LA-UR- 09-03858

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Title:	800 MeV Proton Radiography
Author(s):	Frank Merrill pRad Team
Intended for:	ITEP seminar Moscow, Russia 6/24/2009

Los Alamos
NATIONAL LABORATORY
EST. 1943

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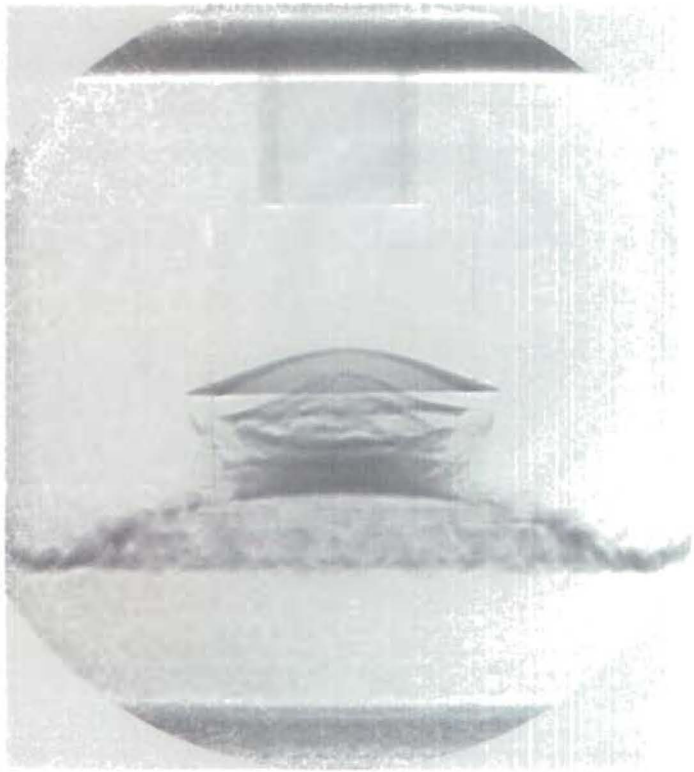
Form 836 (7/06)

Proton Radiography



Frank Merrill, LANL
and the pRad collaboration

pRad Team

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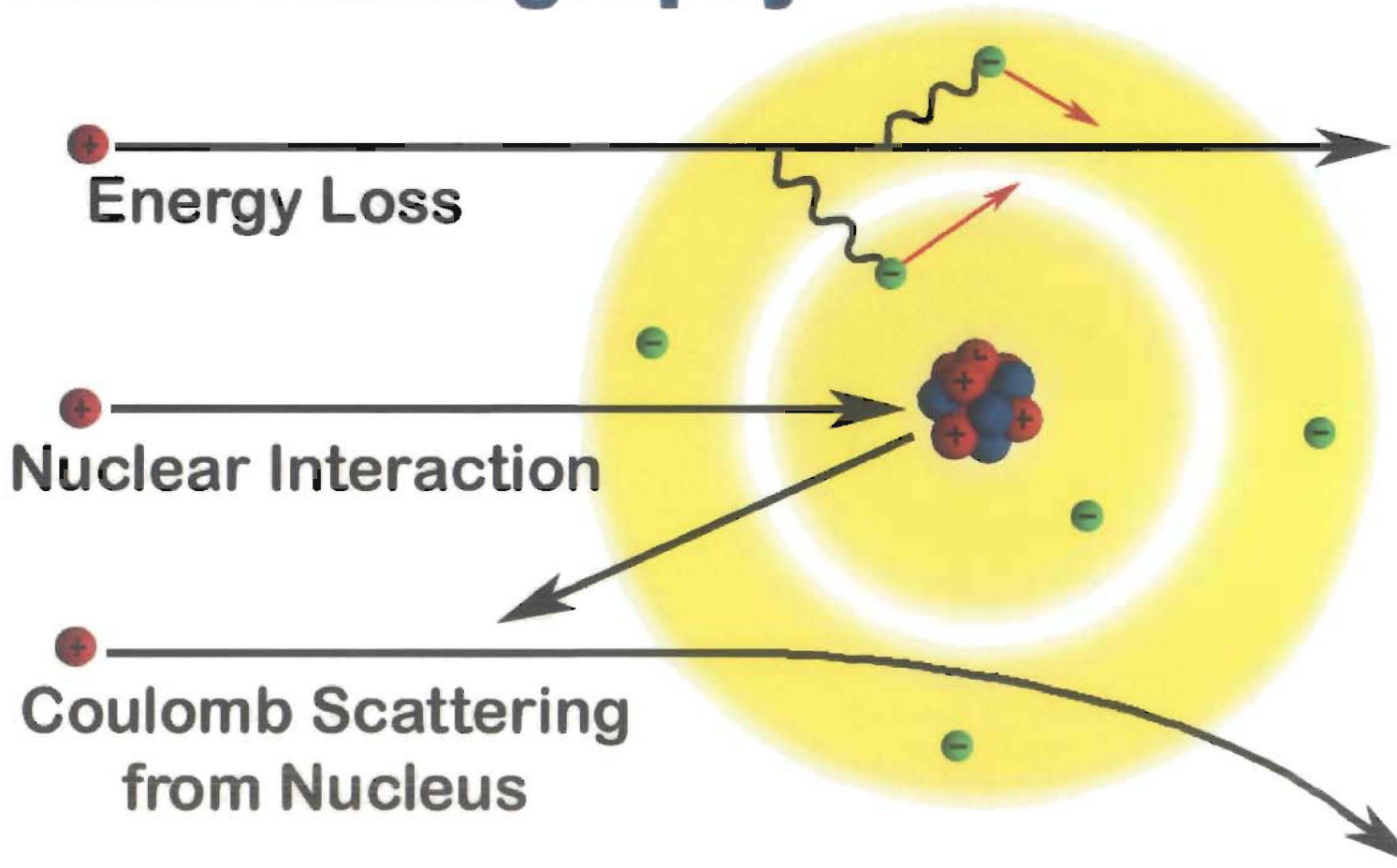
S-7
Rodger Liljestrand

Proton Interactions

Proton Radiography



Marginal Range Proton Radiography

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

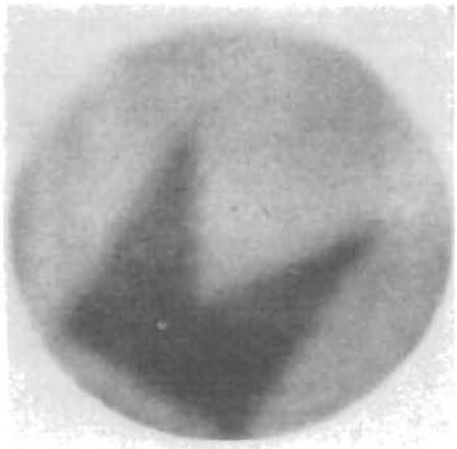


Fig. 1. Proton radiograph of aluminum absorber 7 cm in diameter and 18 g/cm² thick, with an additional thickness of 0.035 g/cm² aluminum foil, cut in the shape of a pennant, inserted at a depth of 9 g/cm². The addition of 0.2 percent to the total thickness produces a substantially darker area on the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

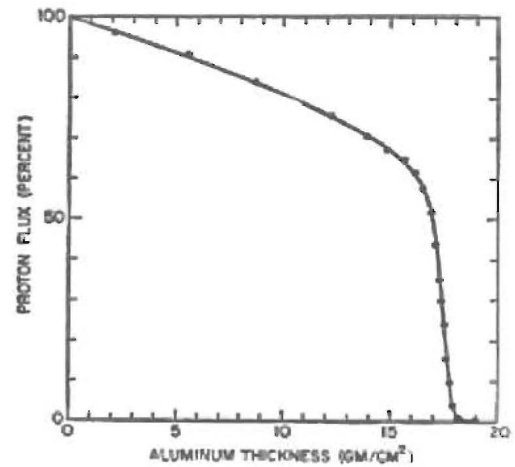


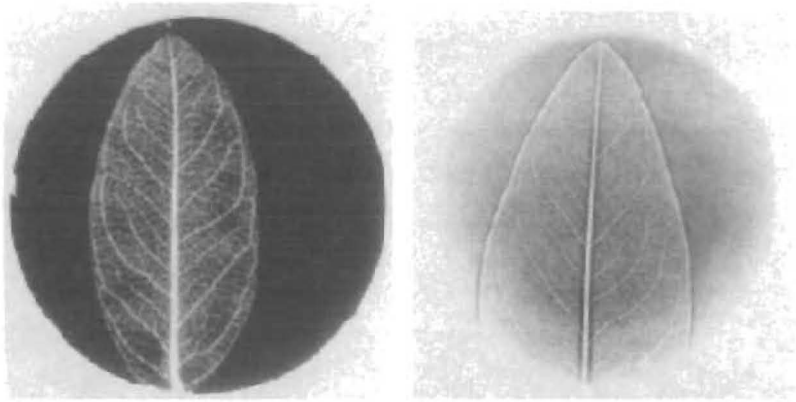
Fig. 2. Proton flux as a function of depth in aluminum. The steeply falling portion of the curve near 18 g/cm² is used to obtain the high contrast of Fig. 1.

Marginal Range Radiography

- 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.

Scattering Proton Radiography

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



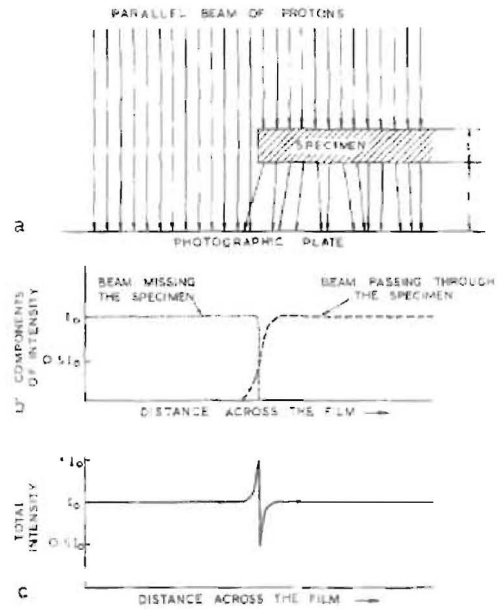


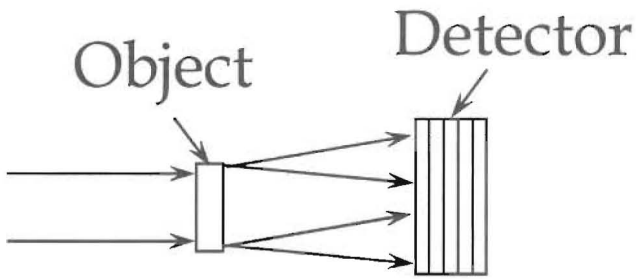
Fig. 7. Illustration of how multiple scattering produces its characteristic edge pattern

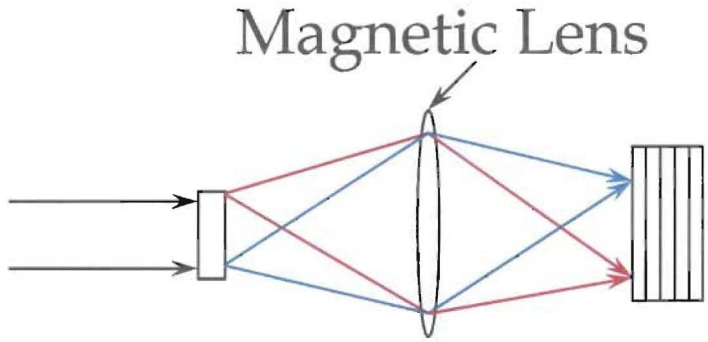
Scattering Radiography

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

1st LANL Proton Radiography (1995)

188 MeV secondary proton beamline at LANSCE





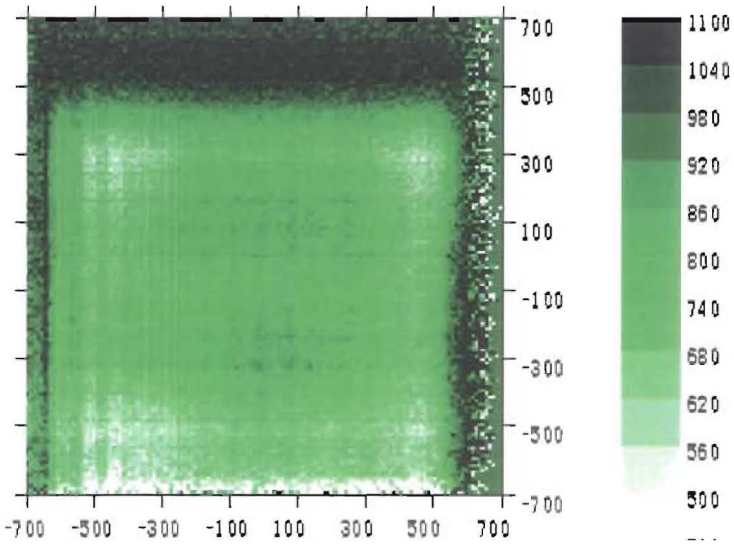
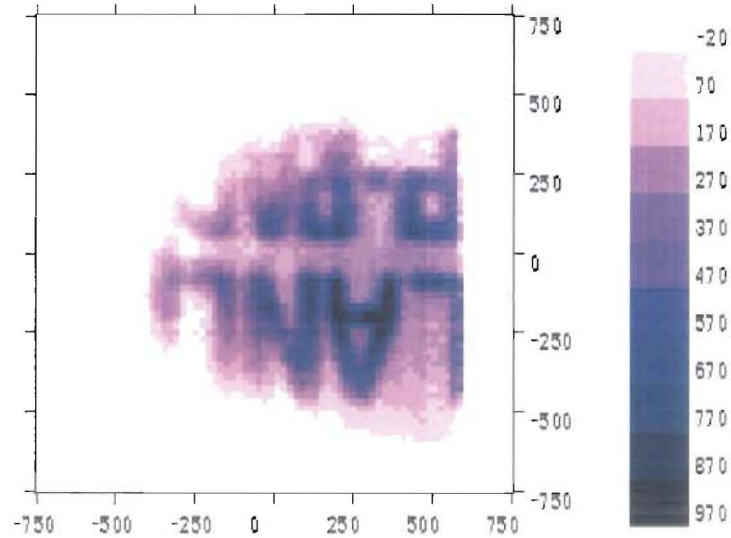
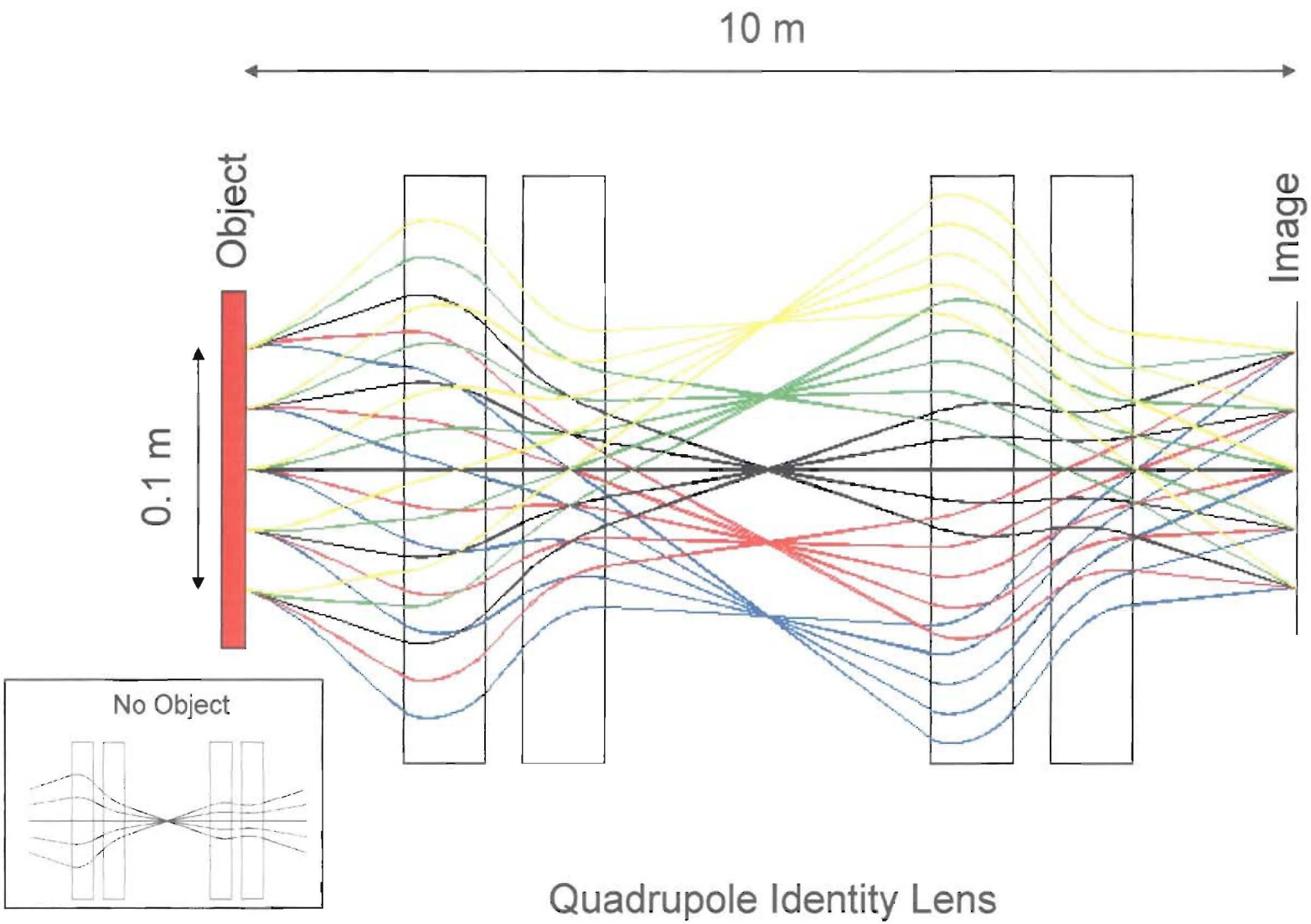


Image at the detector is substantially blurred.



Magnetic imaging lens preserves image with high resolution.

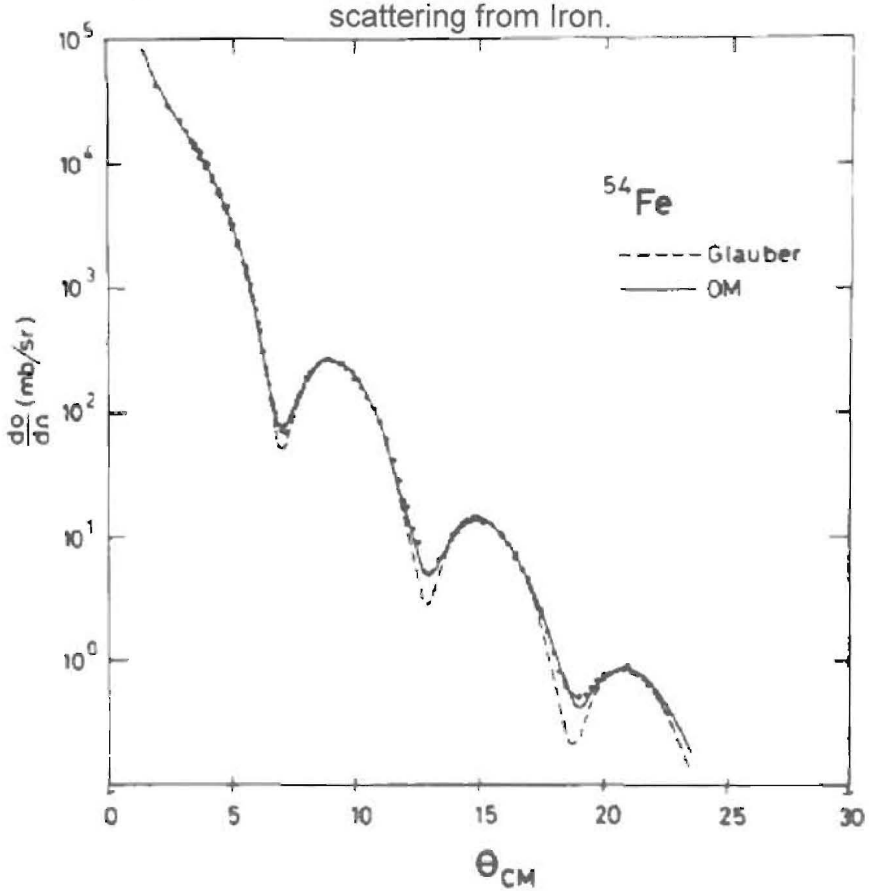
Magnetic Imaging Lens



Quadrupole Identity Lens

Nuclear Interactions

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



Simple Approximation for Modeling Proton Radiography

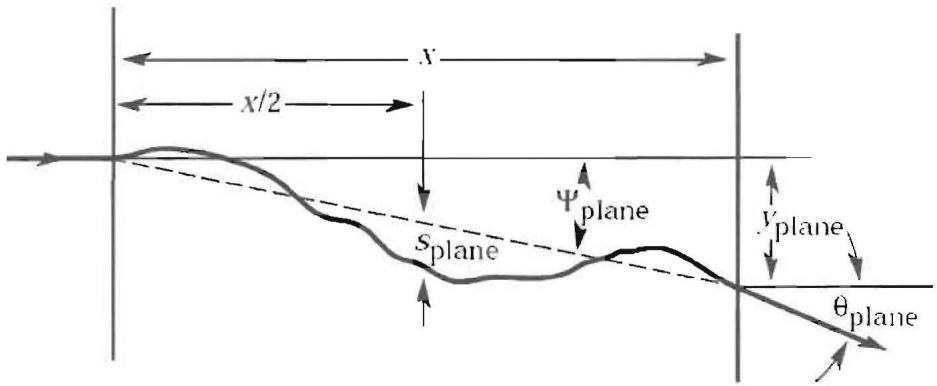
- Characteristic Nuclear Collision Length: λ_c
- Approximate that each interaction removes the proton from the acceptance of the imaging lens.
- Measure the collision Length at 800 MeV

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.

