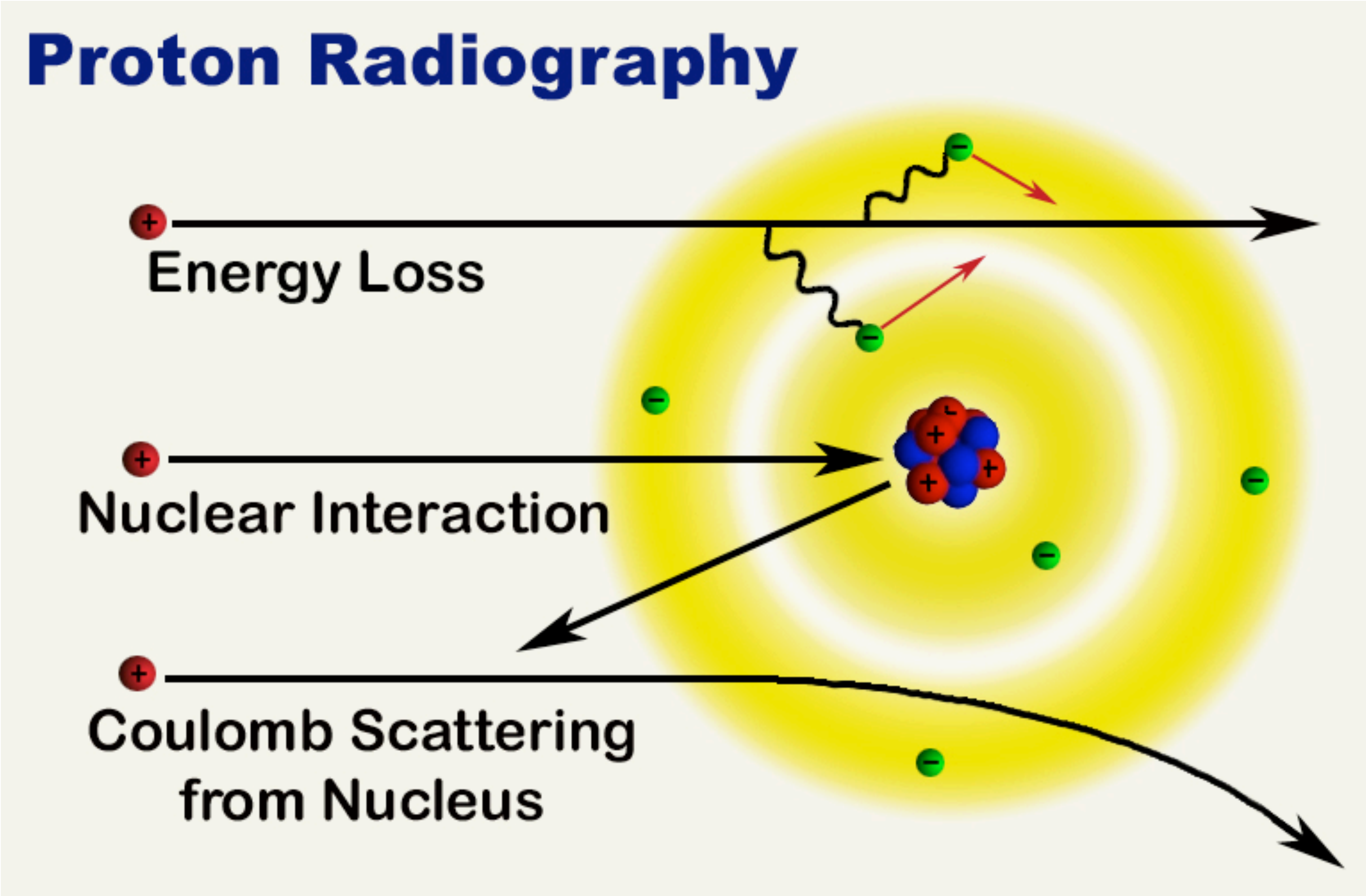
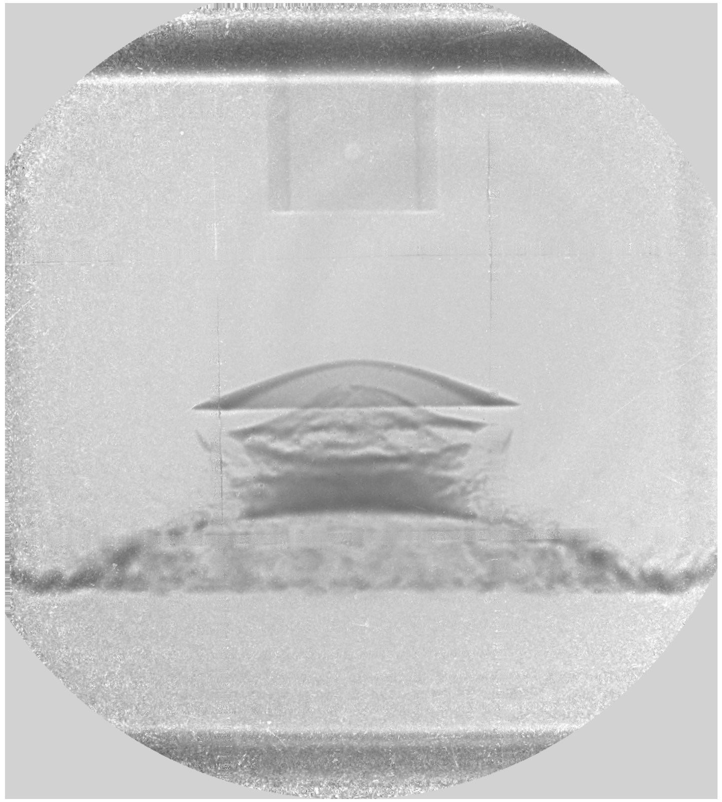
Proton radiography principles



