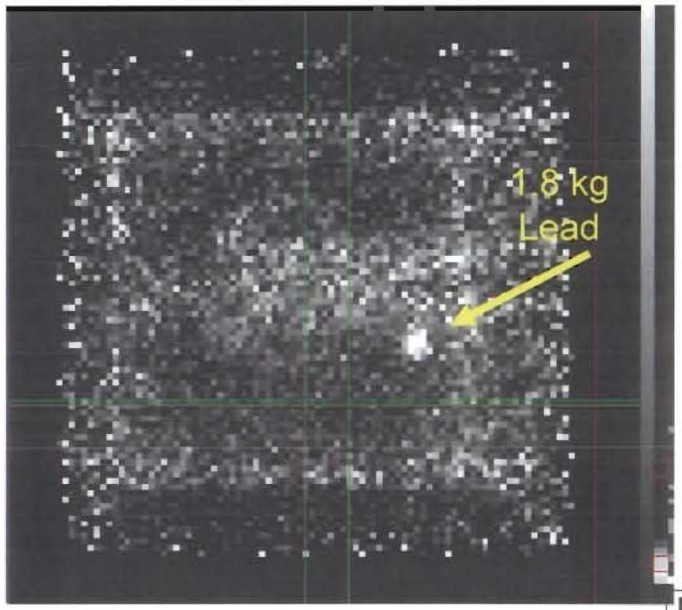
- Technical approach:
  - Measure passive radiation
  - Use muons to generate "scattering density" image
    - » Built in momentum measurement
    - » Automatic calibration using flux through empty detector
  - Combine signals to identify threats
- Advantages over other metho
  - No radiation
  - Simple technology
  - Inexpensive
  - Can penetrate thick cargos
  - Automatic Identification



Momentum measurement using track residuals

We have demonstrated muon tomography in small scale experiments

- 896 channels
- Drift gas: 60% Ar/ 40% Isobutane
- ~100 Hz trigger rate at current geometry
- 1.5 m tall sample area