Transmission

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

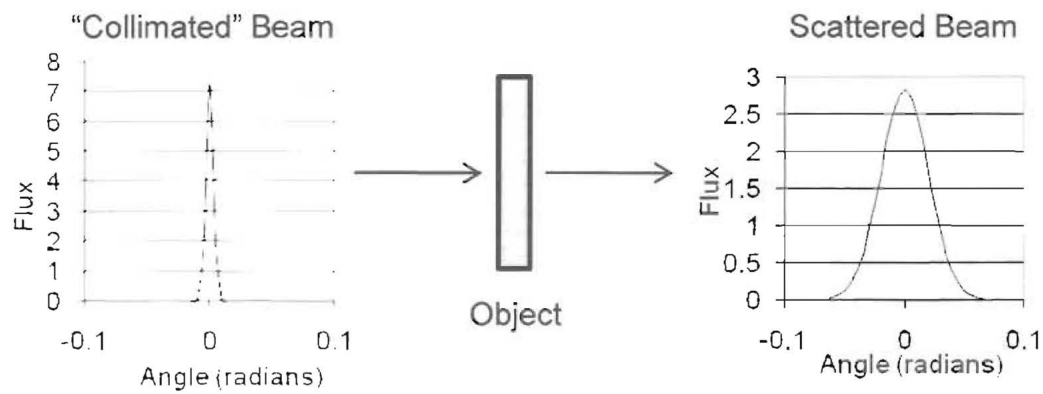
Multiple Coulomb Scattering



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

RMS Width

Full Width Half Maximum=2.35 θ_o



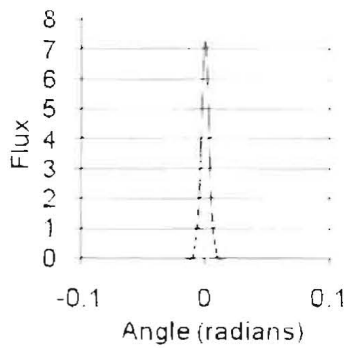
$$\theta_o = \frac{14.1MeV}{\beta p}\sqrt{x/X_o}$$

Typical LANL simplification

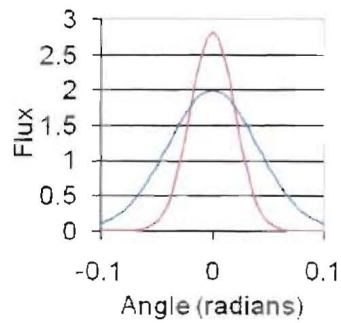
*C. Amsler et al., Physics Letters **B667**, 1 (2008)

Contrast from Multiple Coulomb Scattering

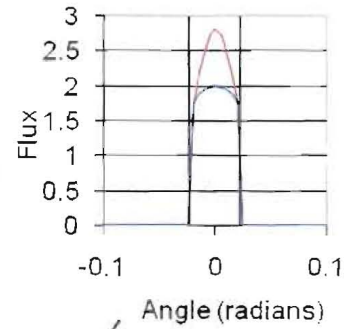
Incident Beam



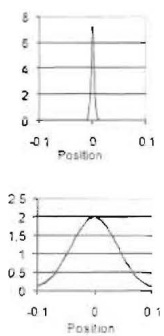
After Object

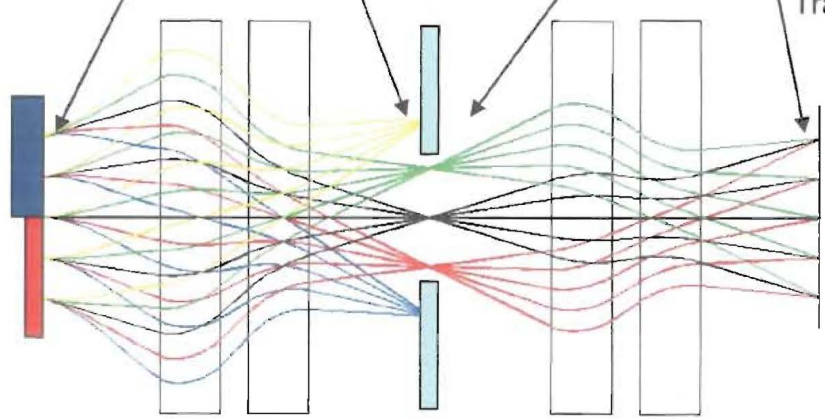


After Collimator



Measured transmission provides information of object thickness





Transmission

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

Areal Density Reconstruction

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

Nuclear removal processes

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

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

Multiple Coulomb Scattering with collimation:

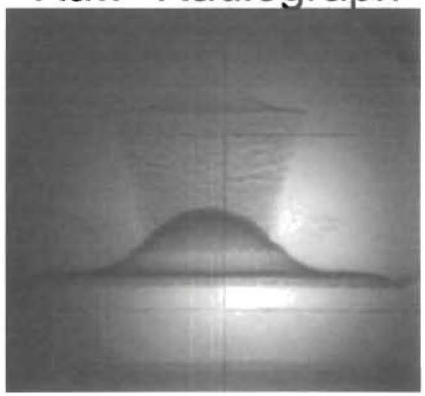
ϑ_o - scattering angle (radians)
x - areal density
x_o - radiation length
p - momentum (MeV)
β - relativistic velocity

$$T = e^{-x/\lambda}\left(1 - e^{-\left(\frac{\theta_c p\beta}{14.1 MeV}\right)^2 \frac{x_o}{2x}}\right)$$

Total Transmission
- inverted to determine areal density, x

Radiographic Analysis

"Raw" Radiograph



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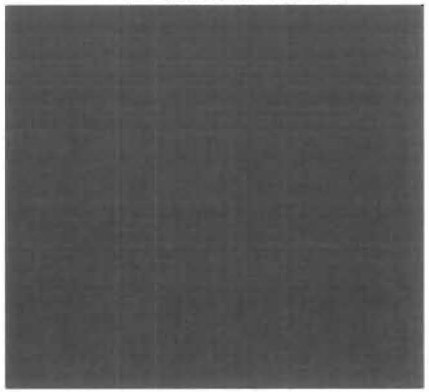
Dark Field



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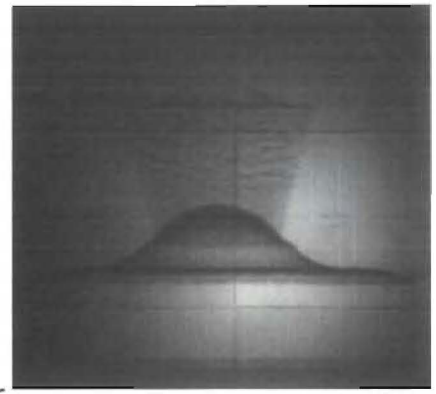

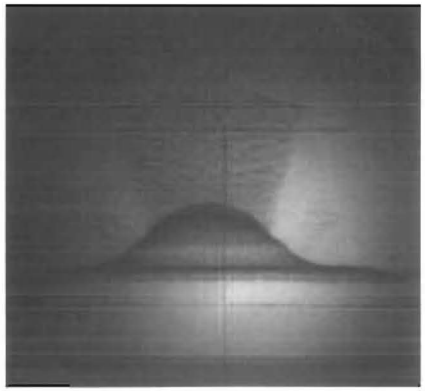

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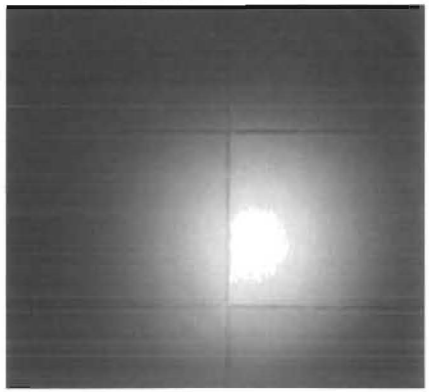
Beam Picture



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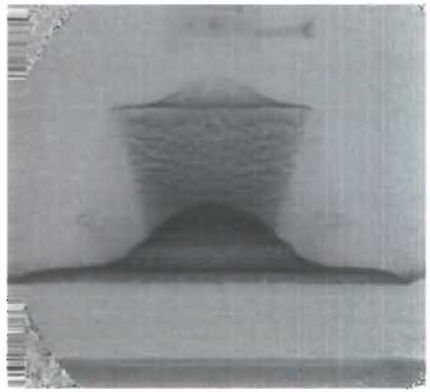
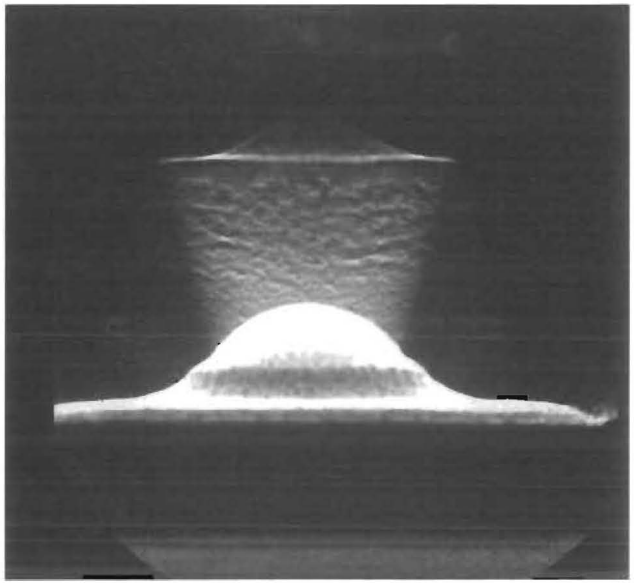
Transmission



Density Reconstruction

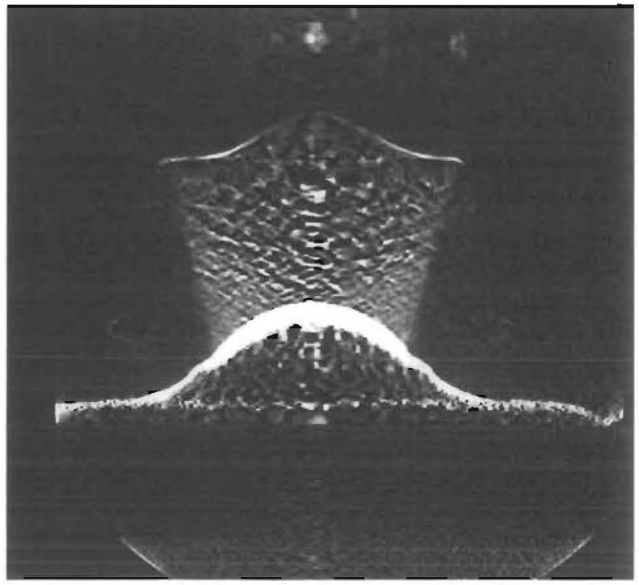
Invert to calculate Areal Density

$$T = e^{-x/\lambda}\left(1 - e^{-\left(\frac{\theta_c p\beta}{14.1\,MeV}\right)^2 \frac{x_o}{2x}}\right)$$



Areal Density (g/cm^2)

Use assumption of cylindrical symmetry to determine volume density (Abel inversion)



Volume Density (g/cm^3)

Radiographic Comparisons

Density Sensitivity

$$FOM = \frac{\Delta N / \sqrt{N}}{\Delta l / l} = \frac{l}{\sqrt{N}} \frac{dN}{dl}$$

Statistical sensitivity per fractional change in object thickness

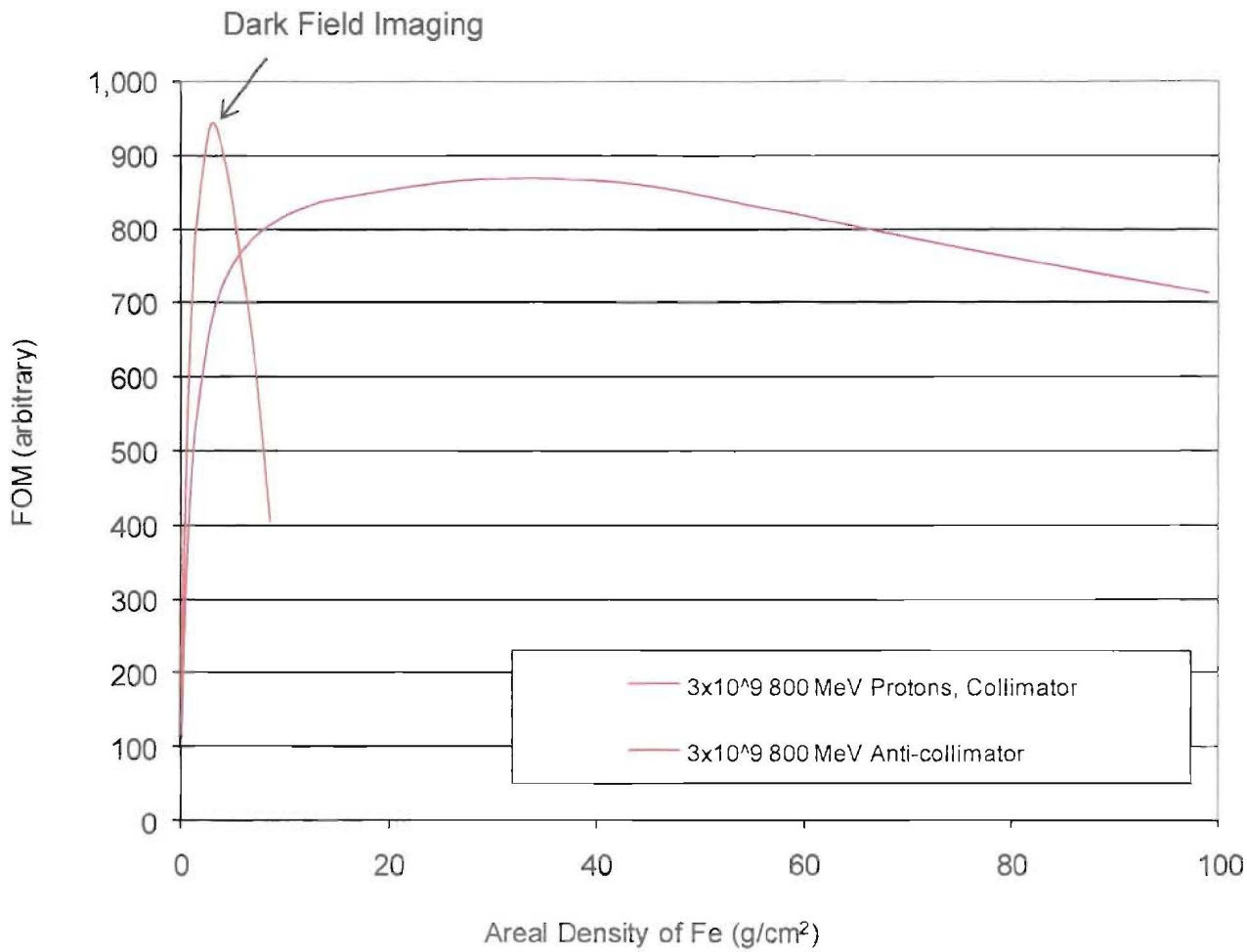
800 MeV Protons*

$$N = N_0 (1 - e^{-x_c / 2l})$$

$$FOM = \sqrt{N_0} \frac{x_c}{2l} \frac{e^{-x_c / 2l}}{\sqrt{1 - e^{-x_c / 2l}}}$$

* Ignore nuclear attenuation

Dynamic Range of 800 MeV Proton Radigraphy



- 800 MeV proton radiography ranges from 0.05 g/cm^2 up to 50 g/cm^2

First Comparison of x-ray to Proton Radiography

Late one night at the accelerator…

A. M. Koehler NATURE VOL. 239 SEPTEMBER 15 1972

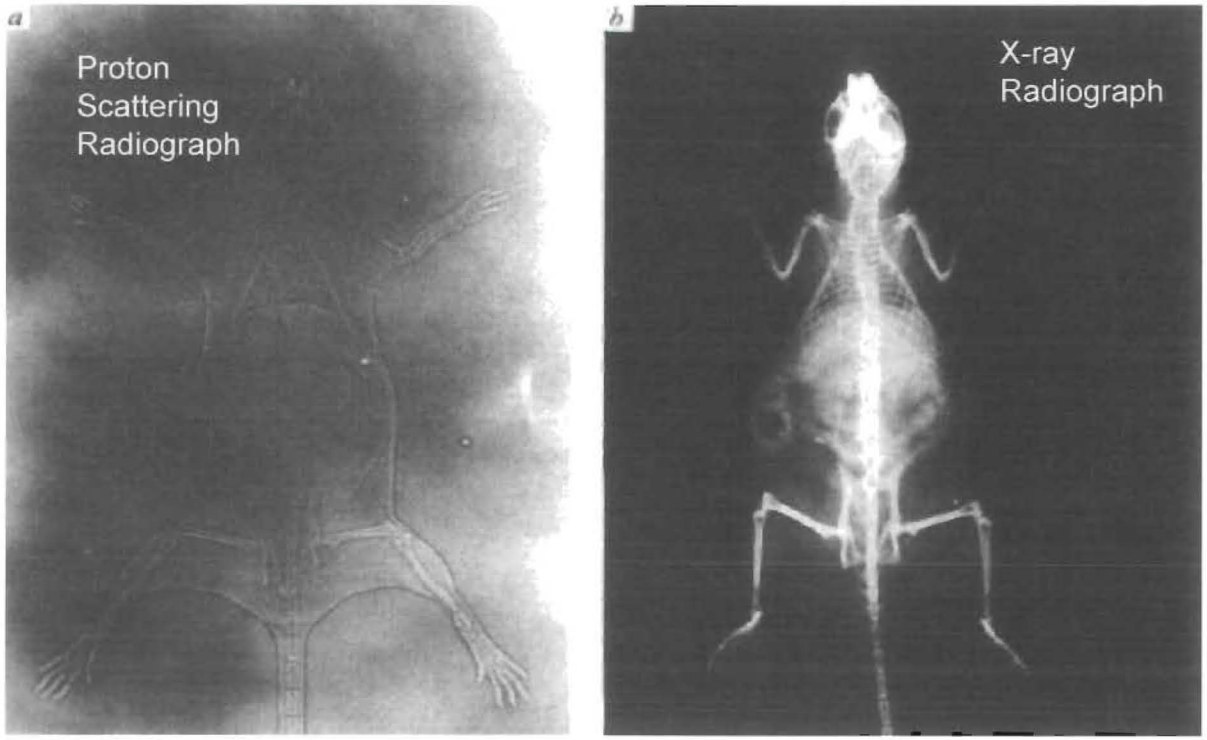


Fig. 1 *a*, Proton radiograph of a mouse with its feet 2.5 cm from the film and its back in contact with the film. *b*, X-radiograph of the same mouse (22 kV on tungsten). Both *a* and *b* have undergone two reversals in processing and so are of the same shading as the original radiograph.

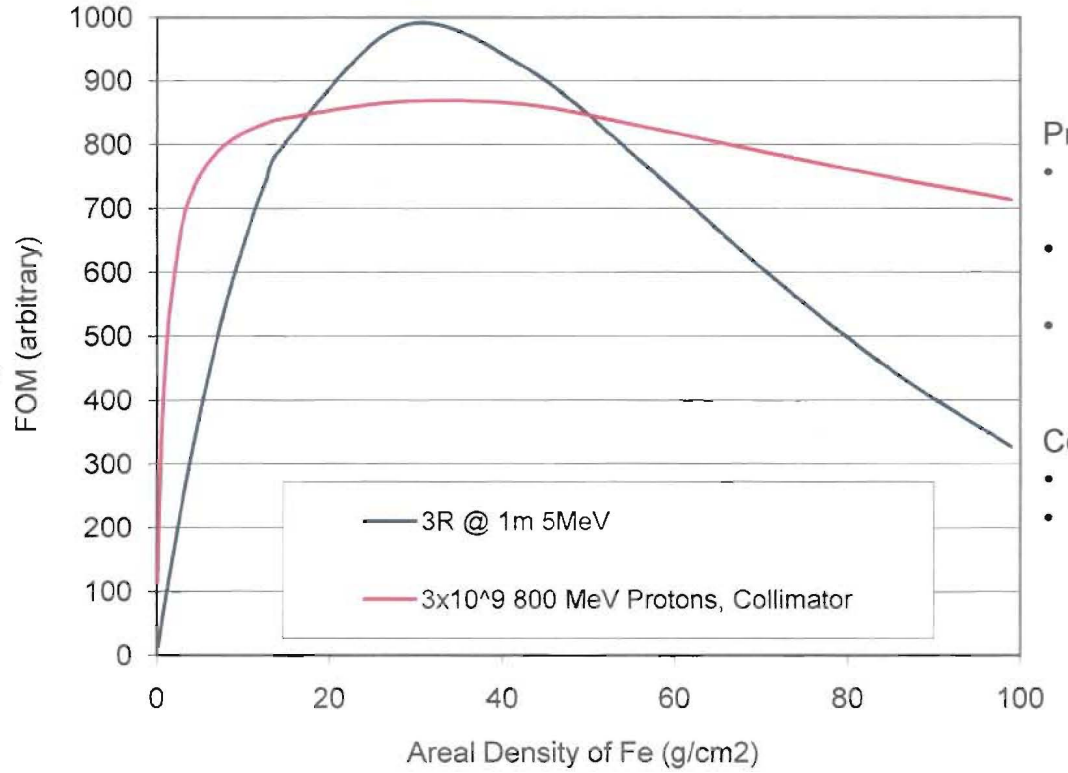
X-Ray Proton Comparison

800 MeV Proton Radiography is roughly equivalent to 5 MeV Brehmsstrahlung x-ray source

X-Rays

Pros:
- Technology is mature and well understood.
- Source is relatively inexpensive.

Cons:
- Multiple-times along the same axis is difficult
- Scatter background results in systematic errors.
- Dynamic range difficult for thick objects



Protons

Pros:
- Multiple-times along the same axis is easy
- Scatter background is significantly reduced
- Dynamic range is easily handled.

Cons:
- Emerging technology
- Proton source is expensive to build.

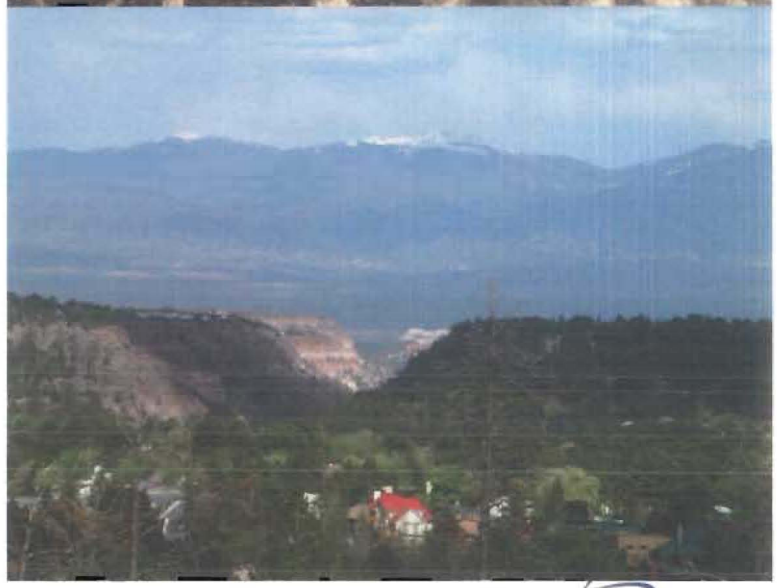
Protons out perform x-rays for multiple time radiography of thick objects.
A proton source is expensive, but if you already have a source the choice is easy.