Proton Radiography Primer

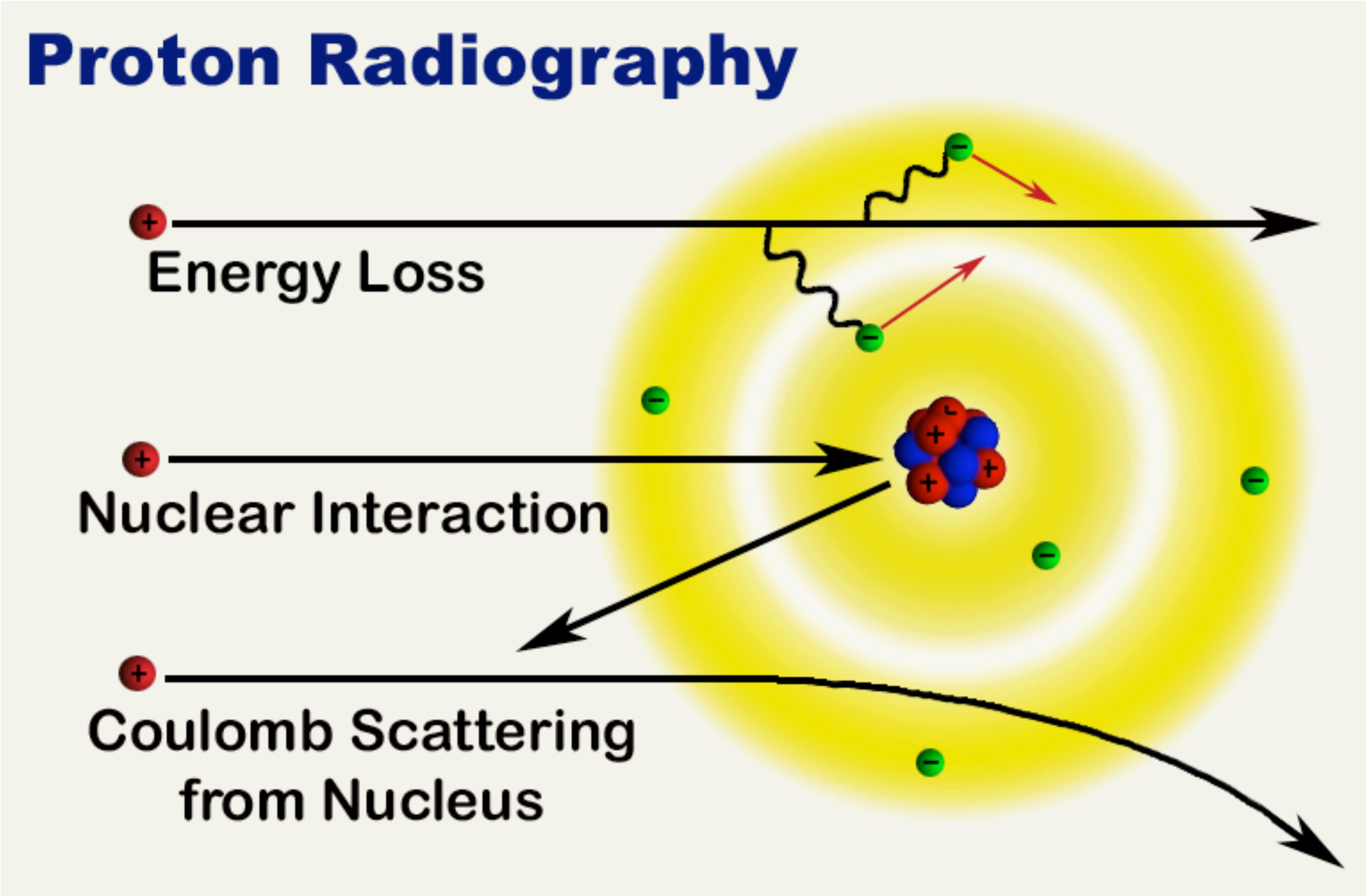


Frank Merrill, LANL

and the pRad collaboration

LA-UR 08-07298

Proton radiography principles



Early Proton Radiography

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

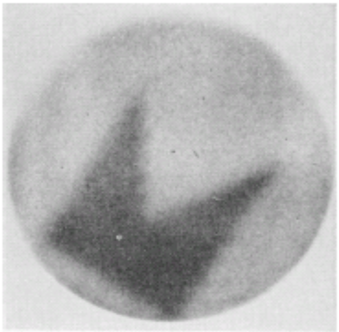


Fig. 1. Proton radiograph of aluminum absorber 7 cm in diameter and 18 g/cm² thick, with an additional thickness of 0.035-g/cm² aluminum foil, cut in the shape of a pennant, inserted at a depth of 9 g/cm². The addition of 0.2 percent to the total thickness produces a substantially darker area on the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

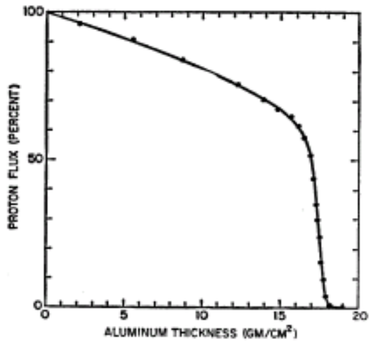


Fig. 2. Proton flux as a function of depth in aluminum. The steeply falling portion of the curve near 18 g/cm² is used to obtain the high contrast of Fig. 1.

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

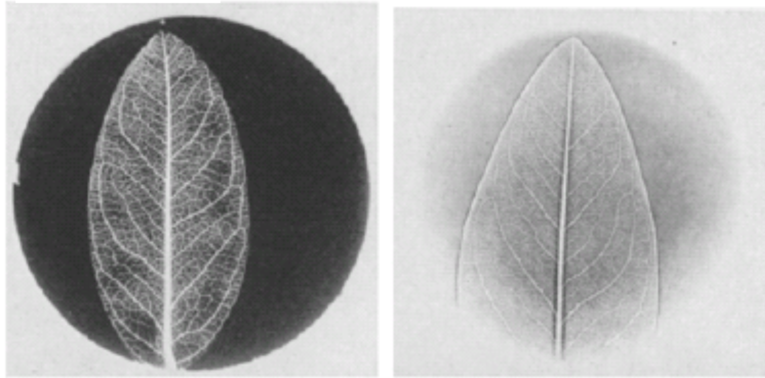


Fig. 6a and b. Radiographs of leaves by a) marginal range radiography with 196 mg/cm² of extra Al absorber, and b) scattering radiography with leaf sandwiched between two 6.9 mg/cm² Al layers and 14 mm from the film

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.