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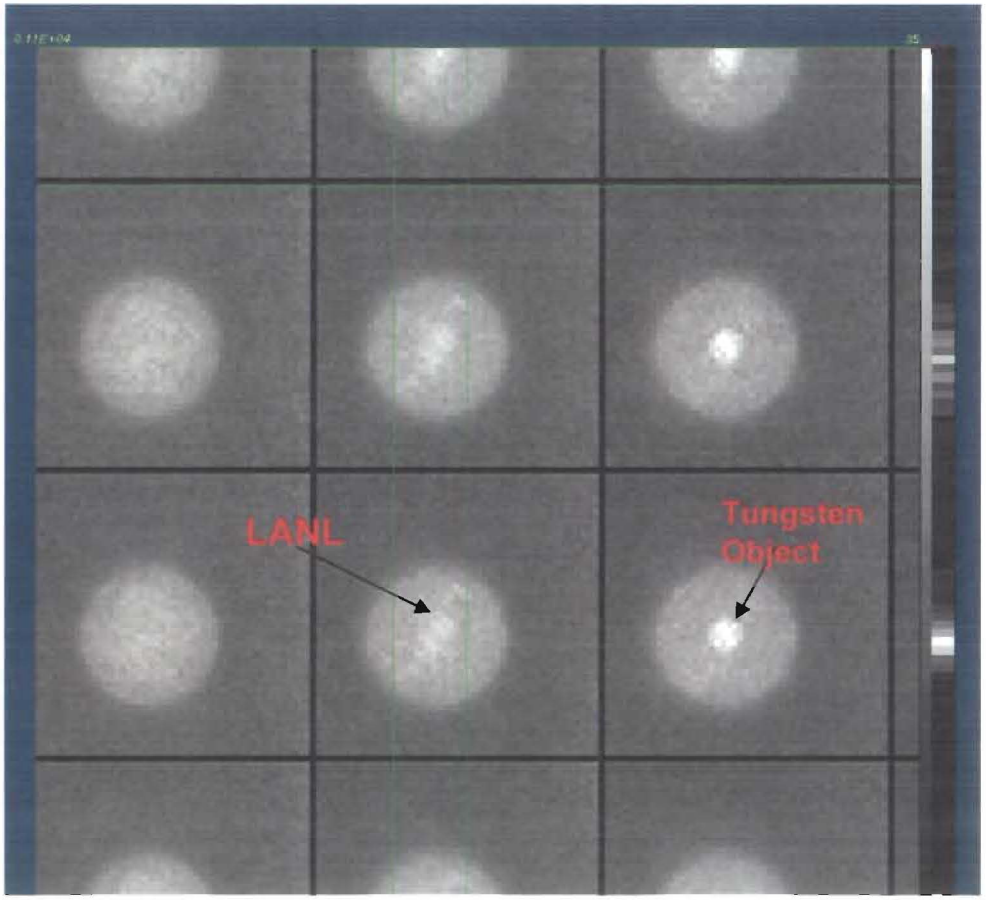
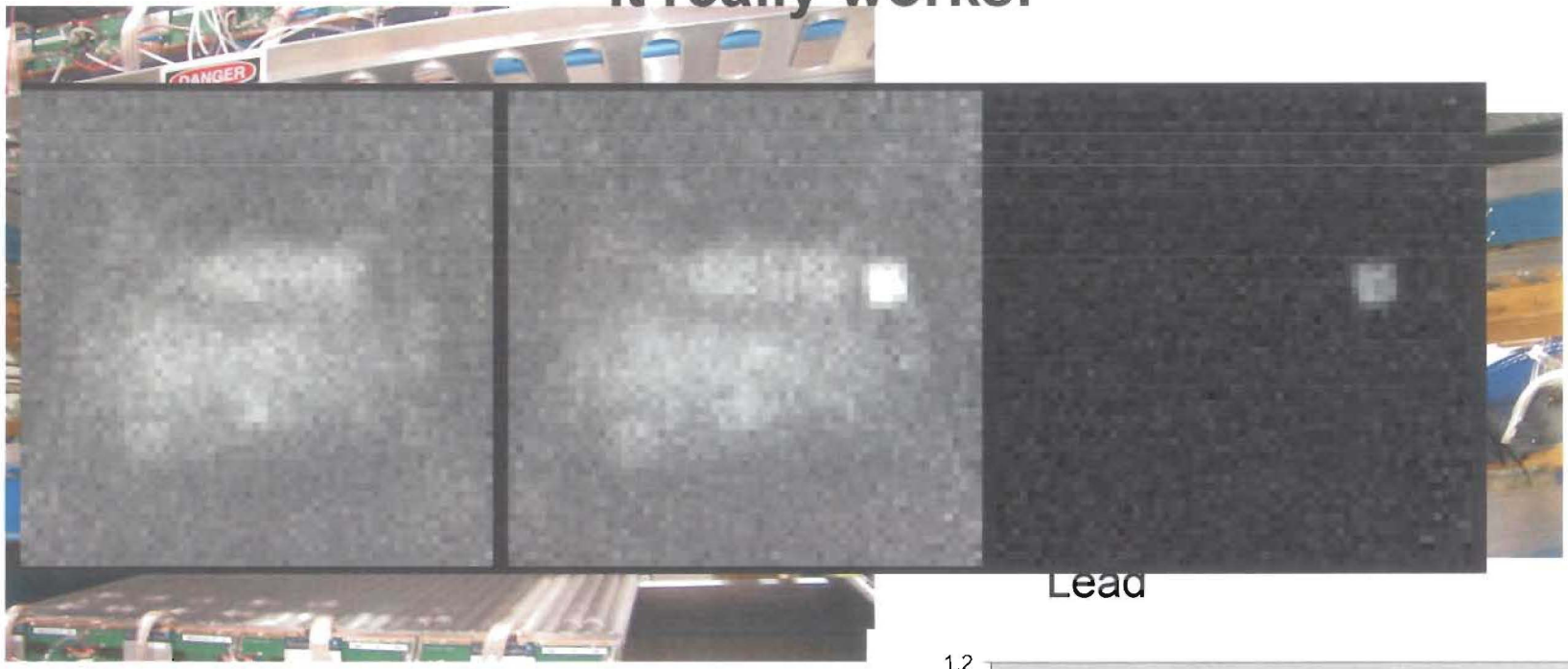
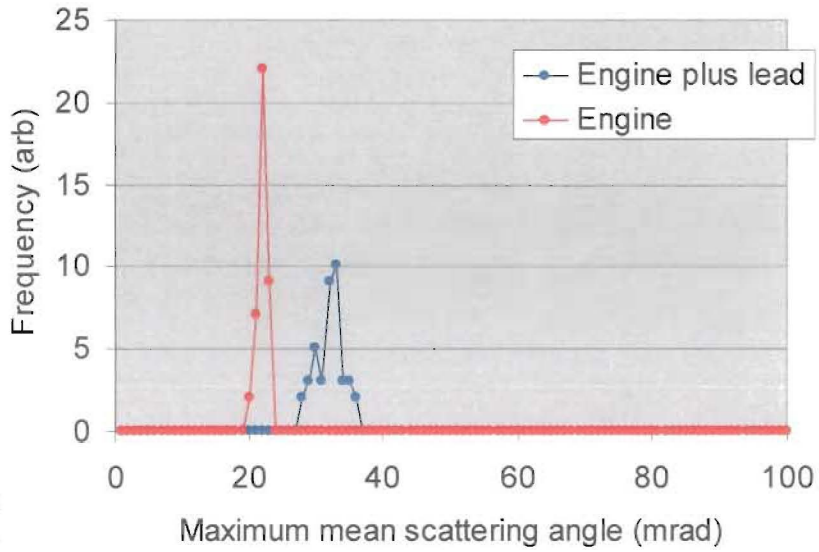
Physics