Los Alamos, New Mexico

Los Alamos is located in the high desert (>2000 m) on the side of an ancient super volcano in northern New Mexico.

Los Alamos

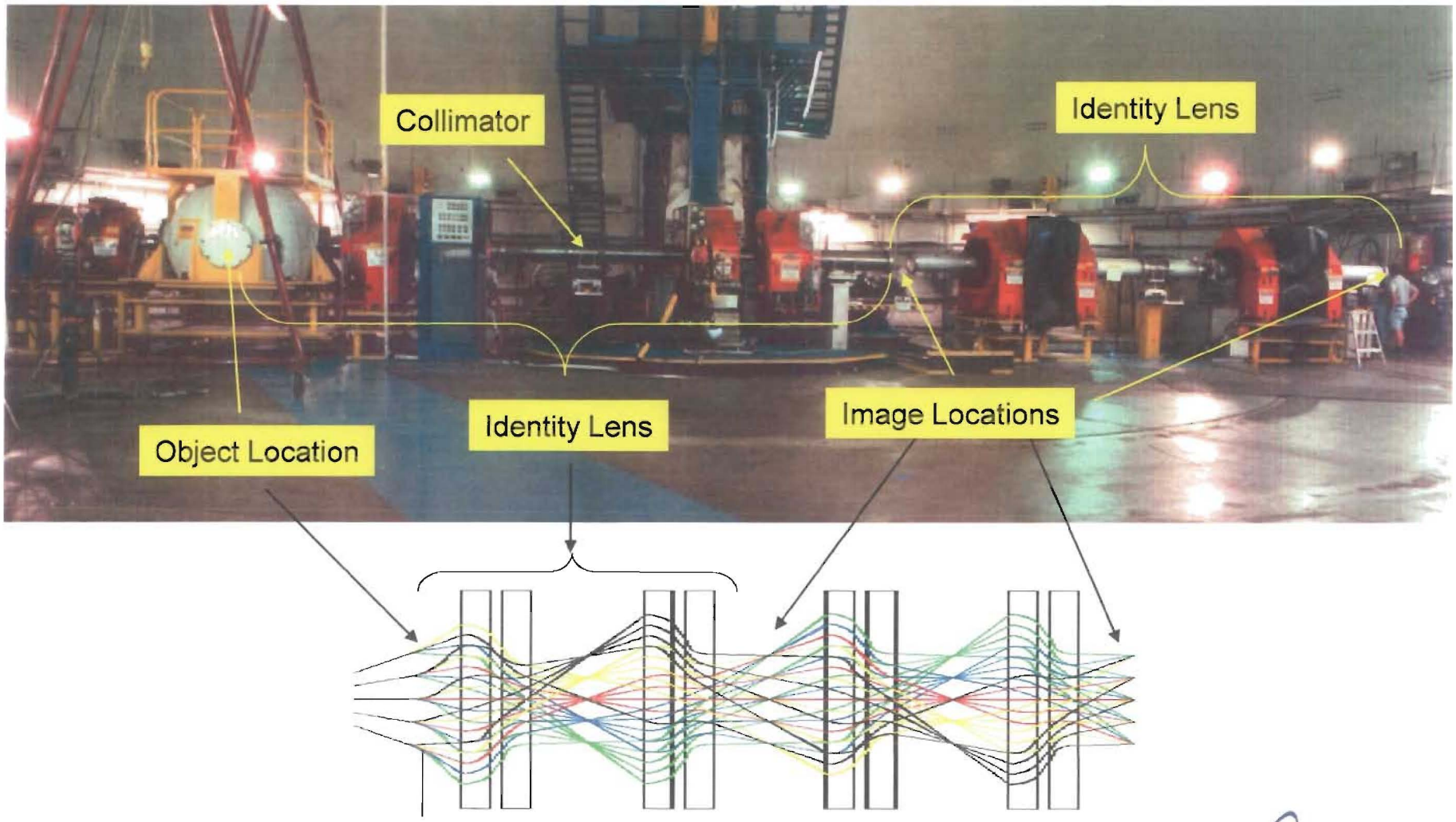
LANSCE



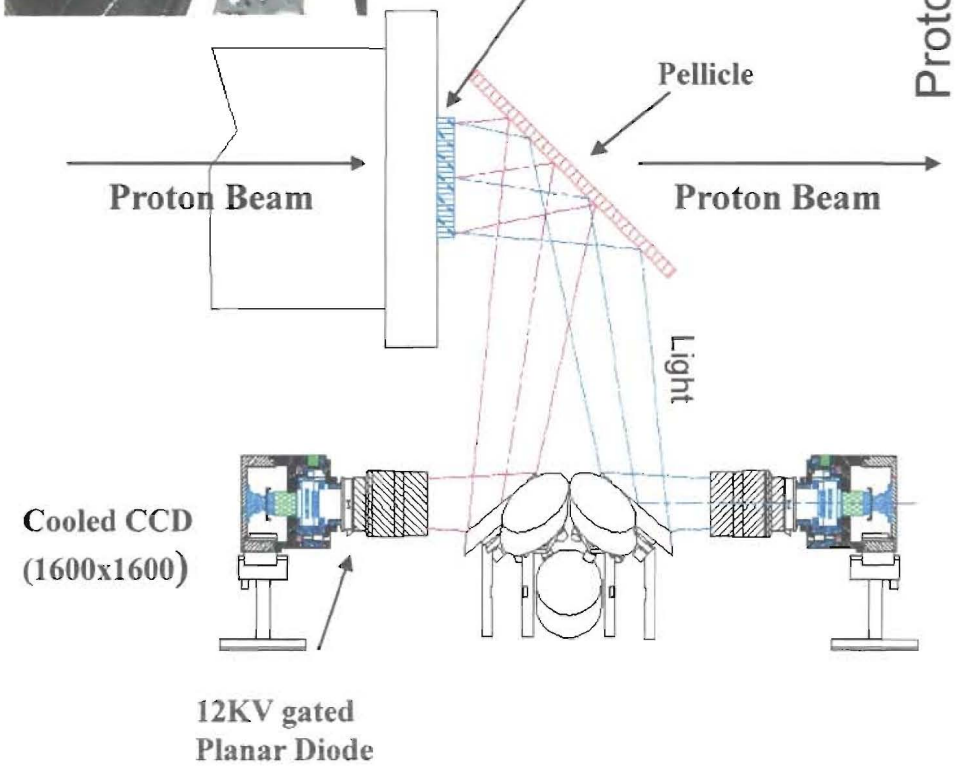
LANSCE Experimental Areas

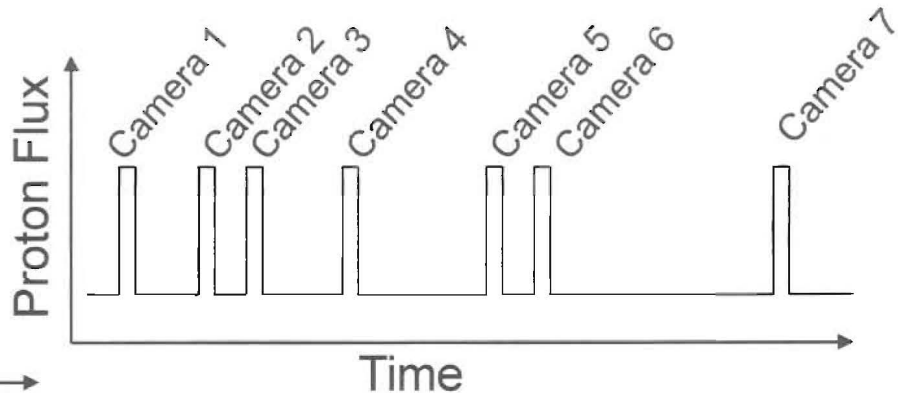
- Lujan Center
  - ***National security research***
  - ***Materials, bio-science, and nuclear physics***
  - ***National user facility***
- WNR
  - ***National security research***
  - ***Nuclear Physics***
  - ***Neutron Irradiation***
- Proton Radiography
  - ***National security research***
  - ***Dynamic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

800 MeV pRad Facility at LANSCE



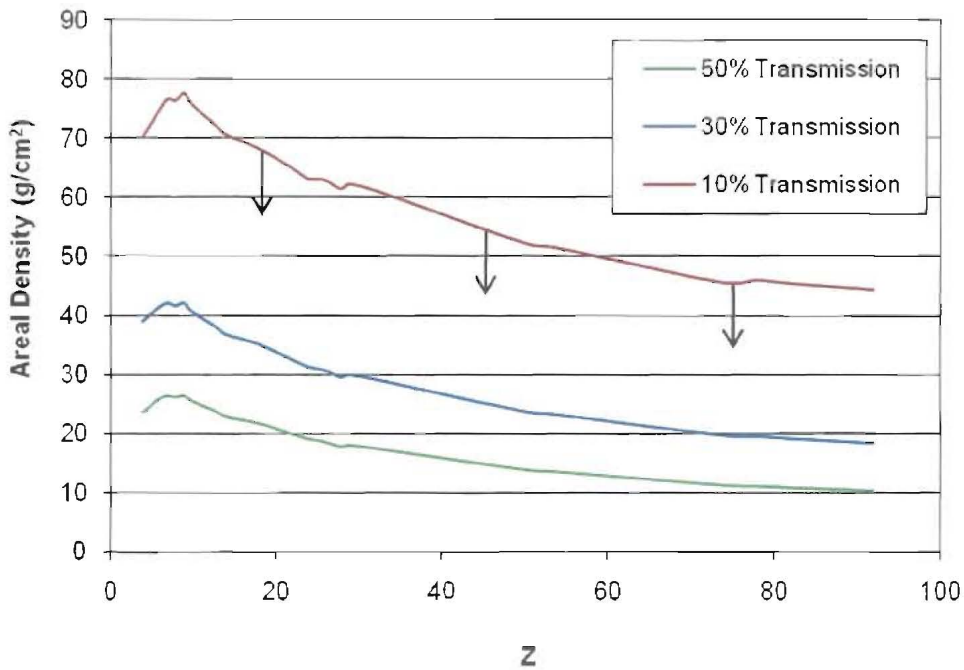
Temporal Resolution





- 19 images at first station
- 22 images at second station
- Typically 100 ns exposure times
- 180 ns inter frame spacing
- Beam available for1000 μs

Sensitivity with 800 MeV Protons



Areal density contours of constant transmission as a function of atomic number.

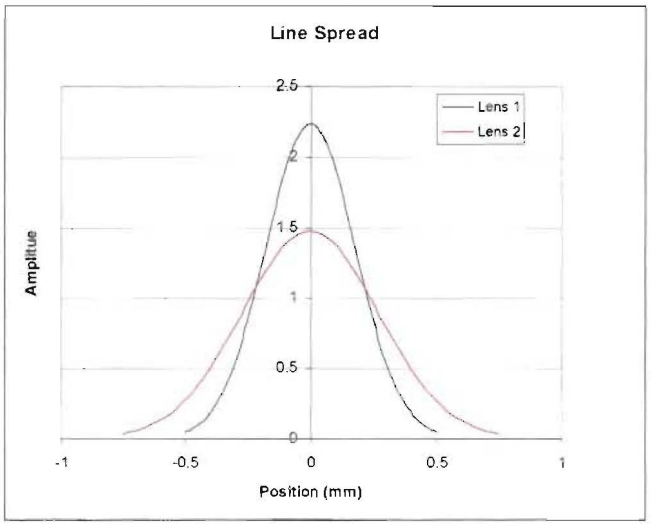
10% transmission is near the lower limit of reasonable transmission.

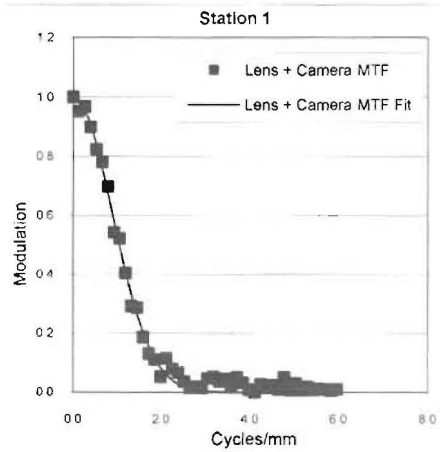
- Perform experiments less than ~50 g/cm^2 with 800 MeV proton Radiography

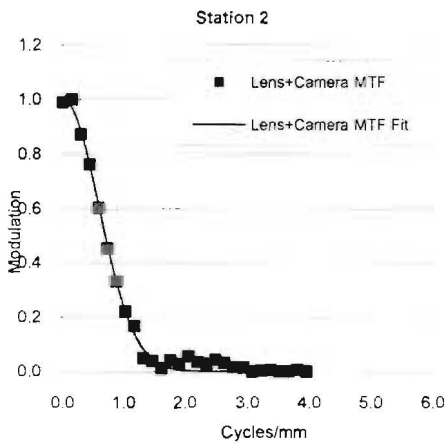
Resolution of 12” Lens

- Bare resolution (rms)
  - Station 1: 178 μm
  - Station 2: 280 μm

Gaussian Line Spread Function

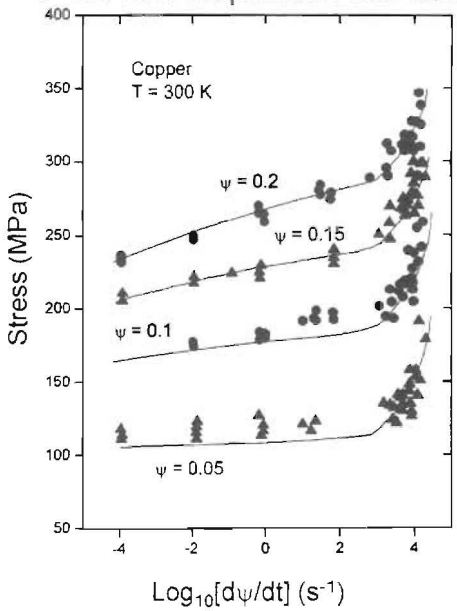


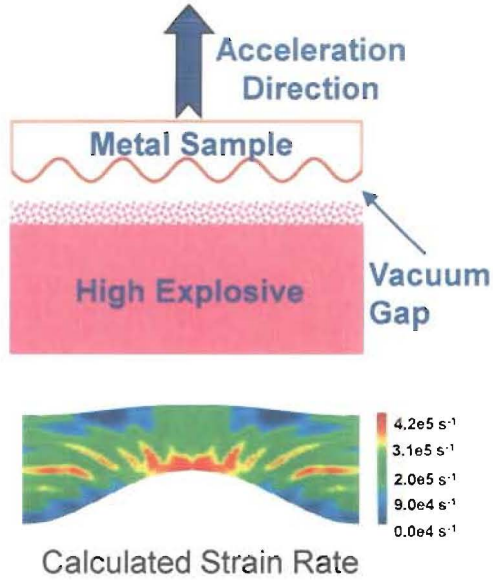




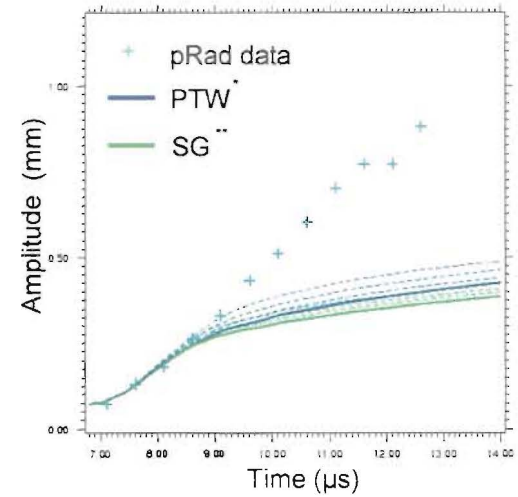
Material Strength Experiments

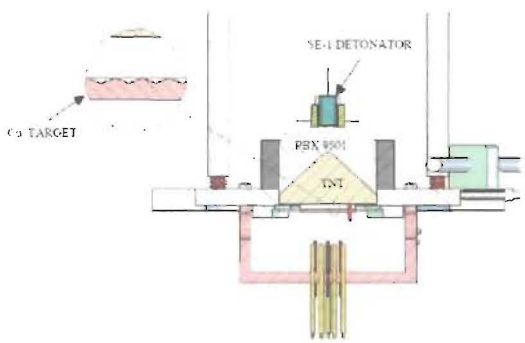
PTW fit to Hopkinson-Bar data*



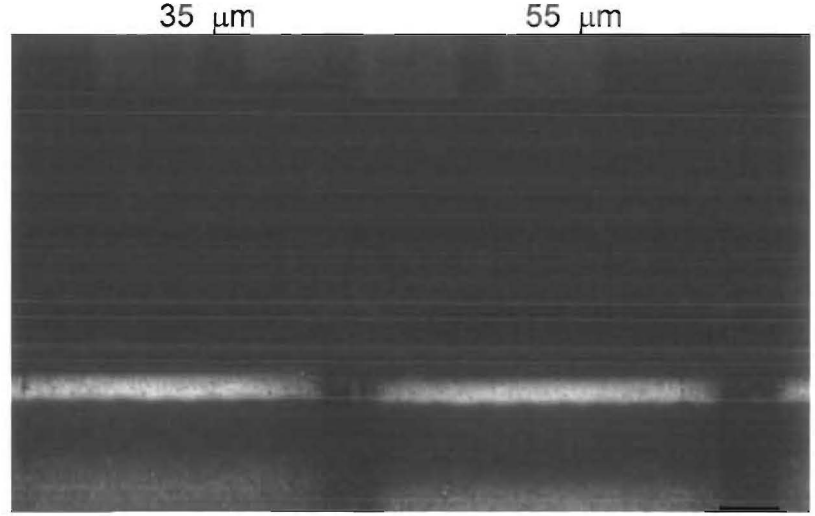


Calculated Strain Rate



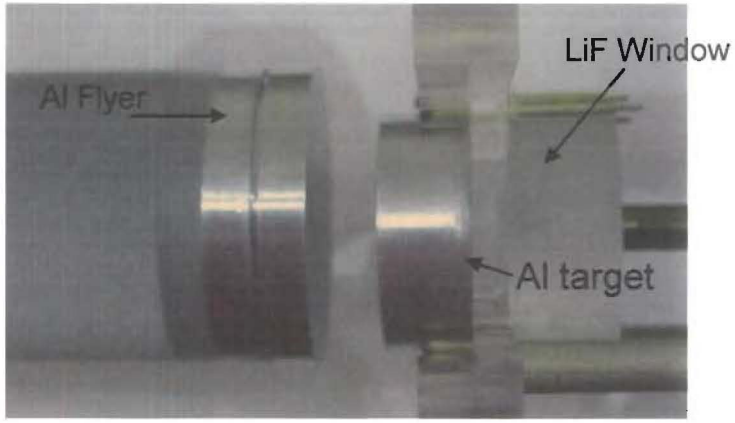


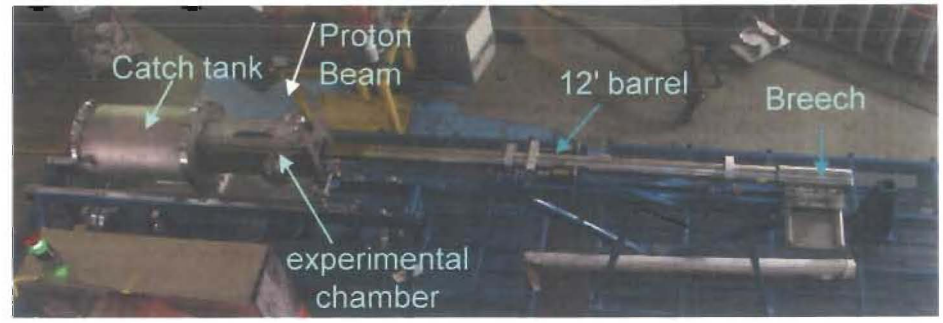
35 μm 55 μm



*D.L.Preston, et al. J.Appl. Phys. **93**, 211 (2003). **D. J. Steinberg, et al. J.Appl. Phys. **61**, 1816 (1987).