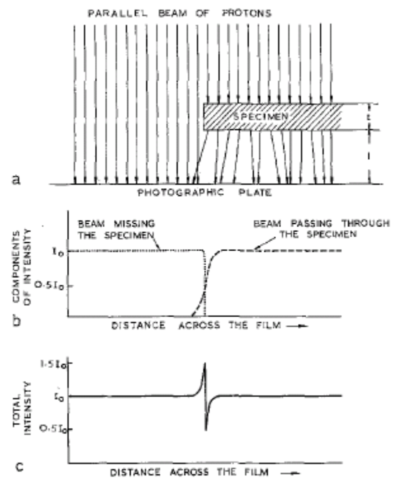


Fig. 7. Illustration of how multiple scattering produces its characteristic edge pattern

Scattering Radiography

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

LANL Transmission Radiography (1995)

188 MeV secondary proton beamline at LANSCE

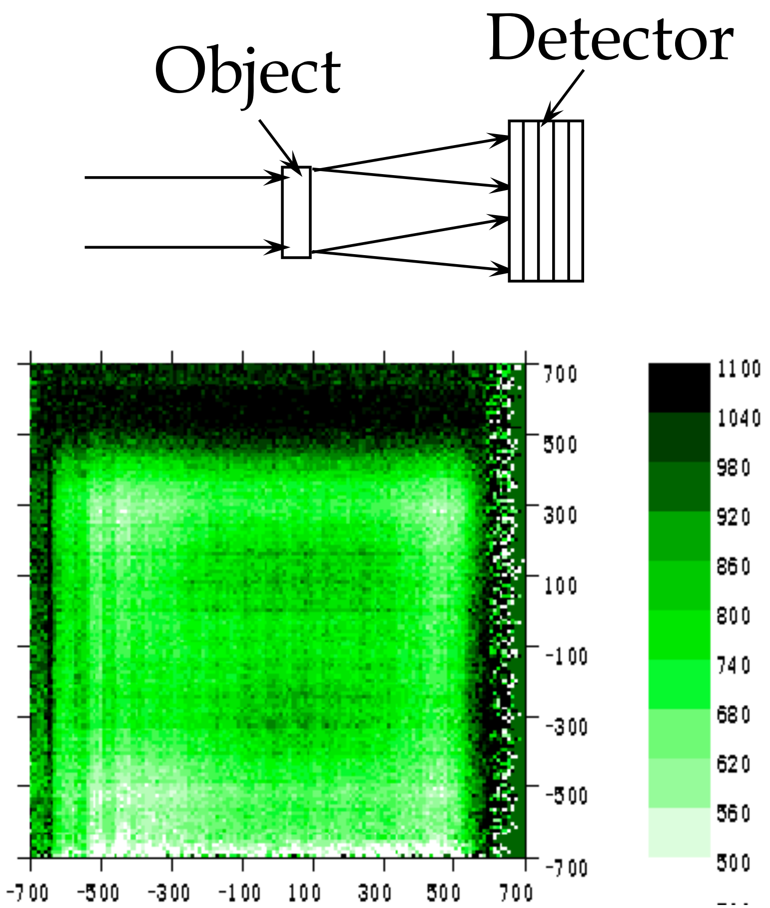
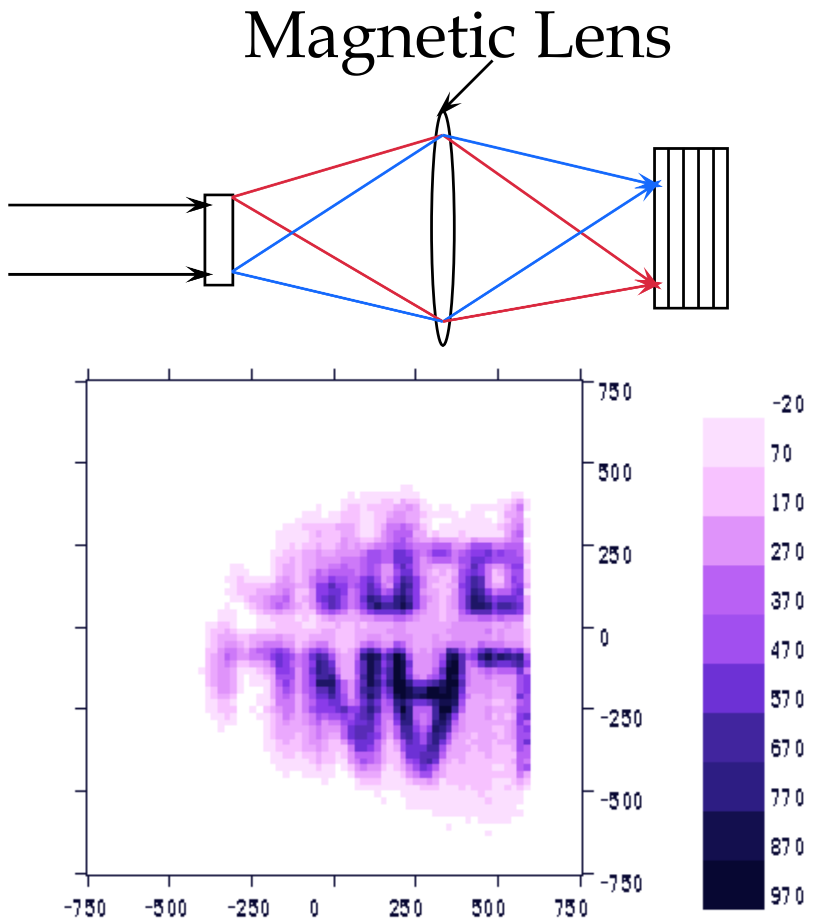
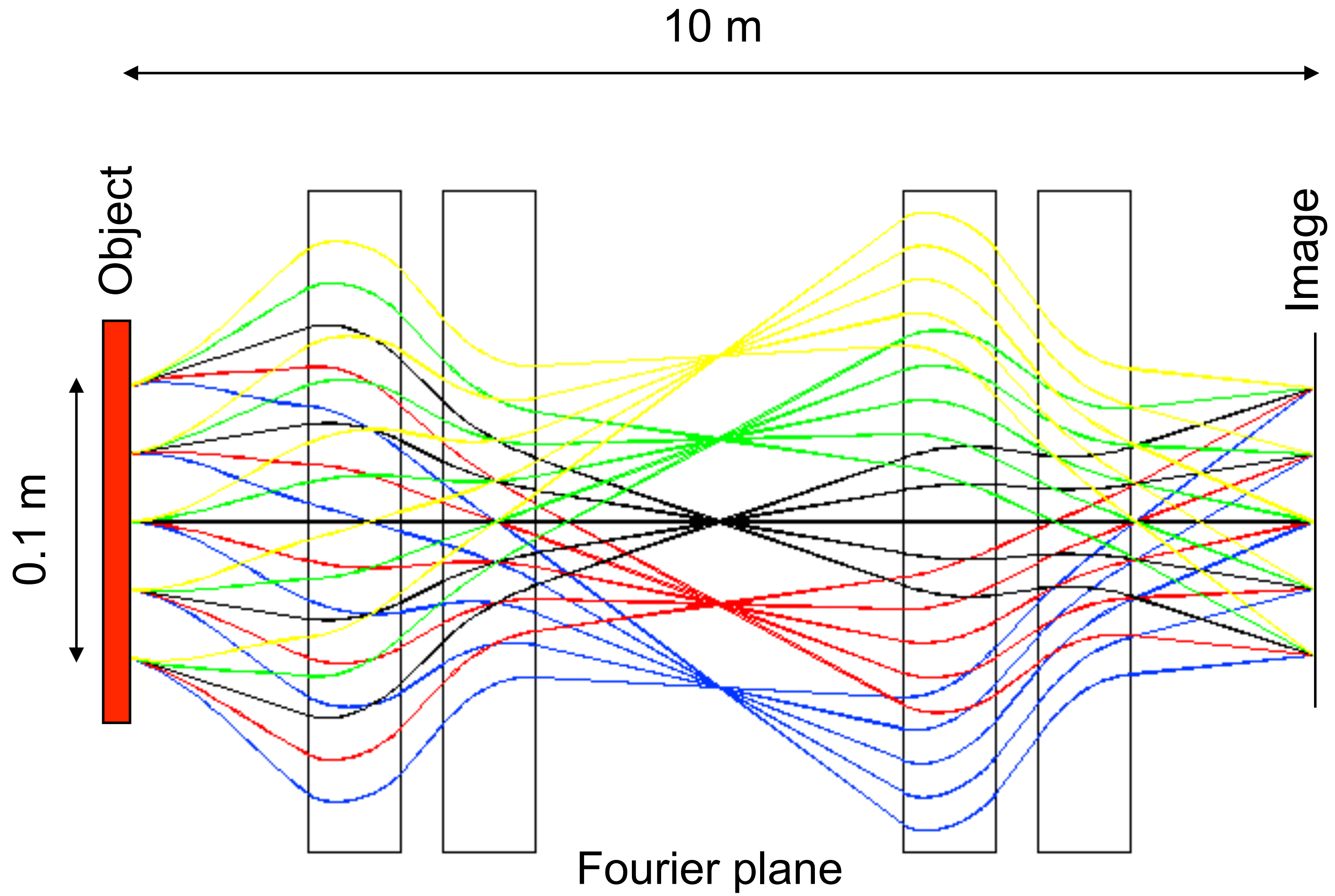