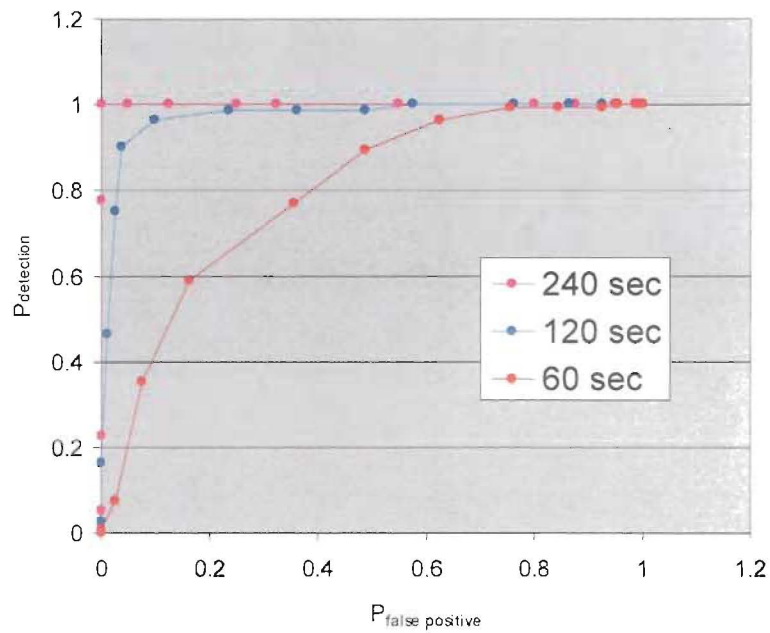
The same objects hidden in an 800 lb 40 gallon barrel of sand



It really works!







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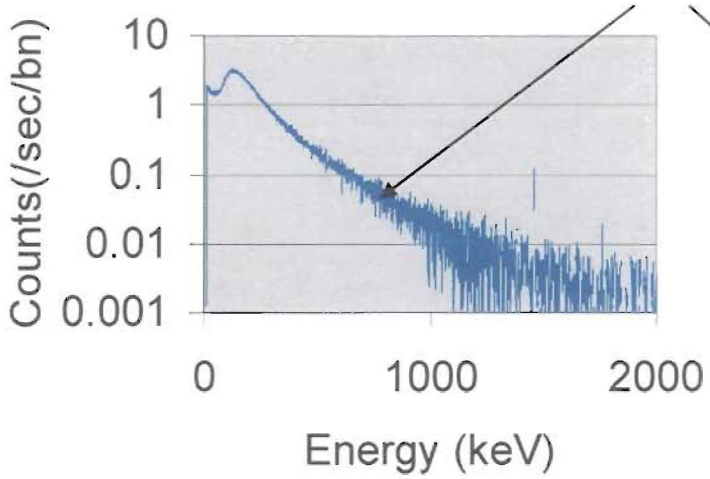
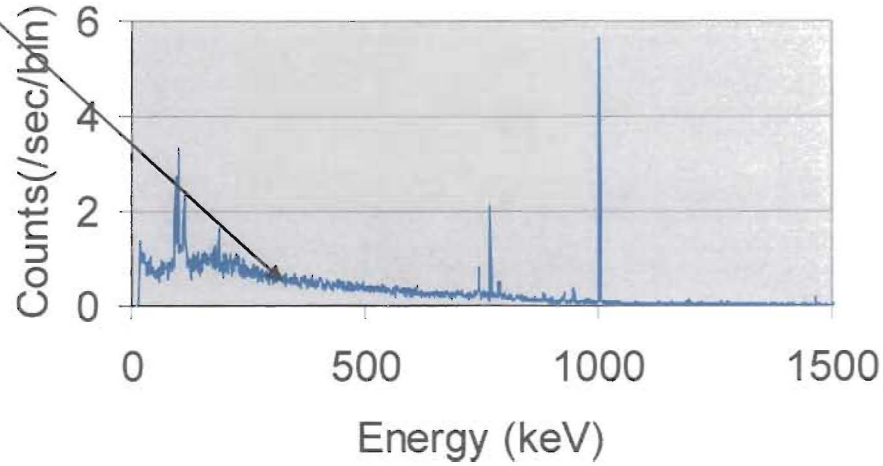
Gamma rays from nuclear threats