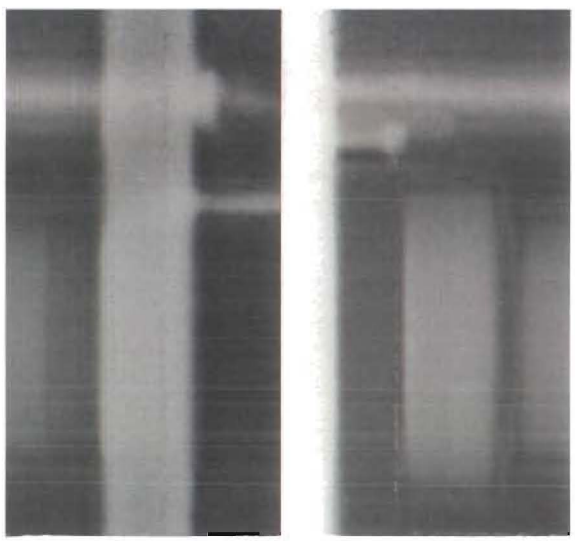
Powder Gun Driven Equation Of State Measurements



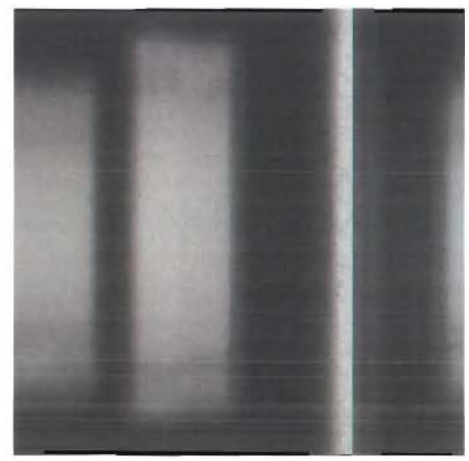


Aluminum

1.4 km/s

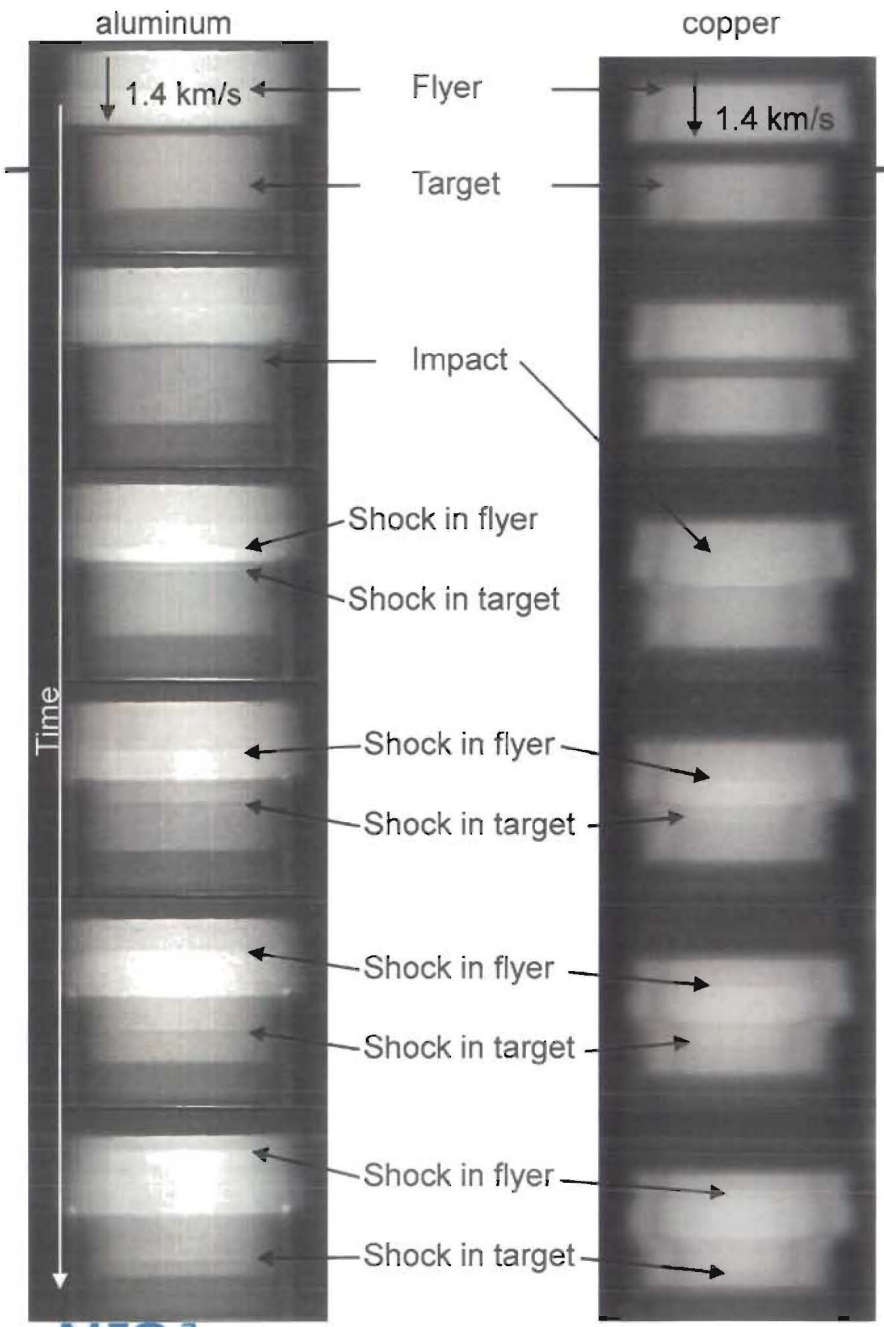


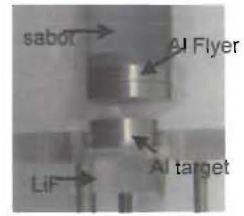
Copper

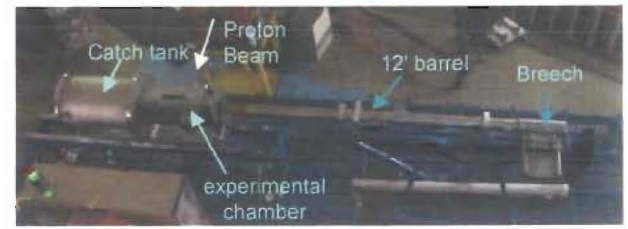


1.4 km/s

Powder Gun Al/Cu Equation Of State







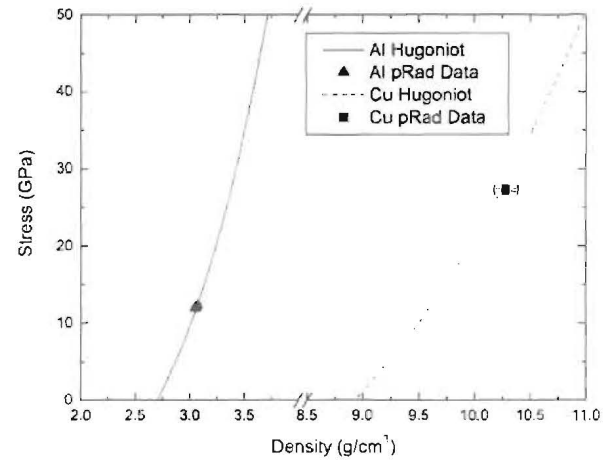
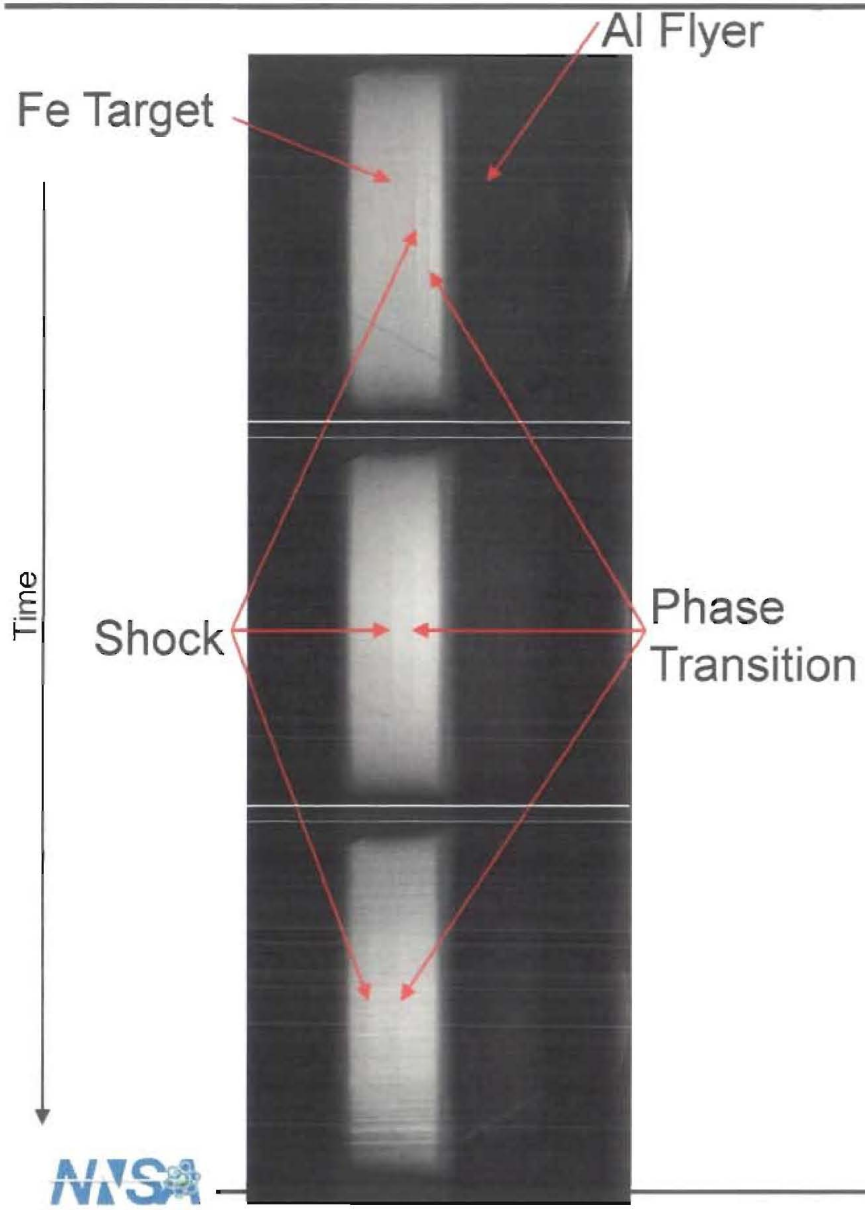
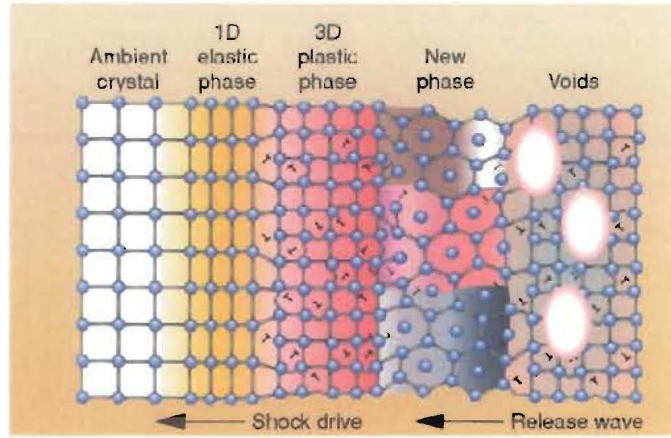


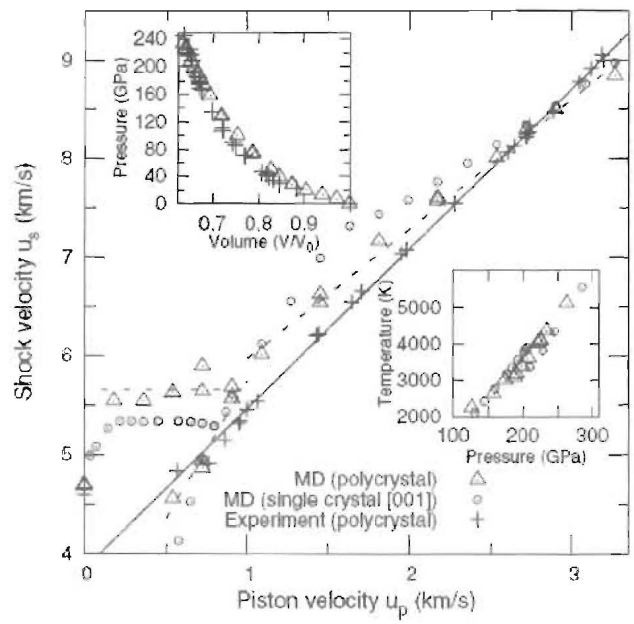
TABLE I. Summary of the experiments with the uncertainties for each quantity shown in parentheses.

Experiment	Impactor/ sample	Impactor velocity (mm/μs)	Peak stress (GPa)	Initial density (g/cm³)	Calculated density (g/cm³)	Measured density (g/cm³)	Agreement
1	Al 6061-T6	1.452 (0.012)	12.27 (0.11)	2.710 (0.003)	3.067 (0.005)	3.070 (0.025)	0.1%
2	Al 6061-T6	1.422 (0.002)	11.98 (0.03)	2.710 (0.003)	3.060 (0.004)	3.056 (0.020)	0.1%
3	OFHC Cu	1.30 (0.04)	28.59 (0.91)	8.928 (0.003)	10.30 (0.05)	10.28 (0.08)	0.2%
4	OFHC Cu	1.249 (0.002)	27.16 (0.06)	8.928 (0.003)	10.241 (0.006)	10.28 (0.08)	0.4%

Solid-Solid Phase Transitions in Iron







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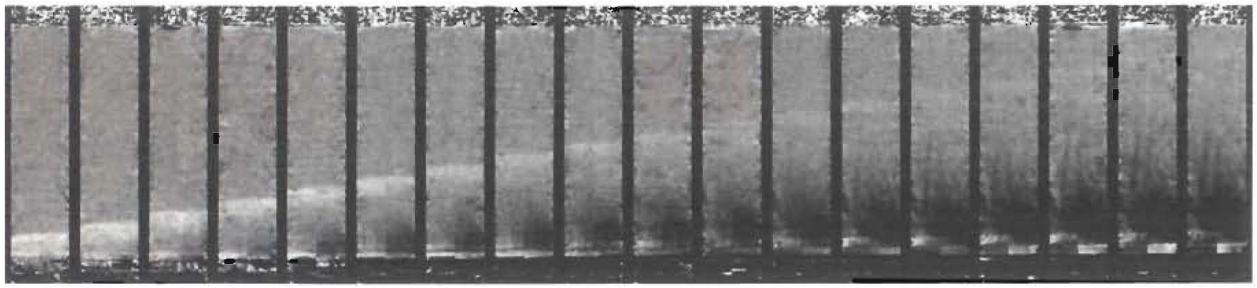
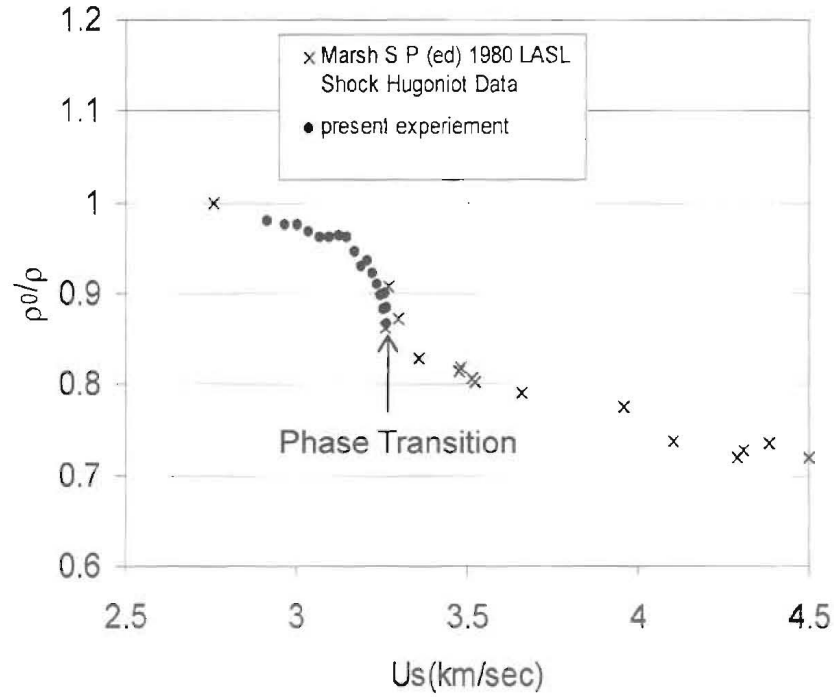
Taylor Wave EOS Measurements



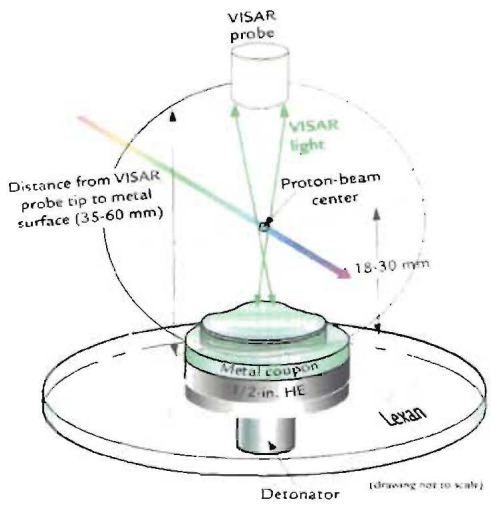
Shock position measured in each radiograph combined with time between radiographs provides a shock velocity measurement as a function of time.

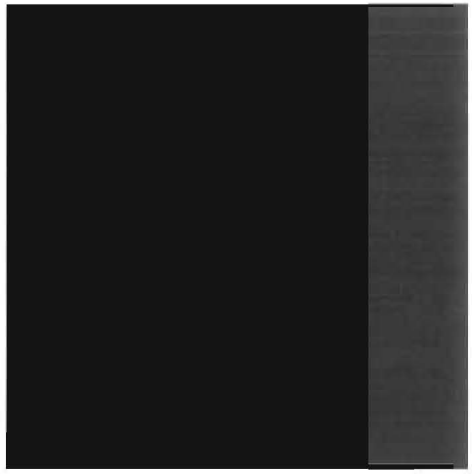
Infer density jump from measurement of relative transmission.

As the Taylor wave traverses the tin sample the peak shock pressure decreases, providing a measurement along the Hugoniot.

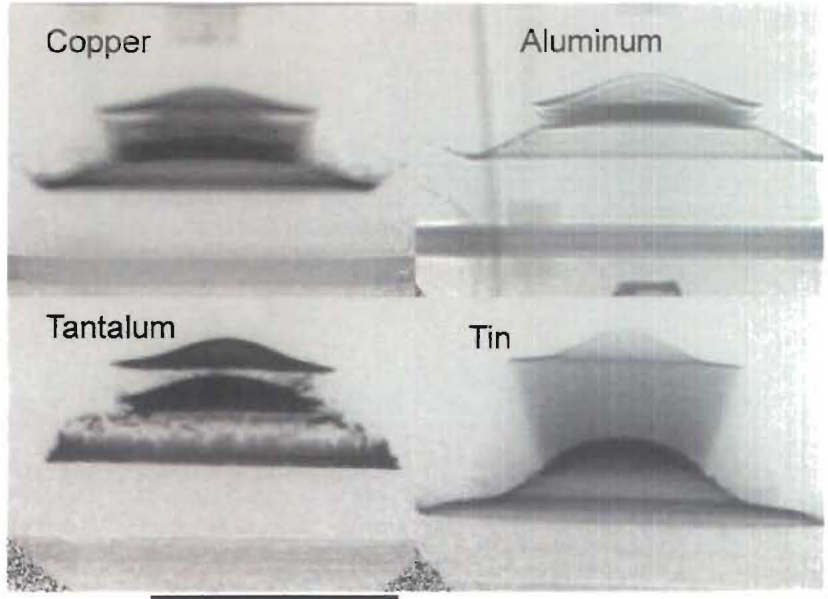


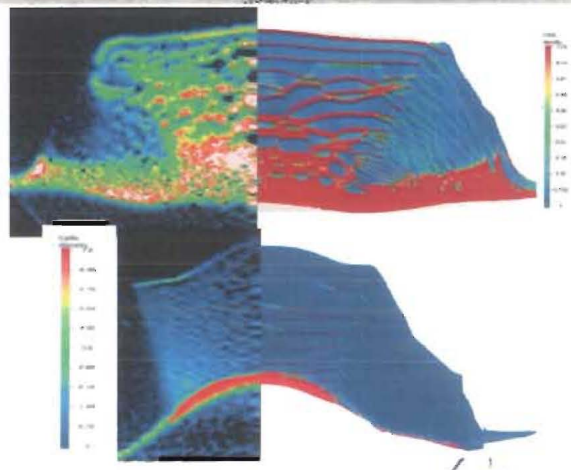
pRad has been used to study the failure of materials driven by point detonated high explosives





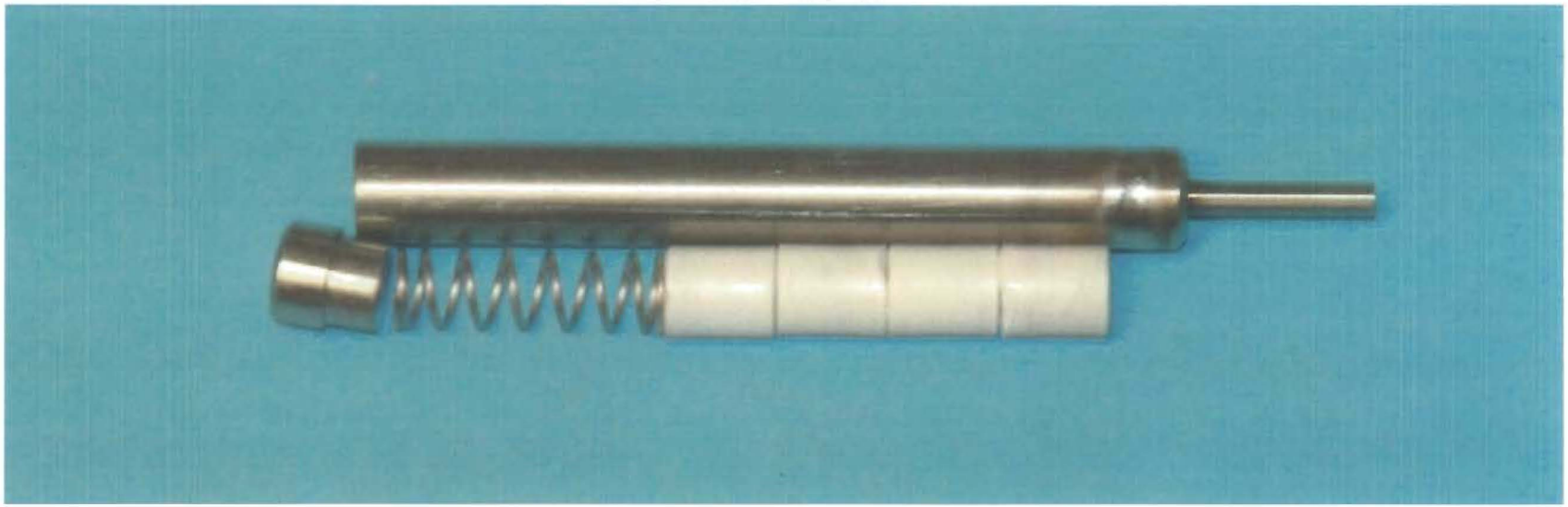
A comparison of spall for different materials





- 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.