Image at the detector is substantially blurred.



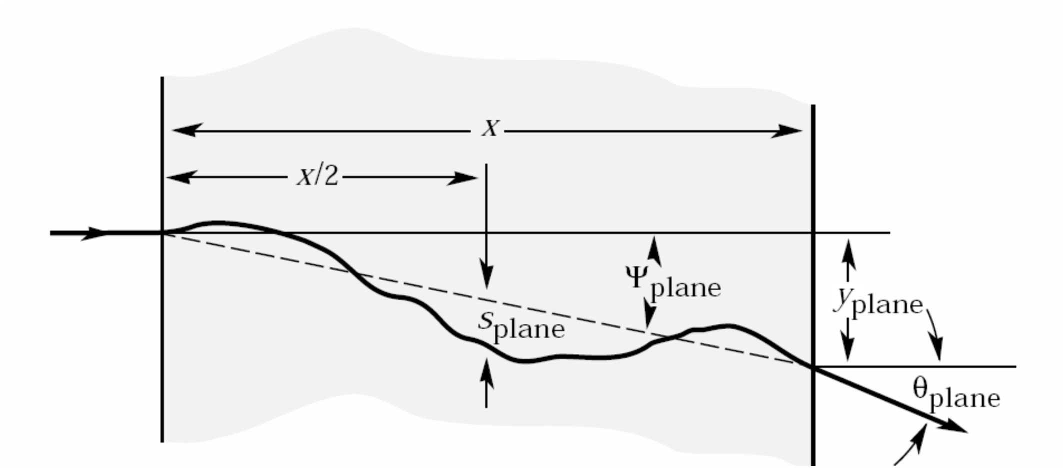
Magnetic imaging lens preserves image with high resolution.