2 mCi ^{90}Sr 5 kg ^{238}U

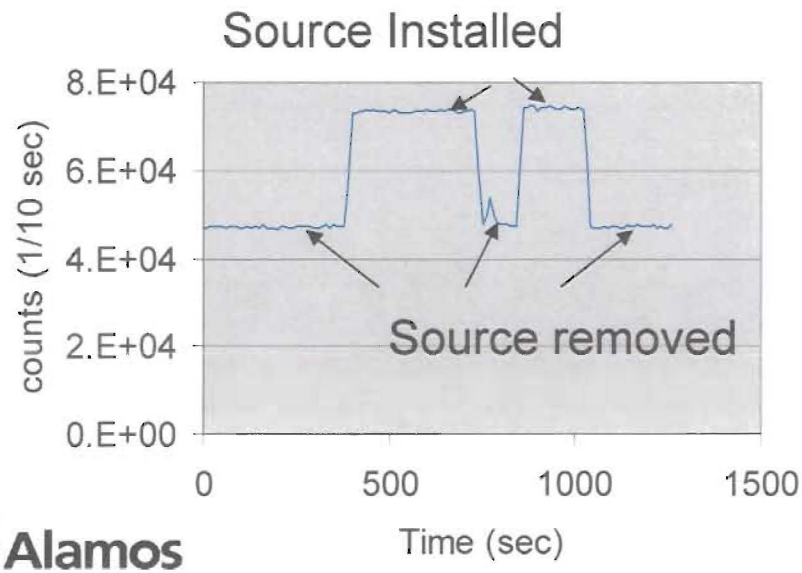
Bhremstralung x-rays

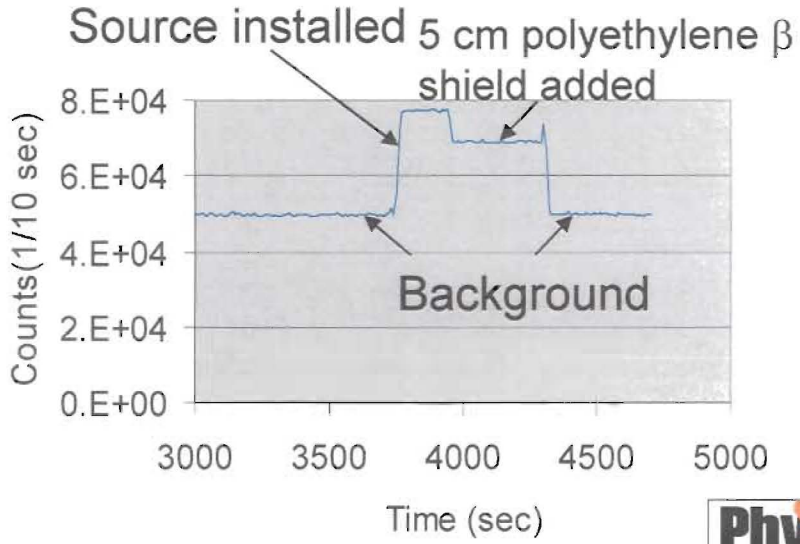
hpGe





Drift Tube





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Physics

Summary

- Charged Particle Radiography
  - Focus with magnetic lens
  - Magnification
  - Efficient detection
  - Large dose
  - Quantitative
  - Movies
- Proton radiography is being used to study a wide range of dynamic material properties and hydrodynamic phenomena
- Muon Tomography (MT)
  - Simulated tests show feasibility of sub-minute order screening of occupied vehicles for shielded threat objects.
  - Significant cargo clutter does not effect performance.
  - Experiments Validate all aspects of MT.