Static Objects Surrogate Fuel Rods



X3 magnifier has T126 ~ 3 meters

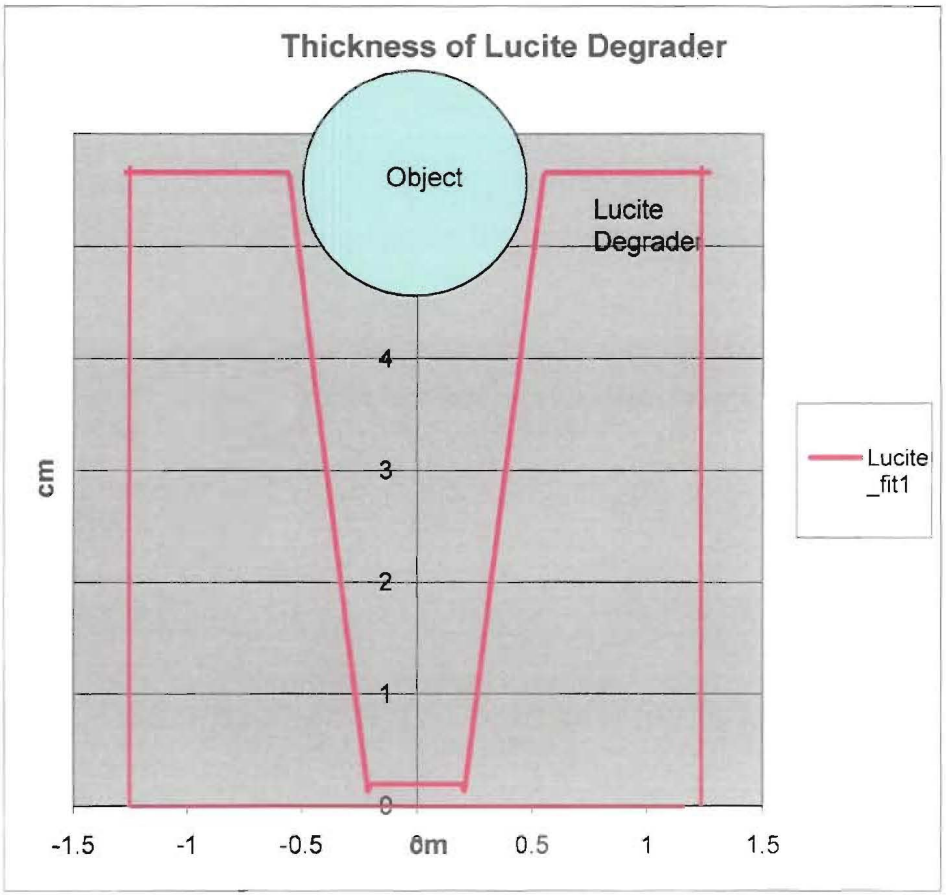
E-Loss through object center ~ 13 MeV ➔resolution ~ 0.5mm at center

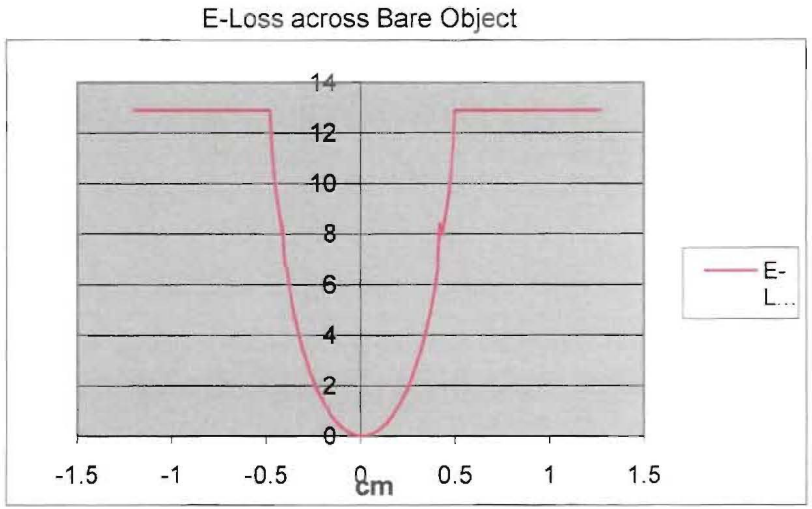
Set the Lens to <E_Loss> ~10MeV ➔ resolution ~ 0.113 mm at center

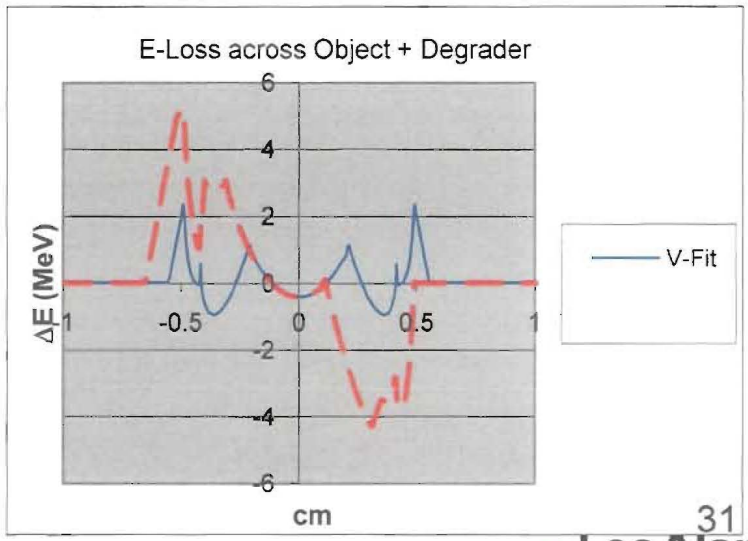
For Static Objects One can reduce chromatic blur by use of "Graded Degraders"

Mitigating Chromatic Blure: E-Loss Flattening Scheme

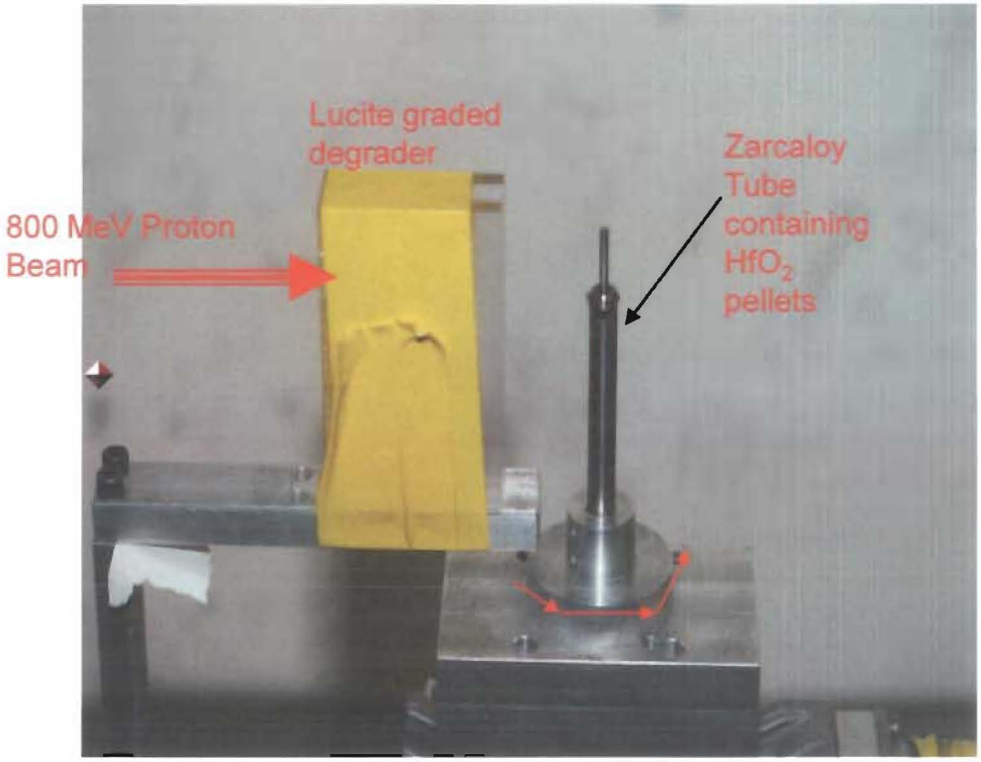
Chromatic term (T126) = 3m*δθ*(dE/E)





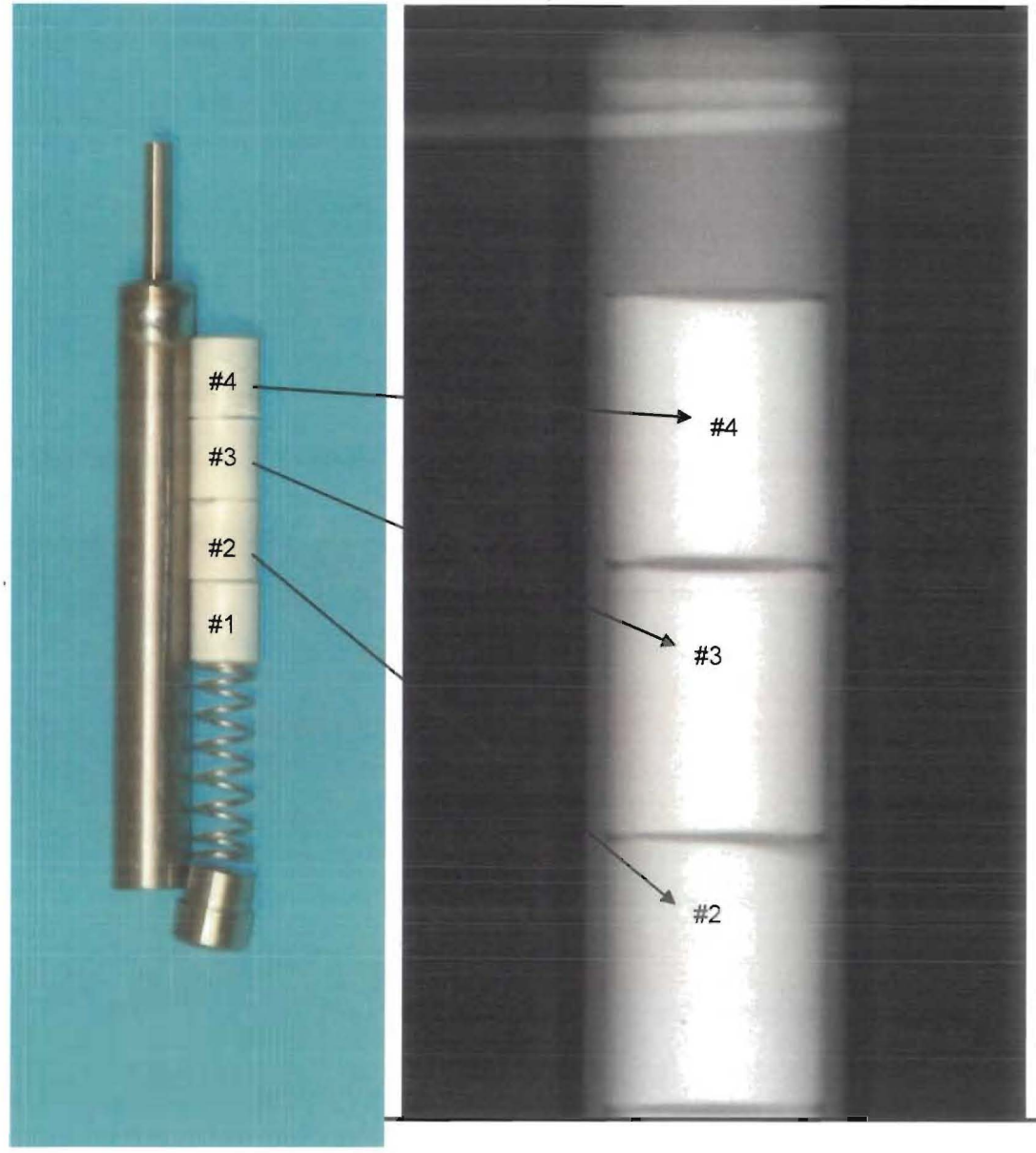


The Set up



Zarcaloy tube was aligned on the graded degrader.
Radiograph pictures were taken at 181 rotational positions

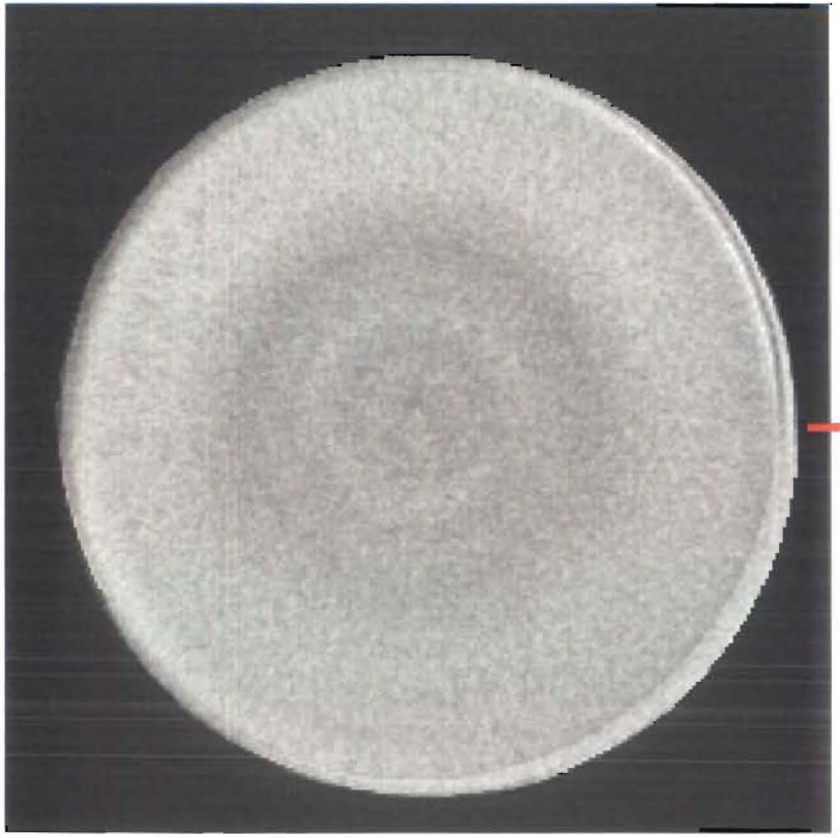
Areal Density



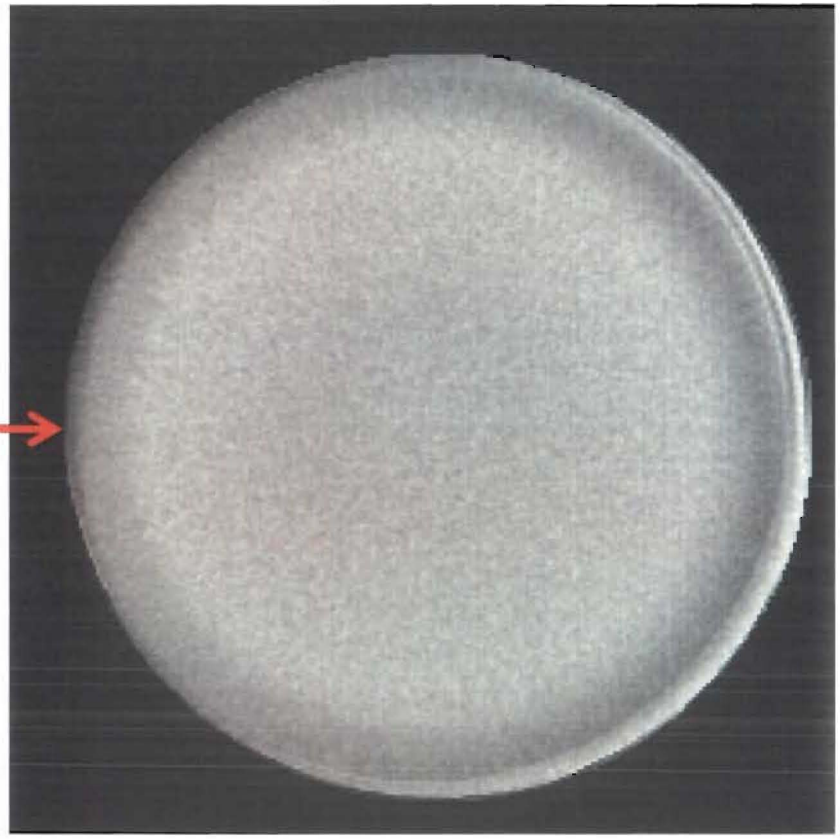
Los Alamos

CT Reconstrusction: Minimize ring artifacts by assuming that the zarcaloy portion of the images is homogeneous and therefore has no ring structure in the density

Dafault ring removal parameter

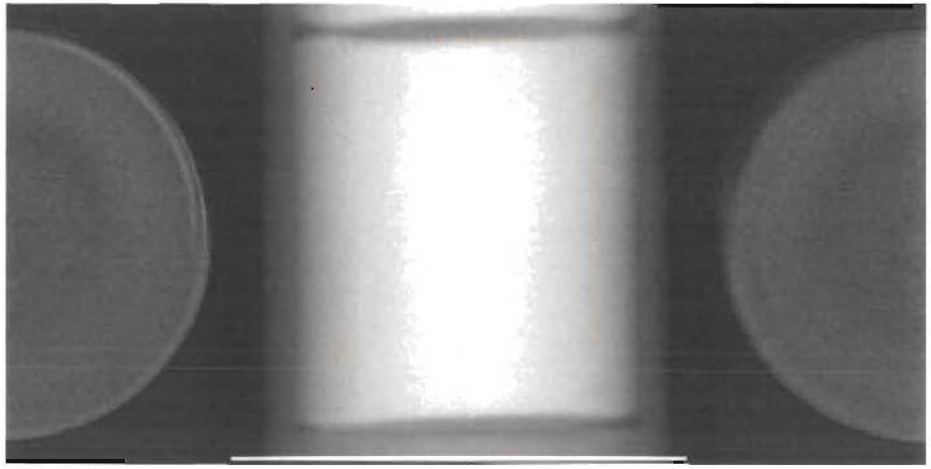


Increased ring removal parameter



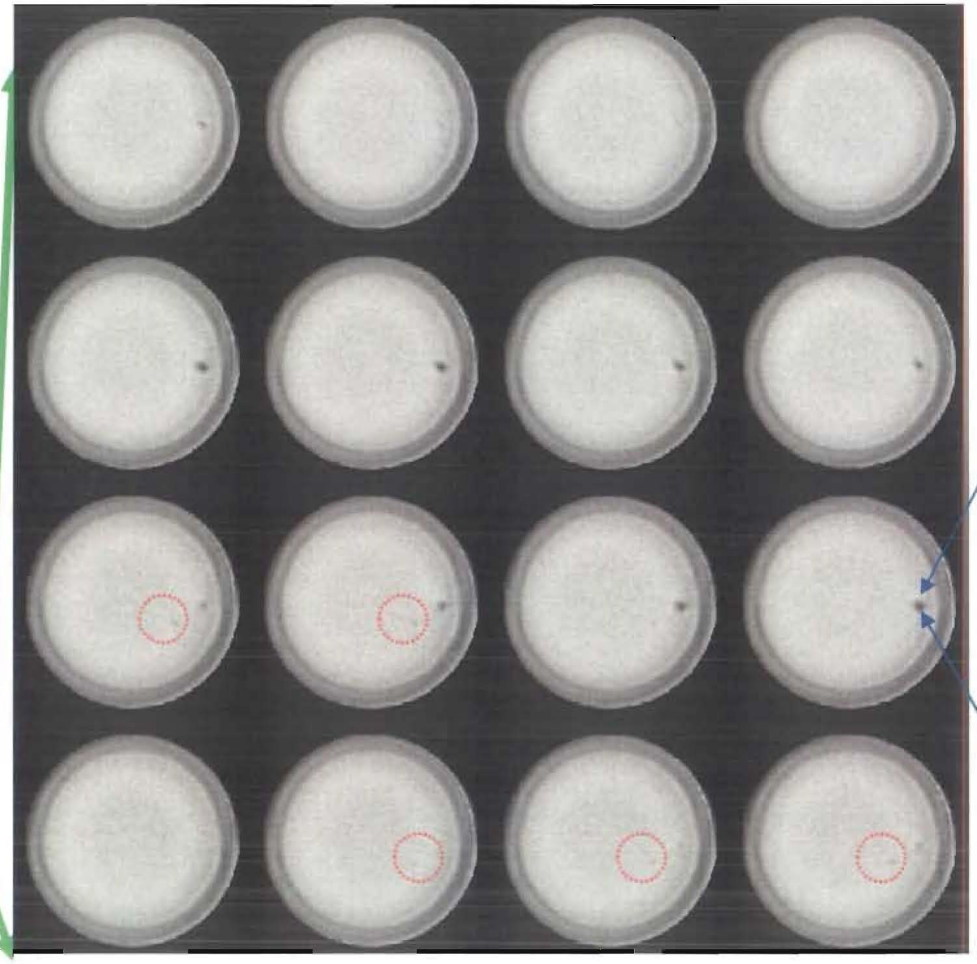
CT Reconstructed Slices:

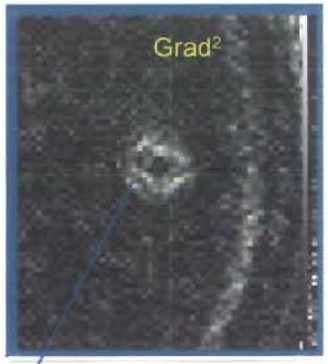
Interesting Regions: Part of Zarcaloy portion, all of Pellet#4, Part of Pellet#3

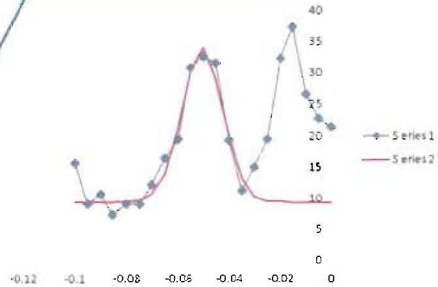


Filtered Back Projection:

Defects in Pellet #4, Slices 78 to 93







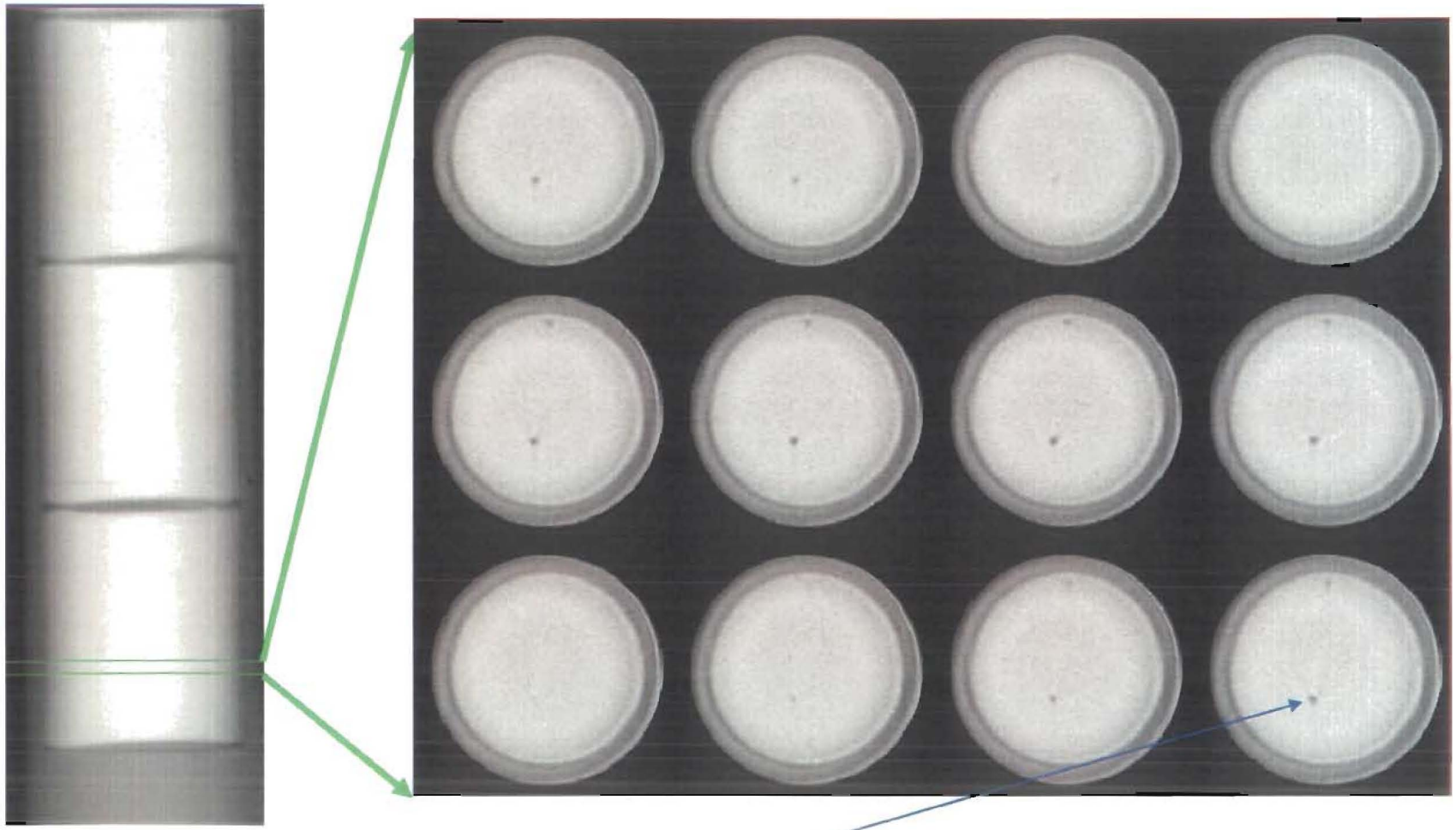
Resolution ~ 80 μm

$\text{Diameter}_{\text{Inclusion}}$ ~ 350 μm

$\text{Length}_{\text{Inclusion}}$ ~ 550 μm

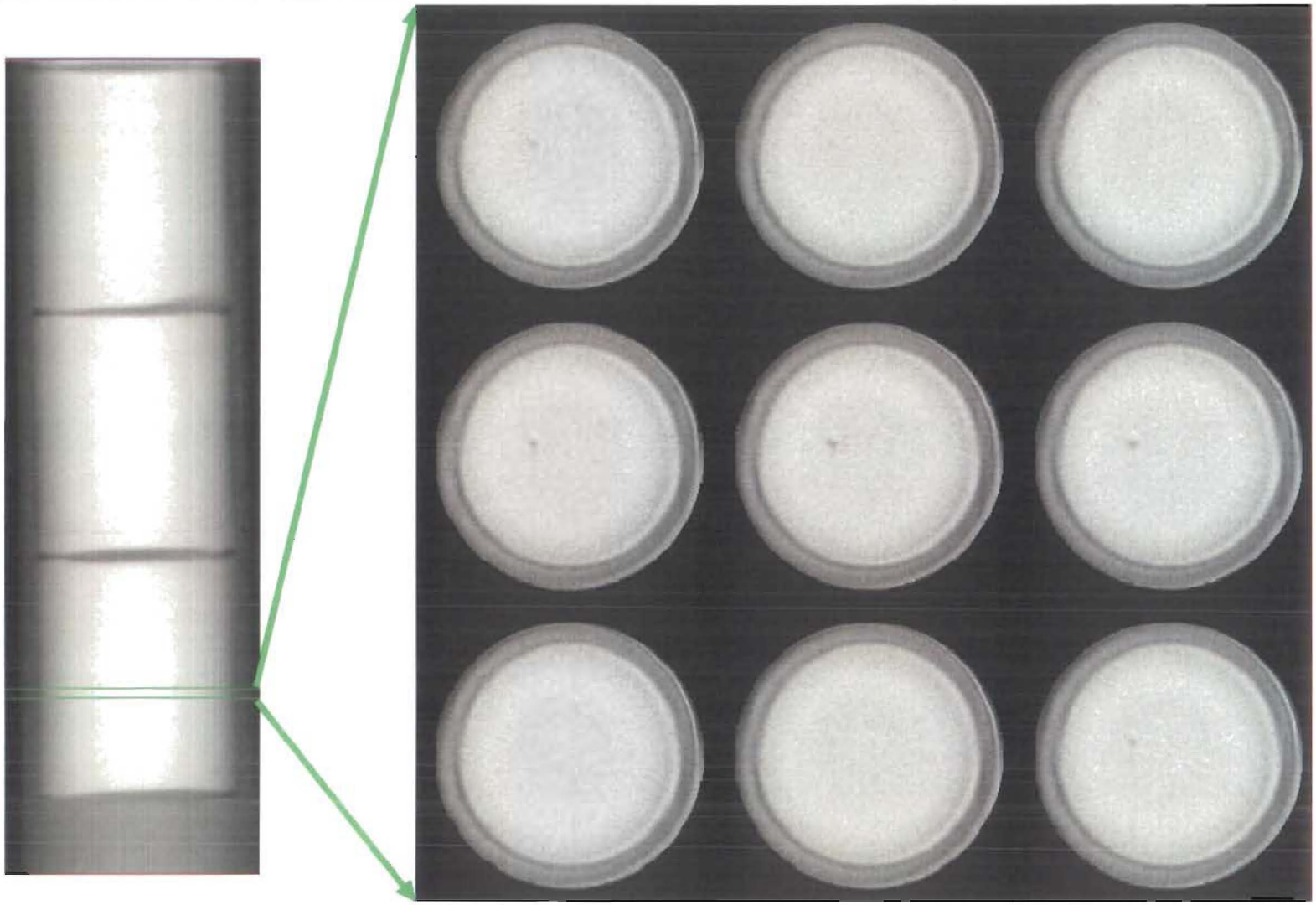
Fainter 250 μm long by ~150 to 200 μm diameter inclusions are shown in the circles

More Defects in Pellet #4: Slices 131 to 142



$\text{Diameter}_{\text{Inclusion}}$ ~ 225 μm
$\text{Length}_{\text{Inclusion}}$ ~ 450 μm

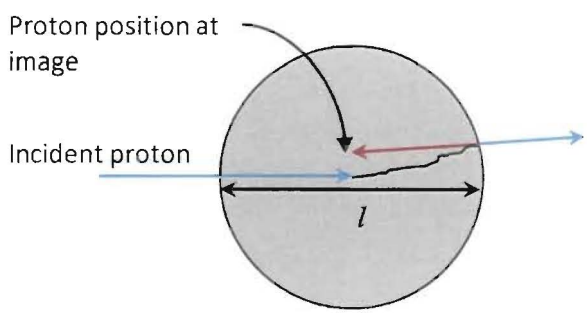
More Defects in Pellet #4: Slices 152 to 160



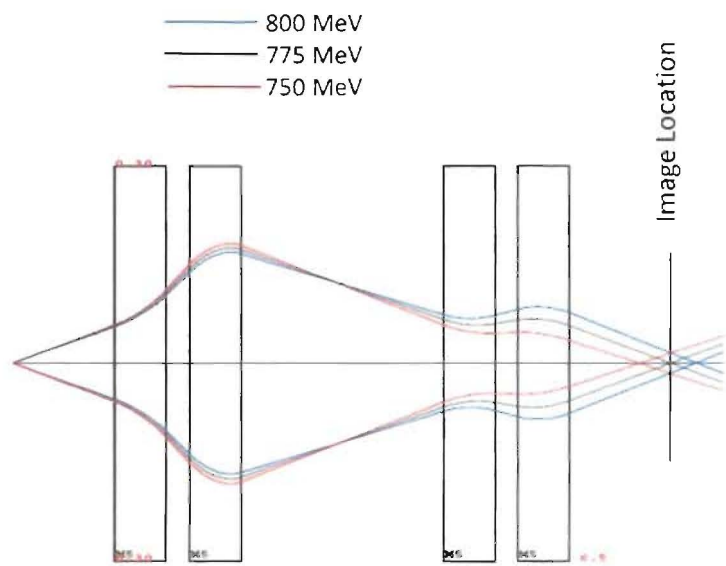
Resolution Limits of Proton Radiography

1. **Object scattering** - introduced as the protons are scattered while traversing the object.
2. **Chromatic aberrations**- introduced as the protons pass through the magnetic lens imaging system.

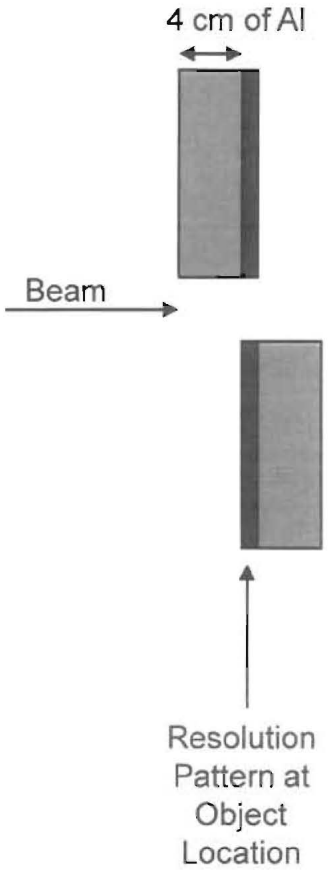
Object Scattering



Chromatic Aberrations

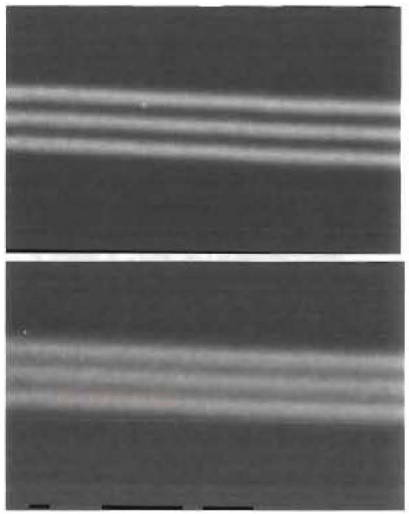


Object Scattering Blur

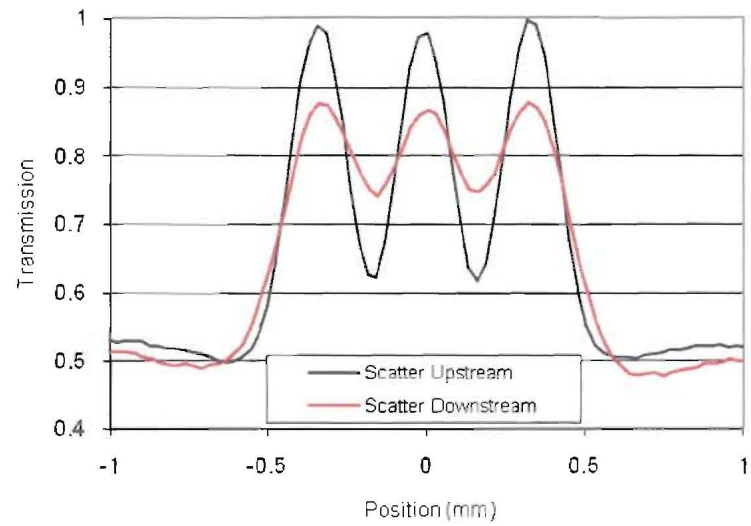


2.5 lp/mm

Sigma=0.061 mm

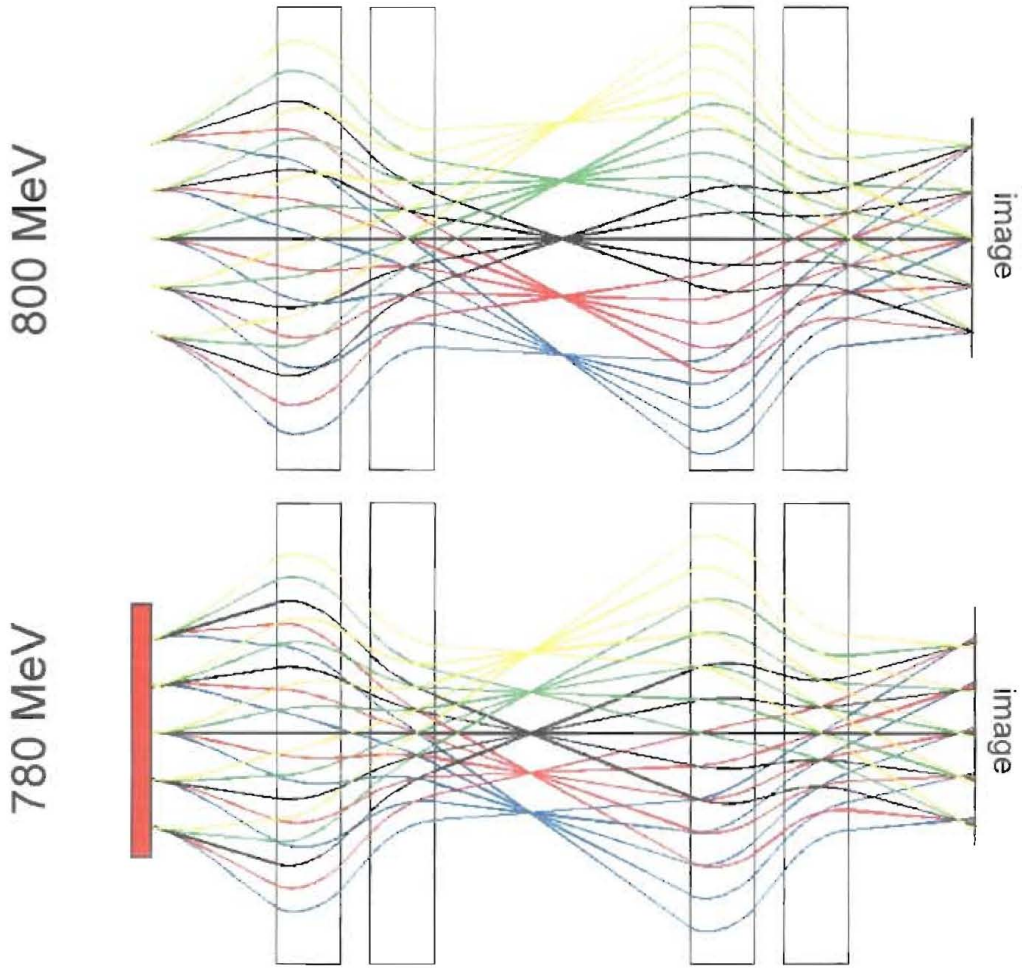


Sigma=0.150 mm



$$\sigma_o = \frac{1}{\sqrt{3}}\theta\frac{l}{2} = \frac{14.1}{\sqrt{6}}\frac{1}{P\beta}\sqrt{\frac{l^3}{x_o}} \propto \frac{l^{\frac{3}{2}}}{P}$$

Chromatic Aberrations



Set the lens to focus 800 MeV protons

Insert an object which results in 20 MeV of energy loss (~ 1 cm of Pb).

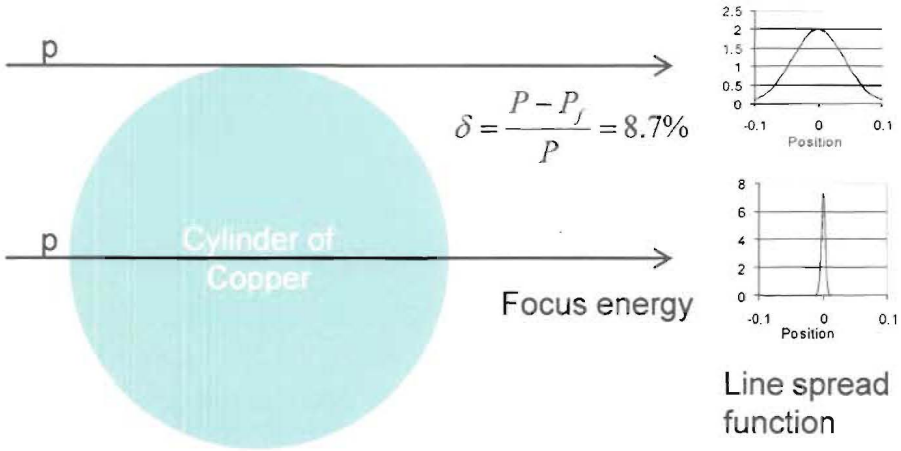
The focal length of the lens is shortened, resulting in blur at the image location.

Blur is proportional to:

$$\Delta x = T_{126}\phi\delta$$

T_{126} – chromatic length
ϕ - scattering angle within the object
δ - fractional deviation from focus energy

Effect of Chromatic Aberrations on Resolution



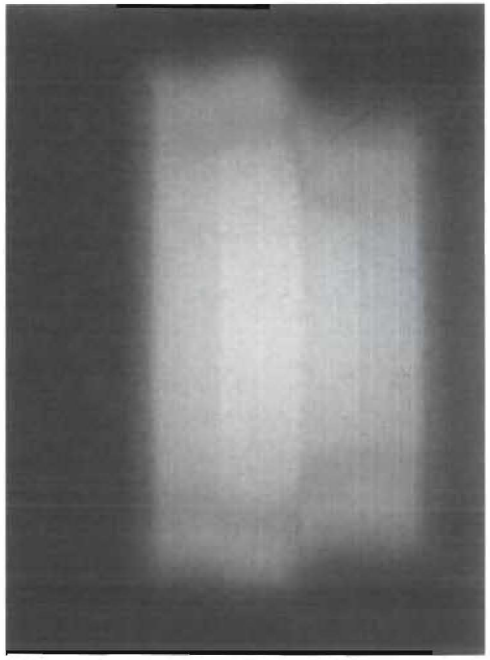
$$\delta = \frac{P - P_f}{P} = 8.7\%$$

Line spread function

$$\Delta x = T_{126}\phi\delta$$

- Objects of varying thickness result in a position dependent energy loss.
- The imaging lens can only be focused for one energy loss. This results in a position dependent blur function.
- The blur function is correlated to the object thickness.

Identity Lens $\frac{P - P_f}{P} = 8.7\%$



copper

Chromatic Blur ⟶ Limning

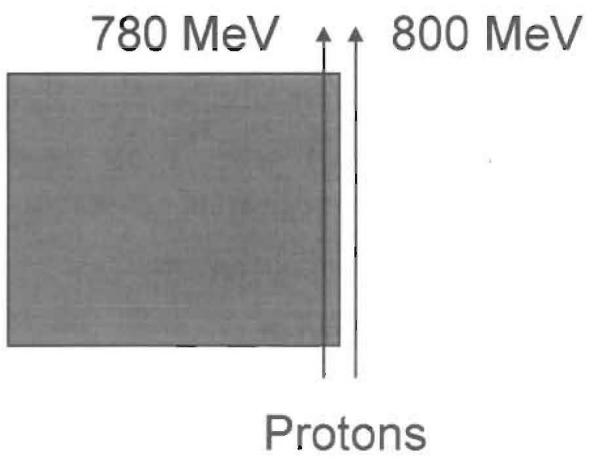
Limb: To outline in clear sharp detail

Like phase-contrast radiography:

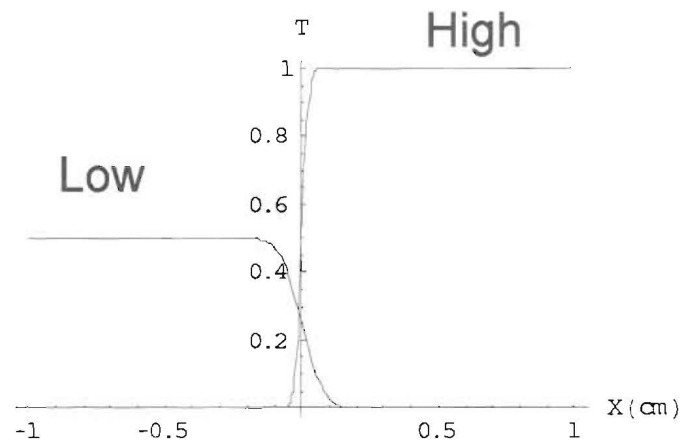
- Useful to enhance edges
- Problem for density reconstruction