Magnetic Imaging Lens



Quadrupole Identity Lens

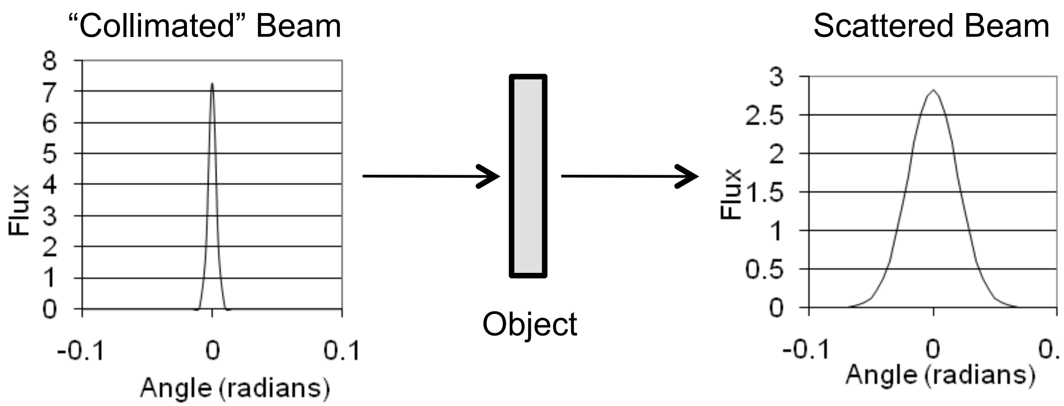
Multiple Coulomb Scattering



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

RMS Width

Full Width Half Maximum=2.35 θ_o

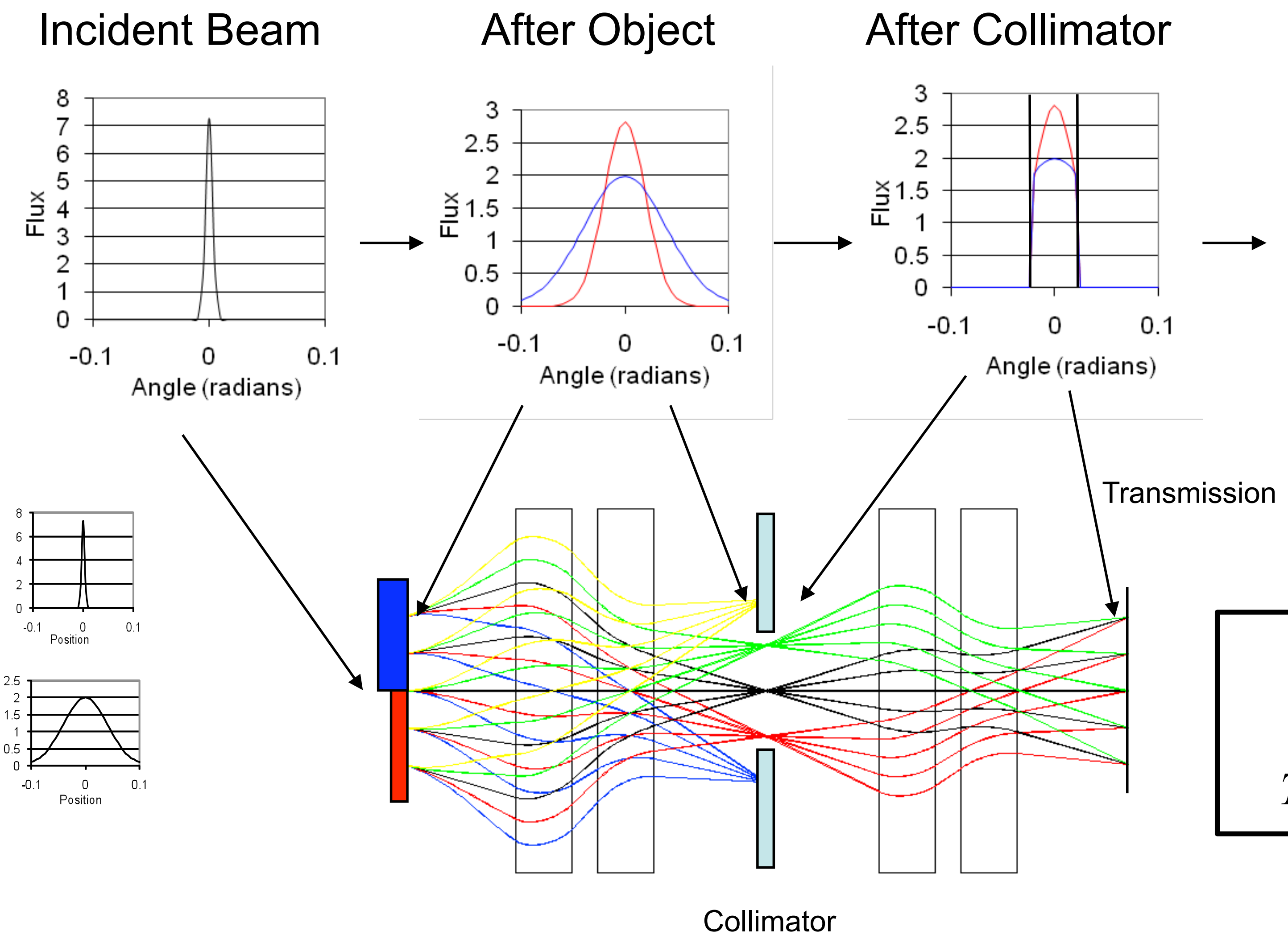


$$\theta_o = \frac{14.1\,MeV}{\beta p}\sqrt{x/X_o}$$

Typical LANL simplification

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

Contrast from Multiple Coulomb Scattering



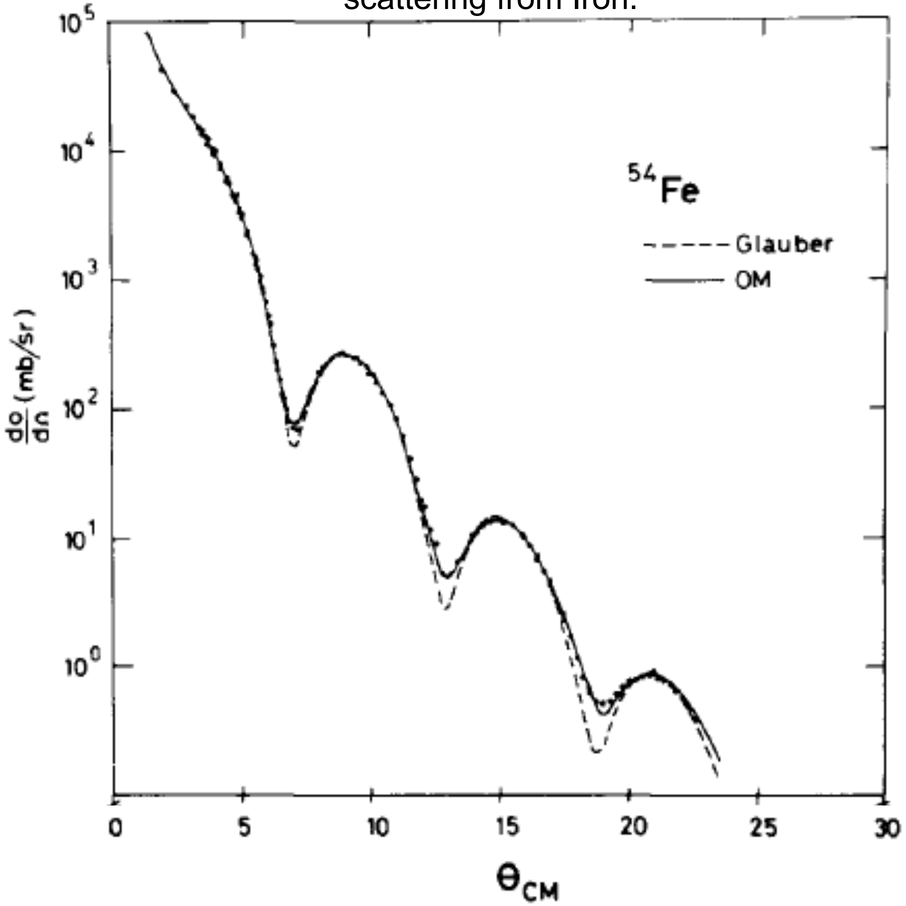
Measured transmission provides information of object thickness

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.