Resolution proportional to energy offset

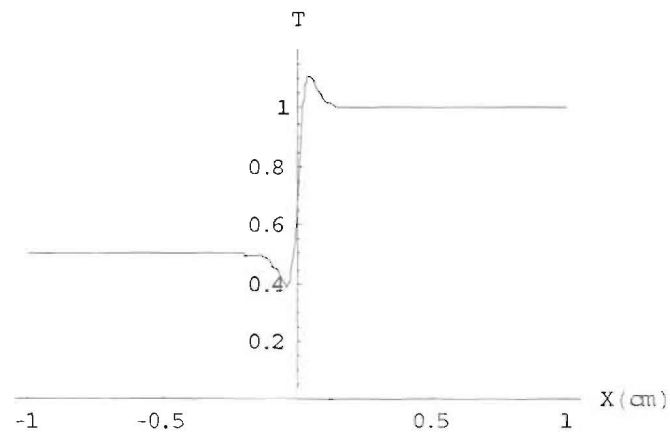
$$\sigma = C\frac{E - E_f}{E_f}\theta$$



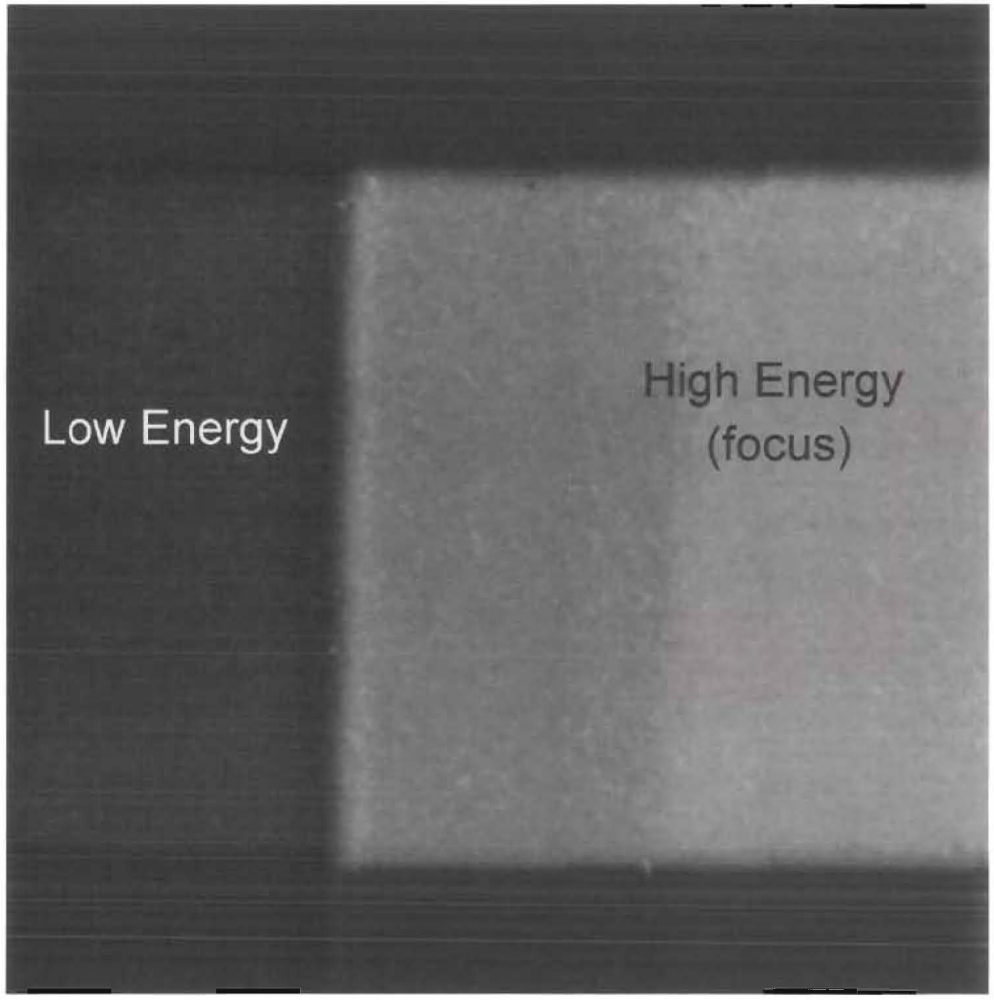
Focus on high energy protons



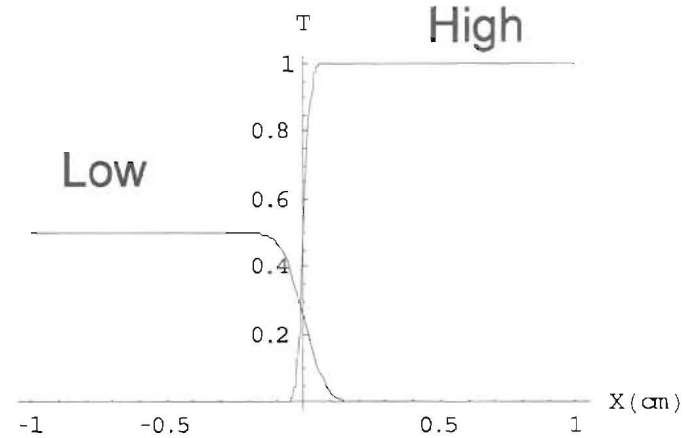
Low + High



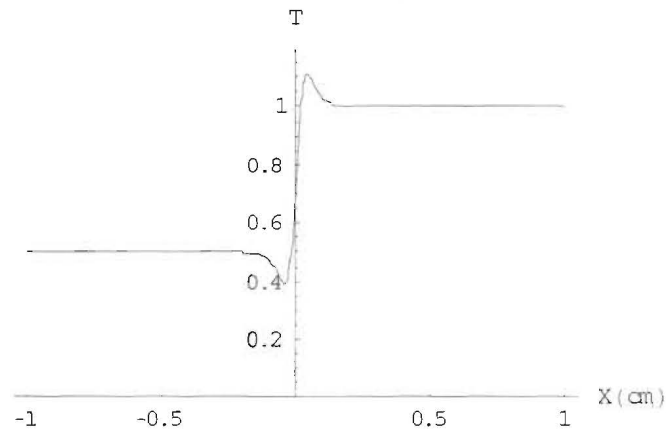
Example: Focused on high energy protons



Focus on high energy protons

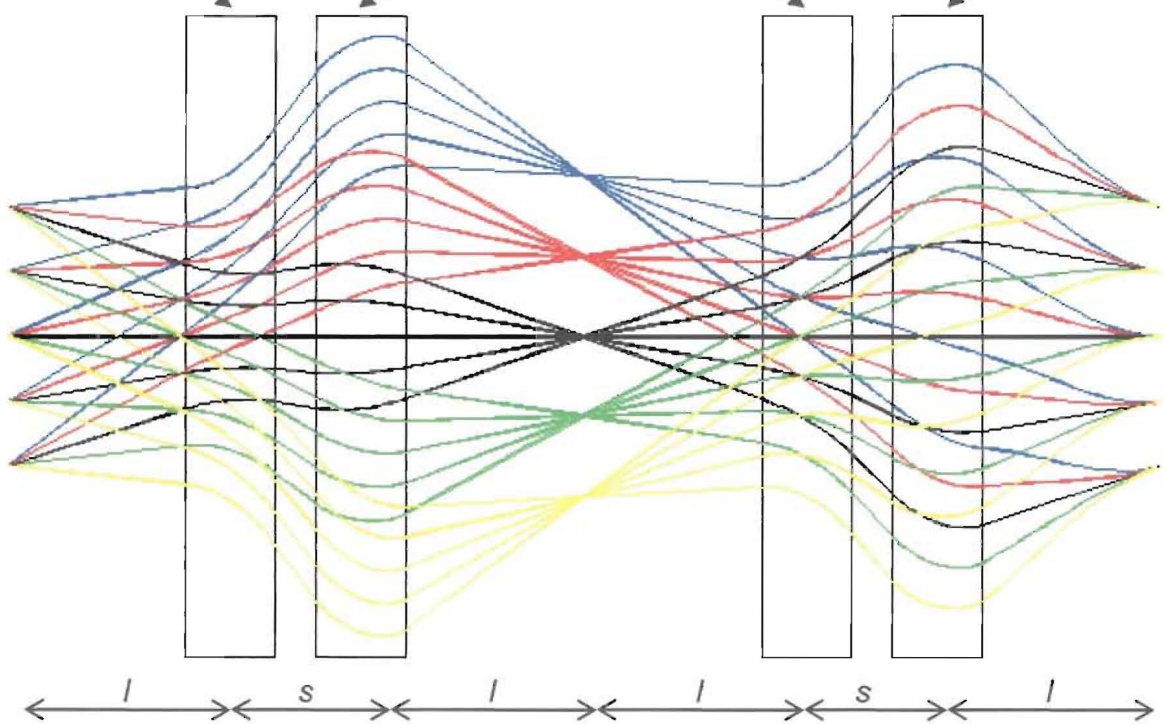


Low + High



Thin Lens Approximation

$$\begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 1/(1+\delta)f & 1 \end{pmatrix} \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -1/(1+\delta)f & 1 \end{pmatrix} \begin{pmatrix} 1 & 2l \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 1/(1+\delta)f & 1 \end{pmatrix} \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -1/(1+\delta)f & 1 \end{pmatrix} \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$$



To make an identity lens

$$f = \sqrt{ls}$$

Chromatic blur is ~proportional to lens length

$$\frac{dM_{12}}{d\delta} = T_{126} = 4(l+s)$$

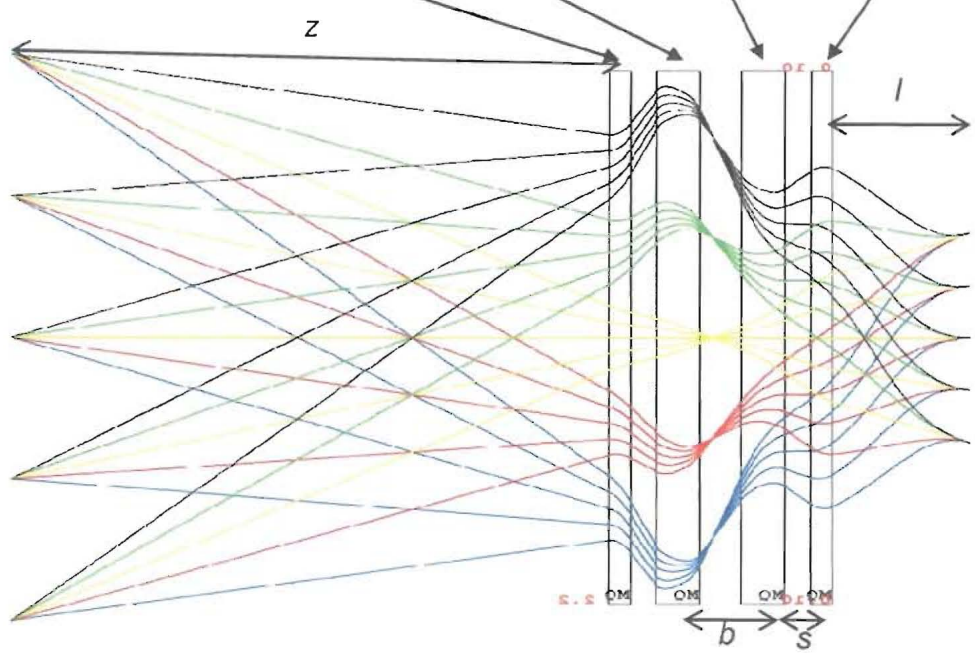
Thin Lens Approximation

$$\begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = \begin{pmatrix} 1 & z \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 1/(1+\delta)f & 1 \end{pmatrix} \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -2/(1+\delta)f & 1 \end{pmatrix} \begin{pmatrix} 1 & b \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 2/(1+\delta)f & 1 \end{pmatrix} \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -1/(1+\delta)f & 1 \end{pmatrix} \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$f = 2\sqrt{\frac{lms + (m-1)s^2}{(m+1)}}$$

$$z = lm + 2(m-1)s$$

$$b = \frac{2s\left(lm + (m-1)\right)}{m(l+2s)}$$



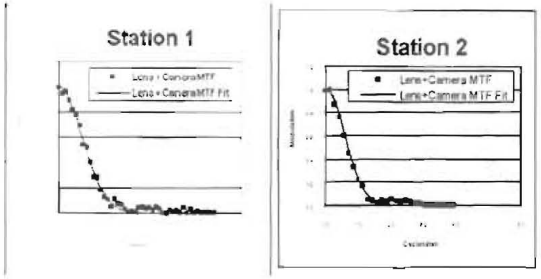
$$\frac{1}{m}\frac{dM_{12}}{d\delta} = \frac{T_{126}}{m} = \frac{m+1}{m^2\left(lm + (m-1)s\right)}\left[(2l^2m^2 + lm(5m-3)s + 2(m-1)s^2\left((2m-1) + \sqrt{(m+1)(lm+(m-1)}\right)\right]$$

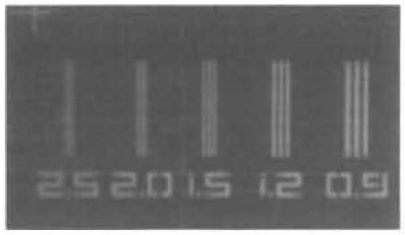
Chromatic blur is a complicated function of lens spacing

$$\frac{T_{126}}{m} \cong 2l + \frac{l}{m} \quad \text{In the limit that} \quad \frac{s}{l} \ll 1$$

Chromatic Aberration and Resolution

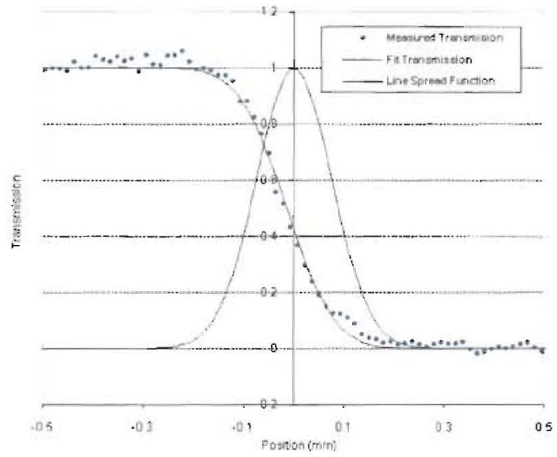
Identity Lens



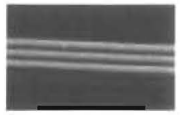


- 12 inch lens
- Station 1: 178 μm
- Station 2: 280 μm
- Gaussian blur function.
- 120 mm field of view

X3 Magnifier

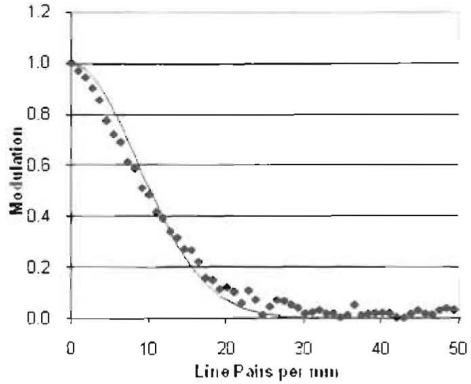


2.5 lp/mm



- 4 inch lens
- Station 1: 65 μm
- Gaussian blur function.
- 44 mm field of view

X7 Lens



- 1 inch lens
- Station 1: 30 μm
- Gaussian blur function.
- 17 mm field of view

Solid-Solid Phase Transition in Iron

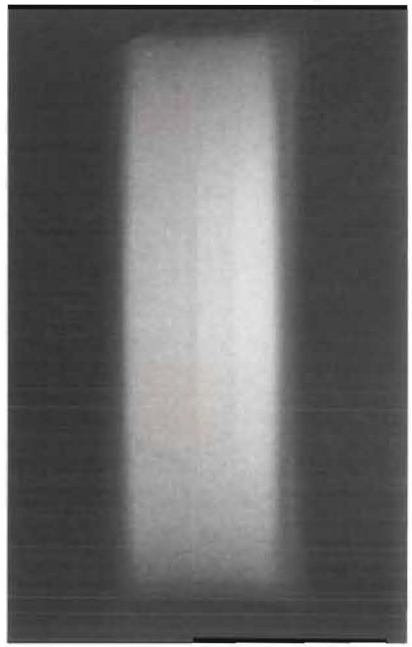
(X3 Magnifier)

Improvement in resolution can be seen from this comparison of radiographs from the identity lens to an equivalent thickness of iron

Identity Lens $\frac{\Delta P}{P} = 8.7\%$

copper

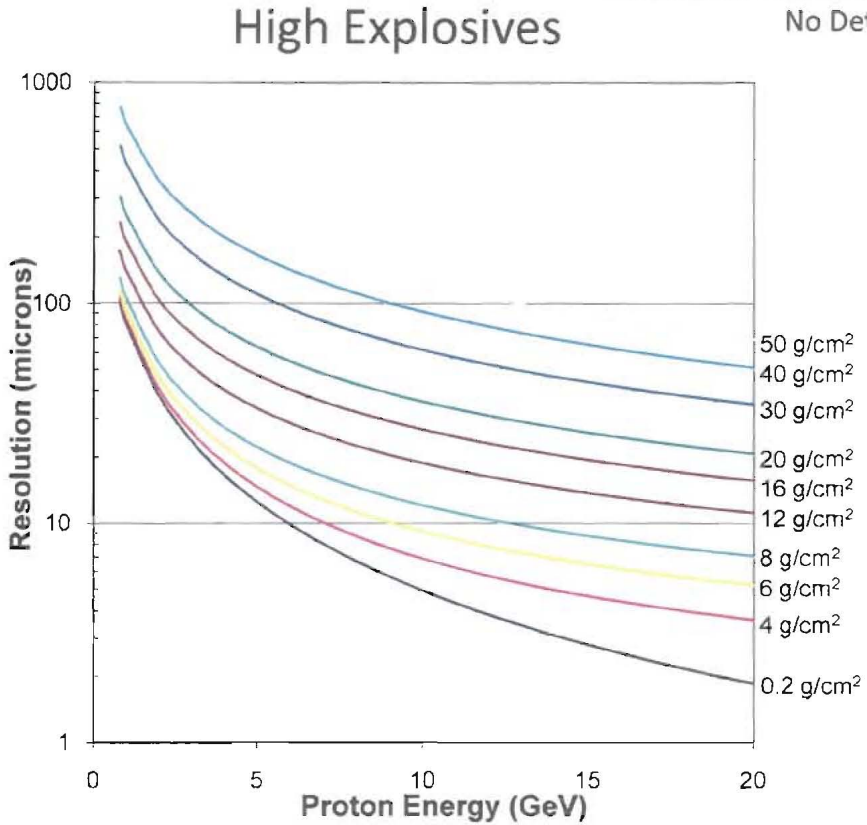
X3 Magnifying Lens $\frac{\Delta P}{P} = 8.1\%$