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

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

Transmission Calculation

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

Nuclear removal processes:

λ_c - nuclear collision length:

x - areal density

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

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

Multiple Coulomb Scattering with collimation:

θ_0 - scattering angle (radians)

x - areal density

x_o - radiation length

p - momentum (MeV)

β - relativistic velocity

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

Total EstimatedTransmission:

Good to 5-10%

Particle Data Group:
http://pdg.lbl.gov/

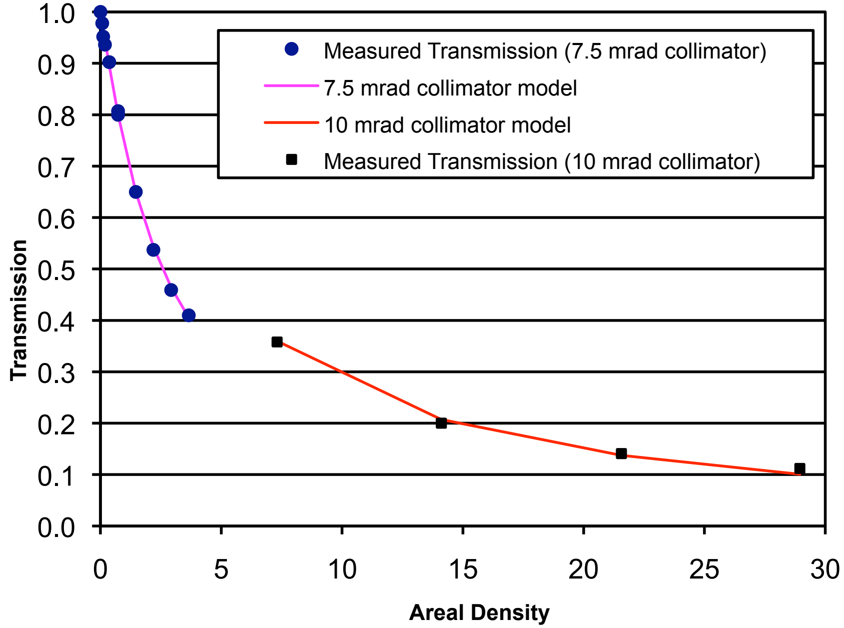
A Useful Table

6. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

Table 6.1 Abridged from `pdg.lbl.gov/AtomicNuclearProperties` by D. E. Groom (2007). See web pages for more detail about entries in this table including chemical formulae, and for several hundred other entries. Quantities in parentheses are for NTP (20° C and 1 atm), and square brackets indicate quantities evaluated at STP. Boiling points are at 1 atm. Refractive indices n are evaluated at the sodium D line blend (589.2 nm); values $\gg$1 in brackets are for $(n-1)\times 10^6$ (gases).

Material	Z	A	$\langle Z/A\rangle$	Nucl.coll. length λ_T {g cm^{-2}}	Nucl.inter. length λ_I {g cm^{-2}}	Rad.len. X_0 {g cm^{-2}}	$dE/dx\|_{min}$ { MeV g^{-1}cm^2}	Density {g cm^{-3}} ({gℓ^{-1}})	Melting point (K)	Boiling point (K)	Refract. index (@ Na D)
H_2	1	1.00794(7)	0.99212	42.8	52.0	63.04	(4.103)	0.071(0.084)	13.81	20.28	1.11[132.]
D_2	1	2.01410177803(8)	0.49650	51.3	71.8	125.97	(2.053)	0.169(0.168)	18.7	23.65	1.11[138.]
He	2	4.002602(2)	0.49967	51.8	71.0	94.32	(1.937)	0.125(0.166)		4.220	1.02[35.0]
Li	3	6.941(2)	0.43221	52.2	71.3	82.78	1.639	0.534	453.6	1615.	
Be	4	9.012182(3)	0.44384	55.3	77.8	65.19	1.595	1.848	1560.	2744.	
C diamond	6	12.0107(8)	0.49955	59.2	85.8	42.70	1.725	3.520			2.42
C graphite	6	12.0107(8)	0.49955	59.2	85.8	42.70	1.742	2.210			
N_2	7	14.0067(2)	0.49976	61.1	89.7	37.99	(1.825)	0.807(1.165)	63.15	77.29	1.20[298.]
O_2	8	15.9994(3)	0.50002	61.3	90.2	34.24	(1.801)	1.141(1.332)	54.36	90.20	1.22[271.]
F_2	9	18.9984032(5)	0.47372	65.0	97.4	32.93	(1.676)	1.507(1.580)	53.53	85.03	[195.]
Ne	10	20.1797(6)	0.49555	65.7	99.0	28.93	(1.724)	1.204(0.839)	24.56	27.07	1.09[67.1]
Al	13	26.9815386(8)	0.48181	69.7	107.2	24.01	1.615	2.699	933.5	2792.	
Si	14	28.0855(3)	0.49848	70.2	108.4	21.82	1.664	2.329	1687.	3538.	3.95
Cl_2	17	35.453(2)	0.47951	73.8	115.7	19.28	(1.630)	1.574(2.980)	171.6	239.1	[773.]
Ar	18	39.948(1)	0.45059	75.7	119.7	19.55	(1.519)	1.396(1.662)	83.81	87.26	1.23[281.]
Ti	22	47.867(1)	0.45961	78.8	126.2	16.16	1.477	4.540	1941.	3560.	
Fe	26	55.845(2)	0.46557	81.7	132.1	13.84	1.451	7.874	1811.	3134.	
Cu	29	63.546(3)	0.45636	84.2	137.3	12.86	1.403	8.960	1358.	2835.	
Ge	32	72.64(1)	0.44053	86.9	143.0	12.25	1.370	5.323	1211.	3106.	
Sn	50	118.710(7)	0.42119	98.2	166.7	8.82	1.263	7.310	505.1	2875.	
Xe	54	131.293(6)	0.41129	100.8	172.1	8.48	(1.255)	2.953(5.483)	161.4	165.1	1.39[701.]
W	74	183.84(1)	0.40252	110.4	191.9	6.76	1.145	19.300	3695.	5828.	
Pt	78	195.084(9)	0.39983	112.2	195.7	6.54	1.128	21.450	2042.	4098.	
Au	79	196.966569(4)	0.40108	112.5	196.3	6.46	1.134	19.320	1337.	3129.	
Pb	82	207.2(1)	0.39575	114.1	199.6	6.37	1.122	11.350	600.6	2022.	
U	92	[238.02891(3)]	0.38651	118.6	209.0	6.00	1.081	18.950	1408.	4404.	

Accurate Areal Density Reconstructions



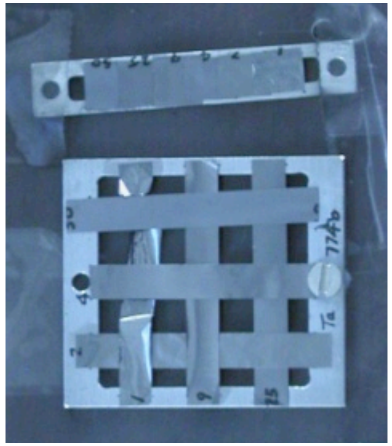
$$T = e^{-\left(x/\lambda_c + \left(\frac{\theta_c p \beta}{14.1\,MeV} \right)^2 \frac{x_o}{2(x + x_f)} \right)}$$

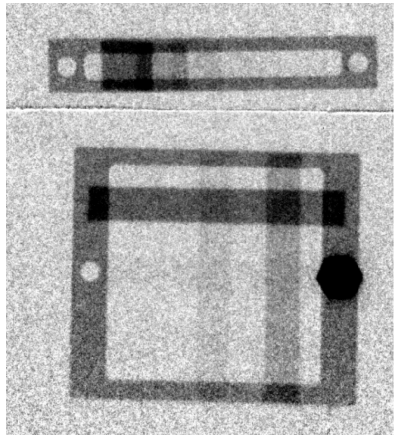
Adjust parameters to fit transmission data:

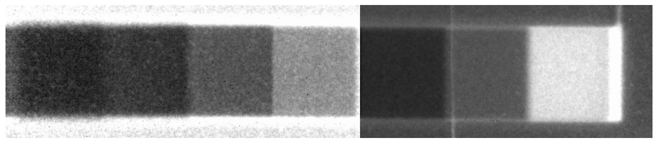
•λ_c - nuclear collision length

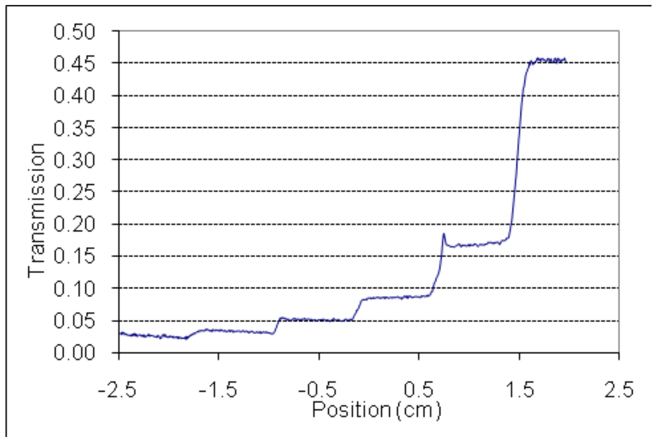
•X_f – fixed radiation length (windows, beam angular spread)

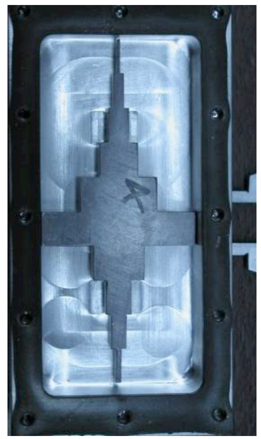
Build a step wedge and adjust parameters to fit measured data