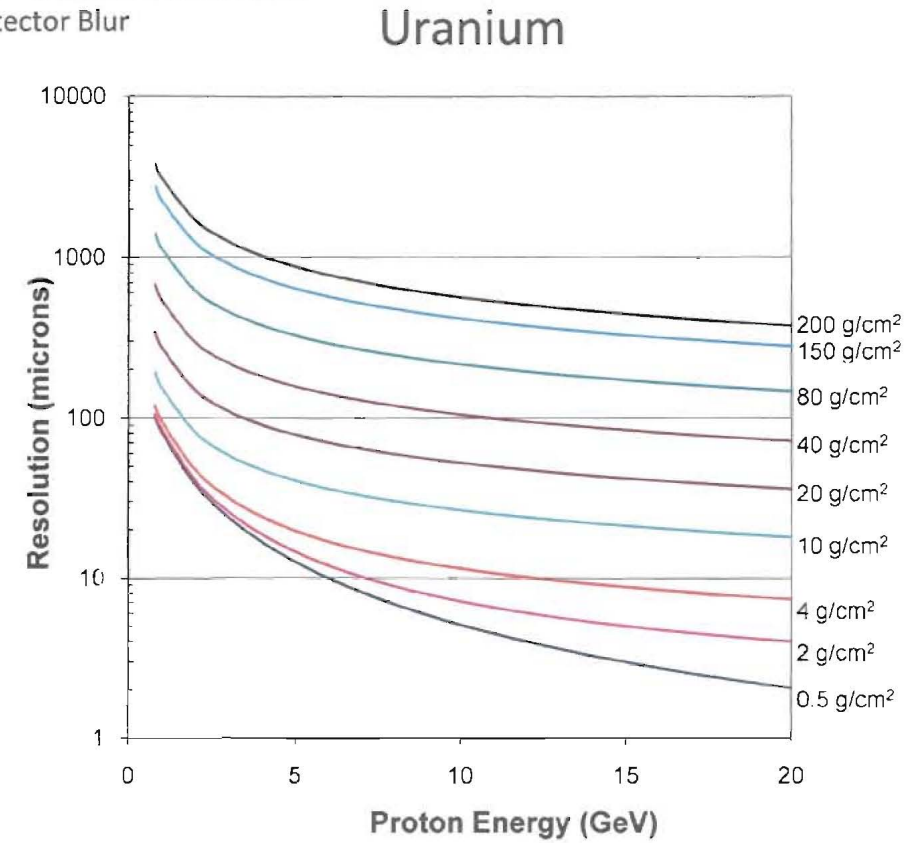


Iron

Results of Scaling 800 MeV Resolution

Resolution: RMS of a ~Gaussian distribution
No Detector Blur

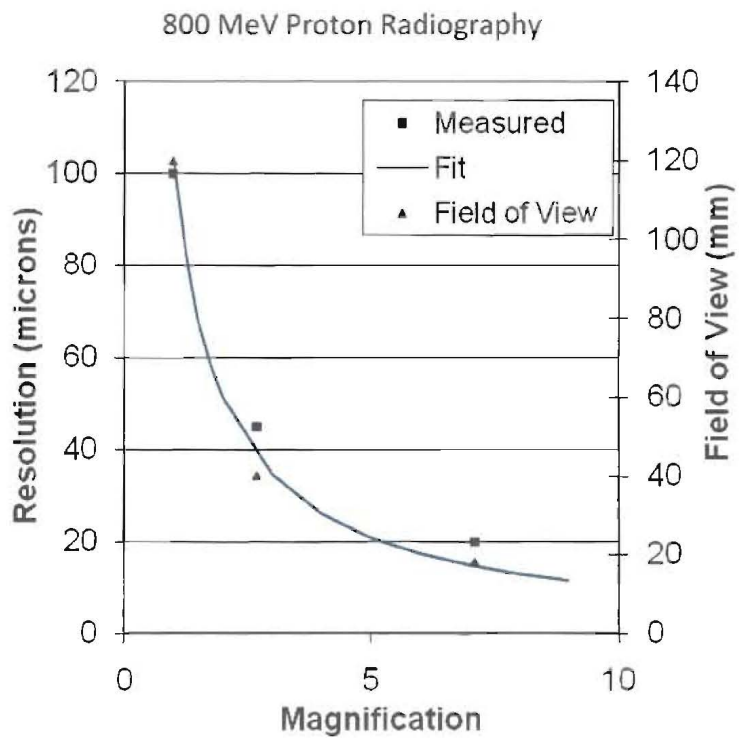


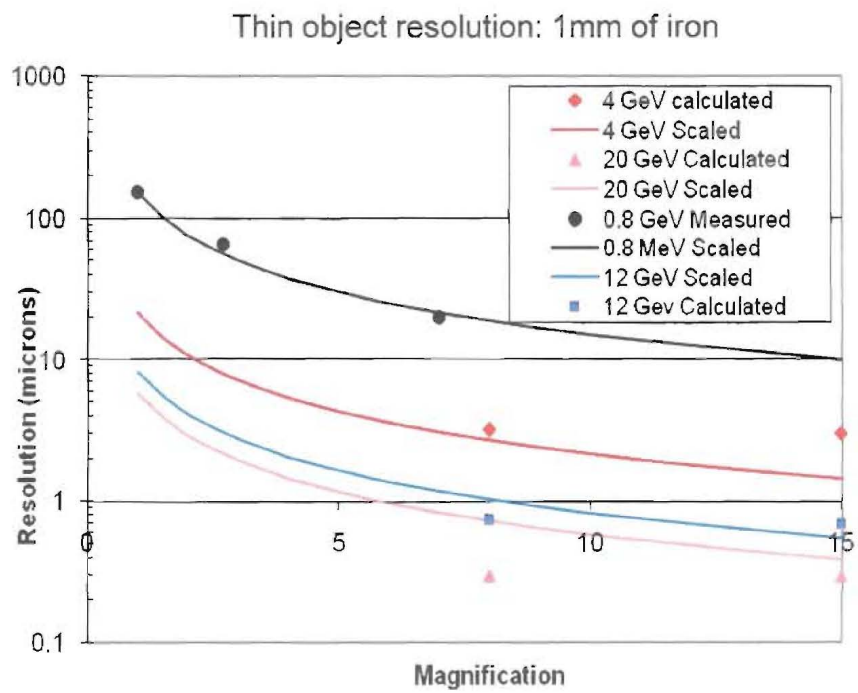


4 GeV Protons
25-350 micron resolution in HE
25-1000 micron resolution in Uranium

20 GeV Protons
2-100 micron resolution in HE
2-350 micron resolution in Uranium

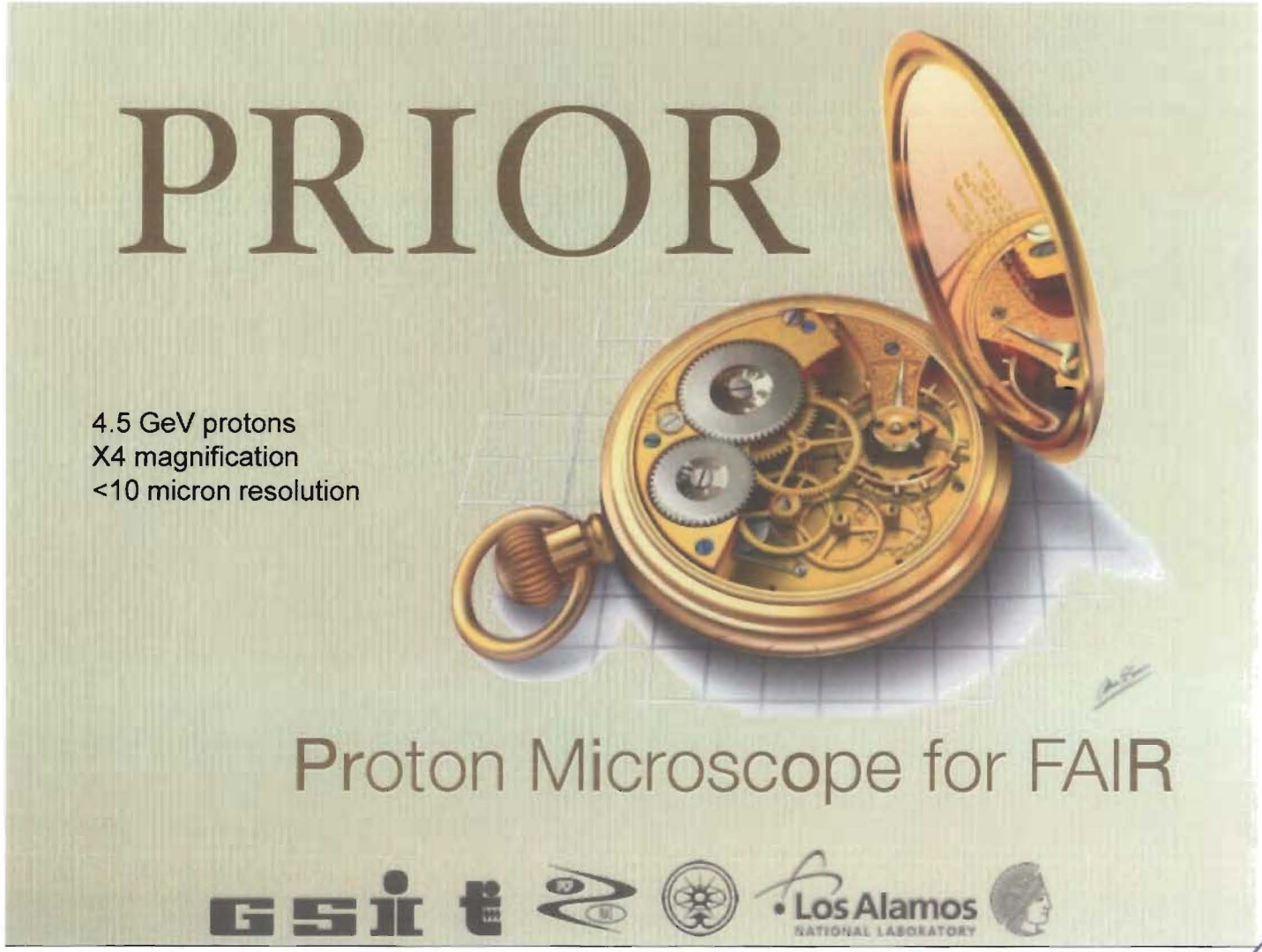
Combine Higher Energy with Magnification



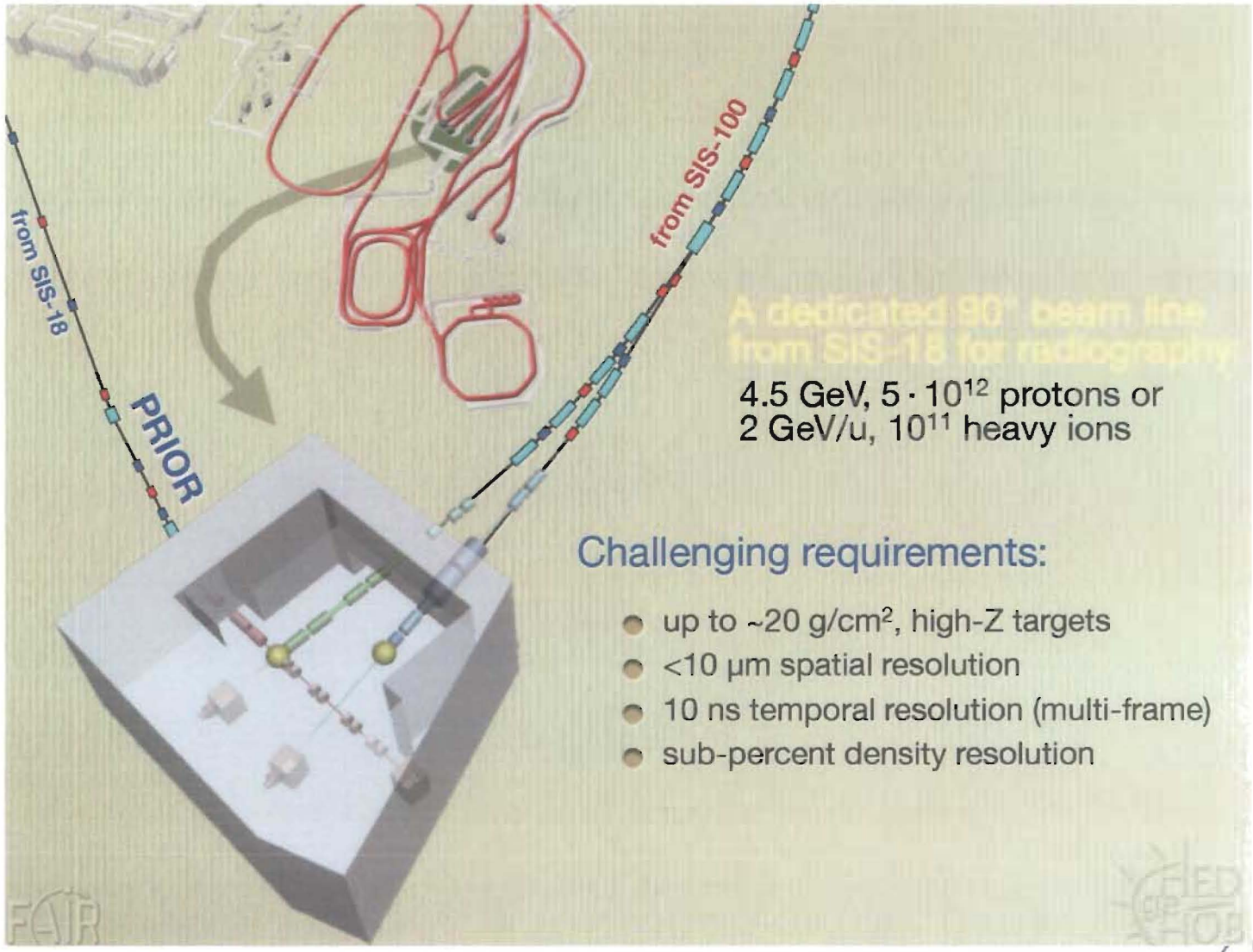


Magnification at high energy could result in high resolution (<1 micron?) with a 20 mm field of view

PRIOR Collaboration

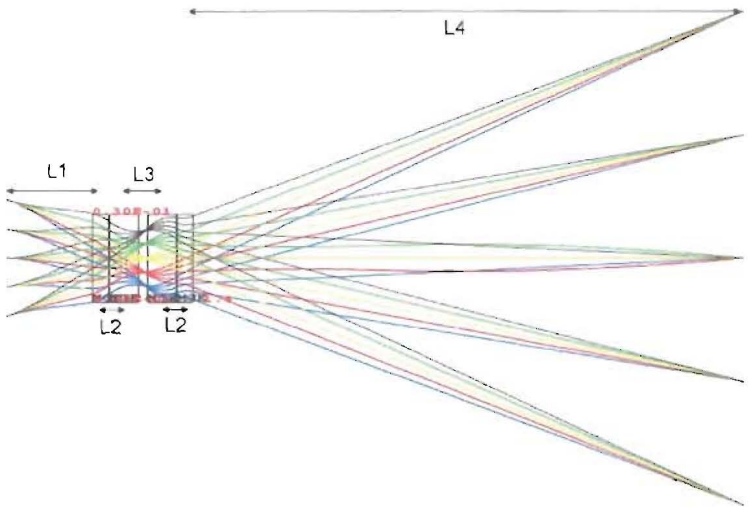


Ion Driven WDM Studies at FAIR



Intermediate Step

Design, build and commission a magnifier for 4.5 GeV proton radiography to use SIS-18 beam at GSI. Study dynamic systems driven by explosives or pulsed power. This allows opportunity for dynamic materials science experiments that can use the higher resolution of the 4.5 GeV beam as well as commissioning the magnifier system for installation at FAIR

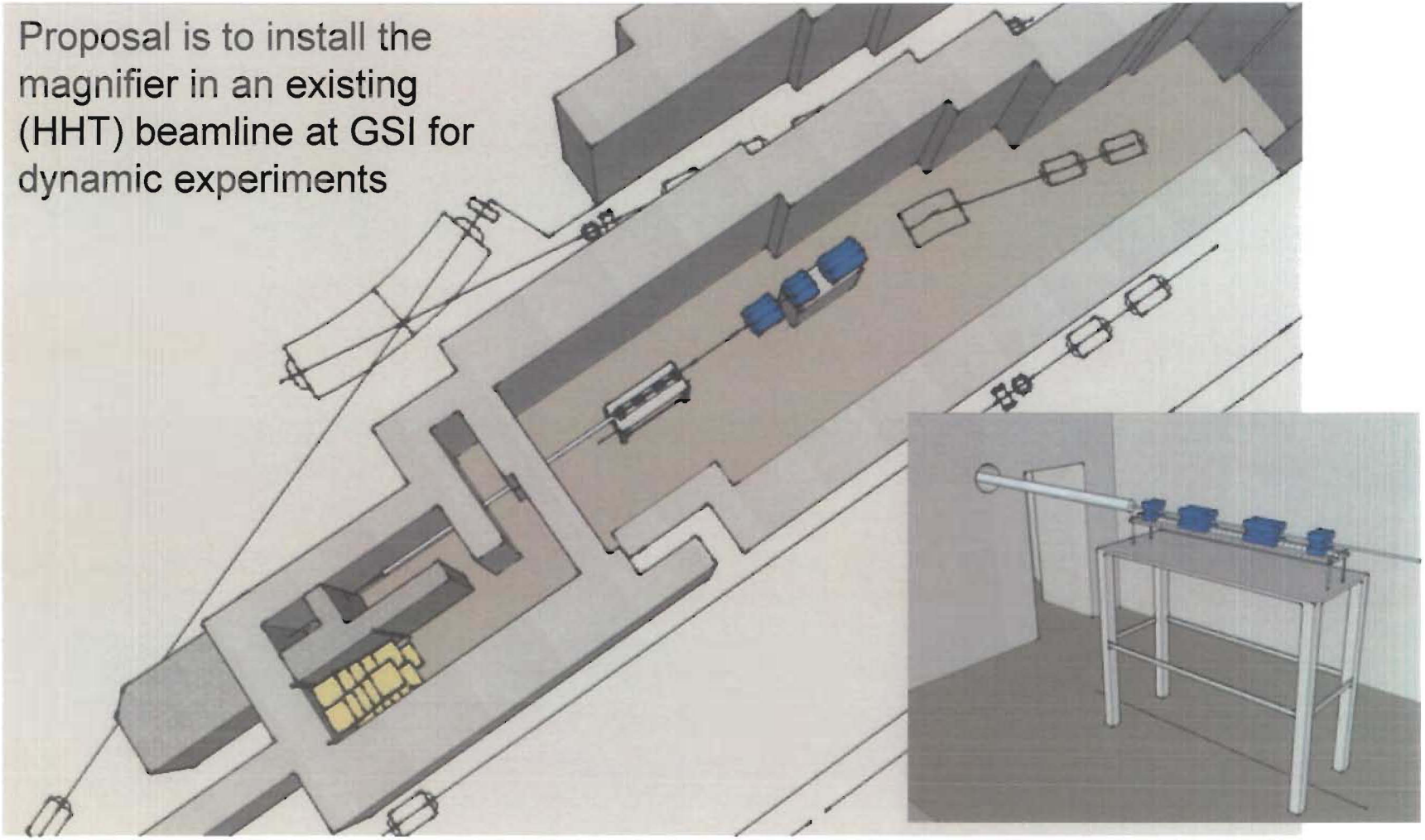


Proton trajectories through the baseline PRIOR lens design.

Parameter	Value
Beam energy	4.5 GeV/c^2
Inner aperture D_i	30 mm
Out aperture D_o	100 m
B_p "pole tip" field	1.1 T
Gradient	115 T/m
"short" quad length	165 mm
"Long" quad length	330 mm
L_1 (object to first quad)	1.3 m
L_2 (first to second)	0.307 m
L3 (second to third)	0.515 m
L4 (last quad to image)	7.576 m
Total length	10.000 m

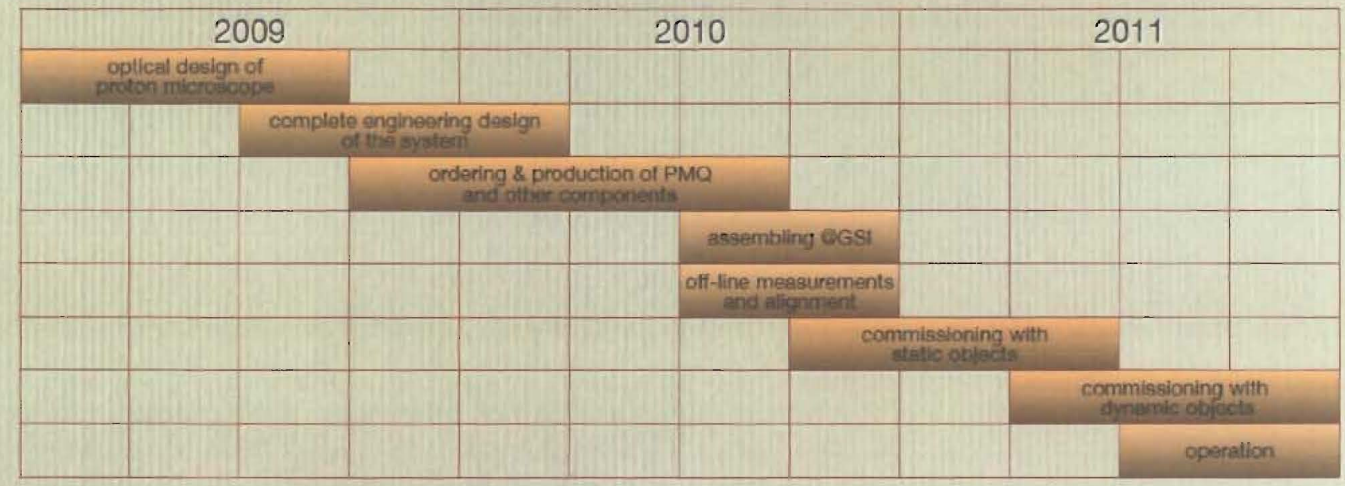
Parameter	Value
Magnification	4.1
C_x horizontal Chromatic length	3.99 m
C_y vertical chromatic length	3.41 m
Angular Acceptance	5 mrad
M_x Horizontal Matching Correlation	-0.45 mrad/mm
M_y Horizontal Matching Correlation	-0.55 mrad/mm

Proposed Magnifier Installation at GSI



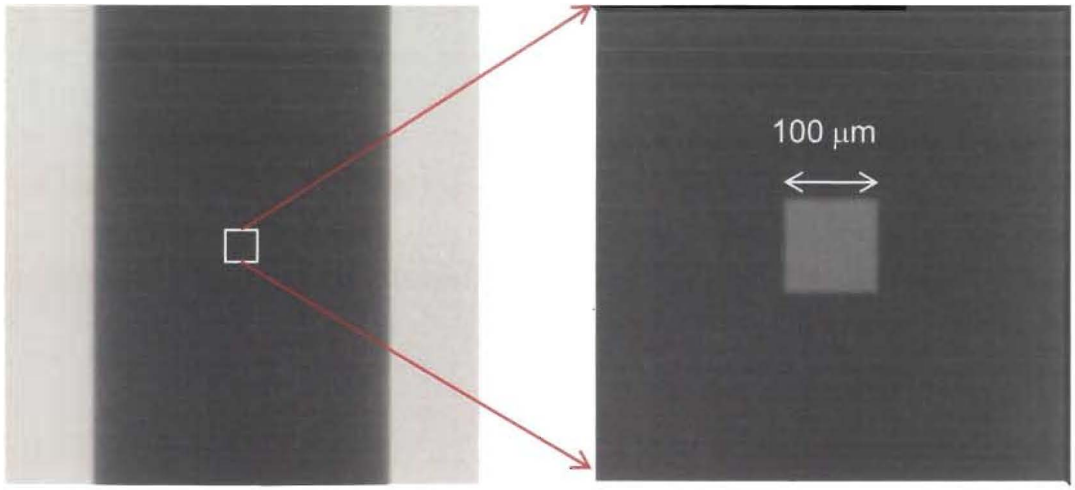
Potential Schedule for Implementation at GSI

Time schedule and milestones

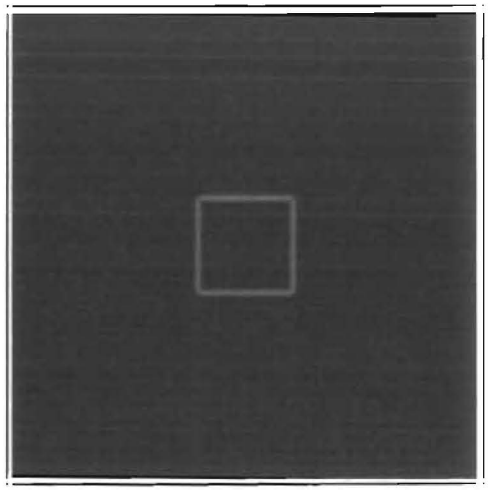


- approval of the project by GSI management Q2 2009
- international scientific workshop at GSI Q3 2009
- ordering production of main components Q4 2009
- submitting first beam time applications Q2 2010
- assembling and off-line measurements Q4 2010
- commissioning with static objects Q1 2011
- commissioning with dynamic objects Q2 2011

Forward Model Simulations of the PRIOR Magnifier

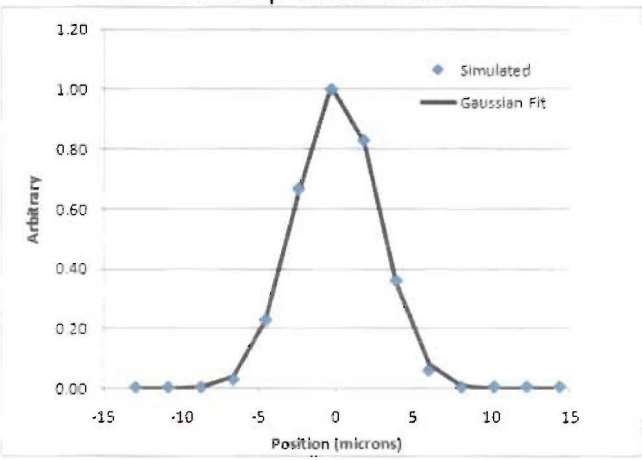


0.5 mm Cylinder of Copper



Derivative of the transmission

Line Spread Function

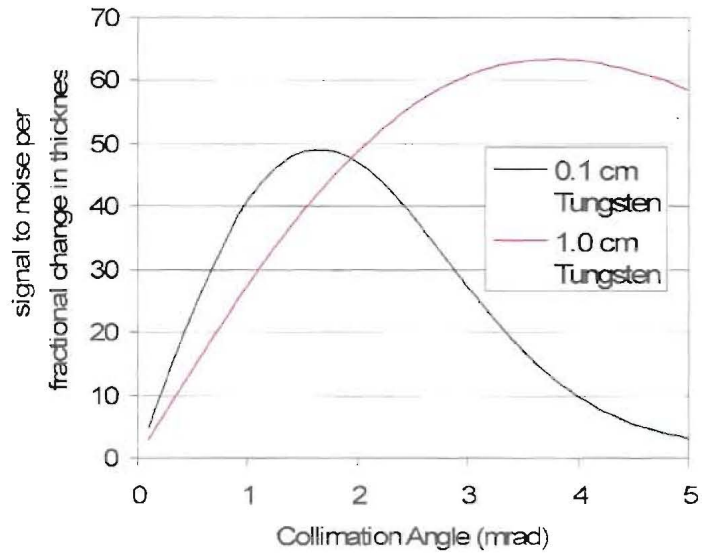


Gaussian Line Spread Function
3 μm RMS resolution

Prediction with no noise

Areal Density Sensitivity

$$FOM = \frac{\Delta N / \sqrt{N}}{\Delta l / l} = \frac{l}{\sqrt{N}} \frac{dN}{dl}$$



Goal:

- 1% density resolution in 10 μm pixel size

Challenges:

- Peak proton current delivered by the SIS-18
- Detector system with high quantum efficiency

Conclusions

- Los Alamos is using proton radiography for dynamic materials science.
- Multi-pulse proton radiography has turned into a useful radiographic probe for dynamic as well as static measurements.
- The next gain in capability will come from combining multi-GeV protons with magnifying lens systems
    - GSI will demonstrate this new capability