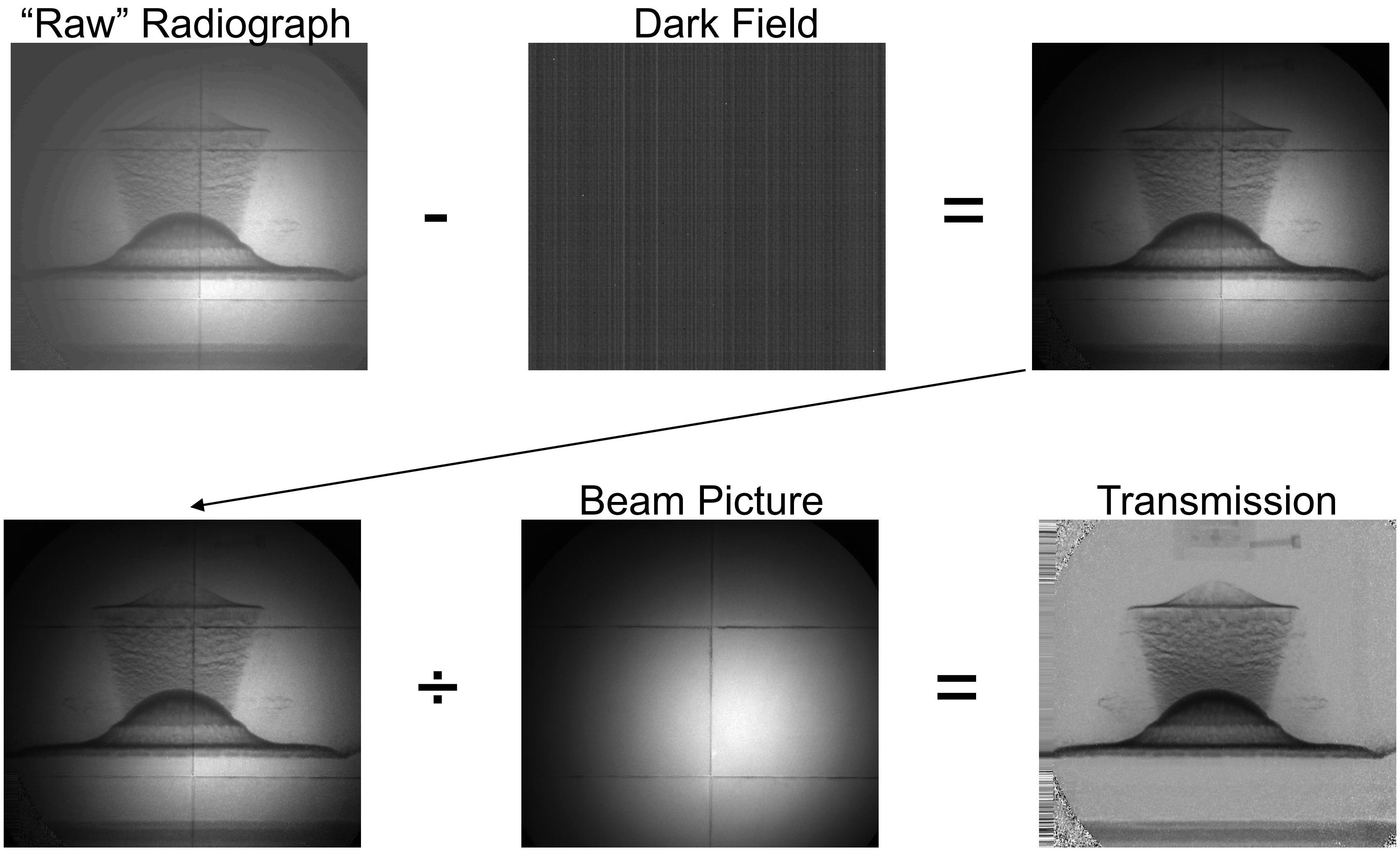








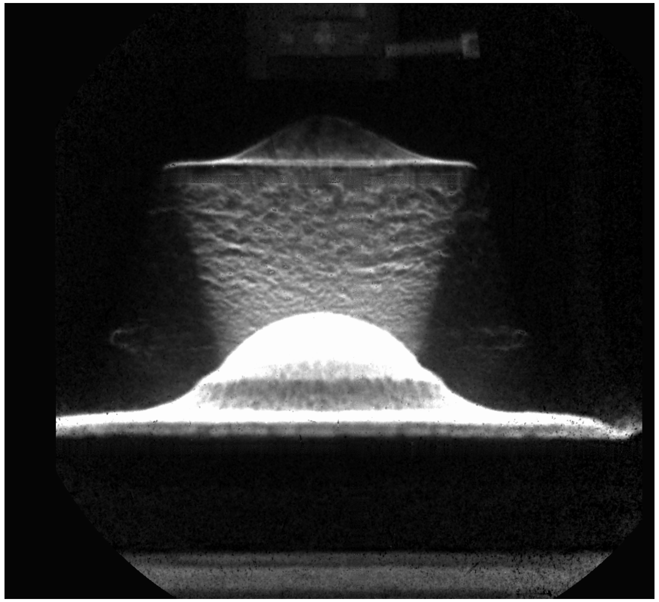
Radiographic Analysis



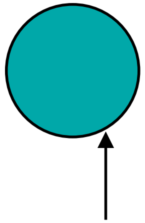
Density Reconstruction

Invert to calculate Areal Density

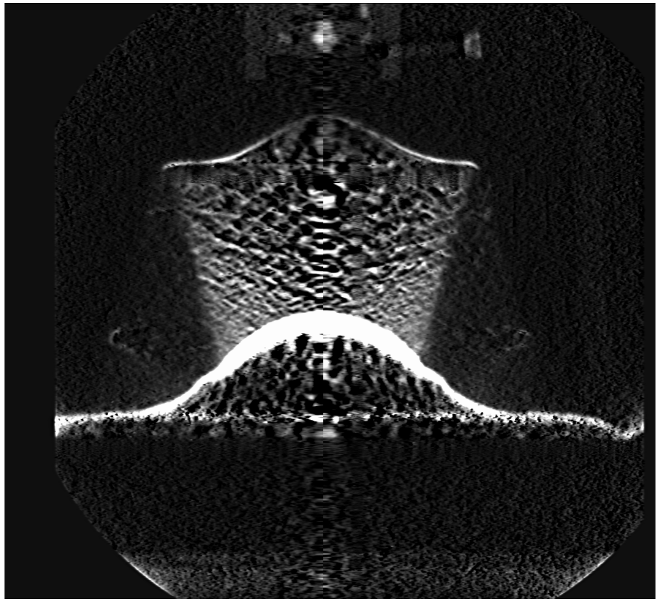
$$T = e^{-x/\lambda}\left(1 - e^{-\left(\frac{\theta_c p\beta}{14.1\,MeV}\right)^2 \frac{x_o}{2x}}\right)$$



Areal Density (g/cm^2)



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



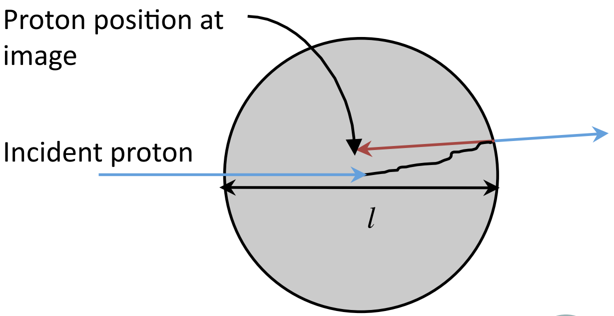
Volume Density (g/cm^3)

Resolution 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.
3. **Detector blur**- introduced as the proton interacts with the proton-to-light converter and as the light is gated and collected with a camera system.

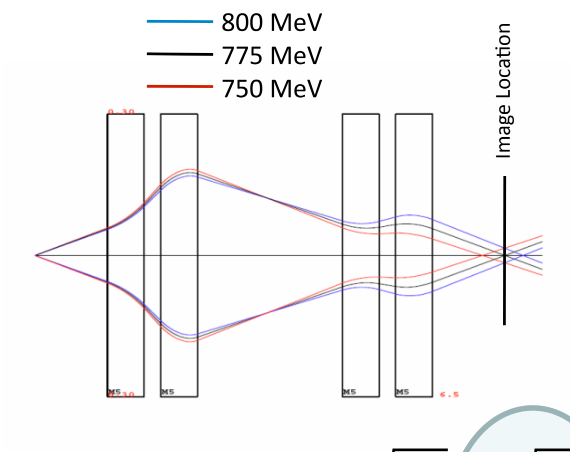
Assume detector development can keep up

Object Scattering



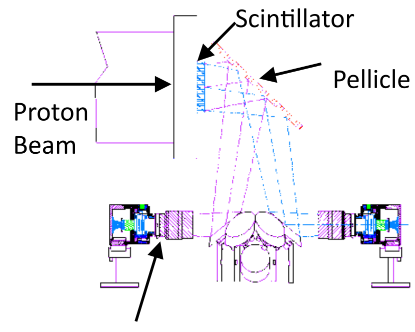
$$\sigma_o = \frac{1}{\sqrt{3}}\theta\frac{l}{2} = \frac{14.1}{\sqrt{6}}\frac{1}{P\beta}\sqrt{\frac{l^3}{x_o}} \propto \frac{l^{3/2}}{P}$$

Chromatic Aberrations



$$\sigma_c = l_c\theta\frac{\delta P}{P^2}\frac{14.1}{\beta}\sqrt{\frac{l}{x_o}} \propto \sqrt{\frac{l}{P^3}}$$

Detector Blur



Scintillator

$$\sigma_s = \theta l_s \propto \frac{l_s\sqrt{l}}{P}$$

Camera

Resolution is independent of proton energy

NNSA — Los Alamos

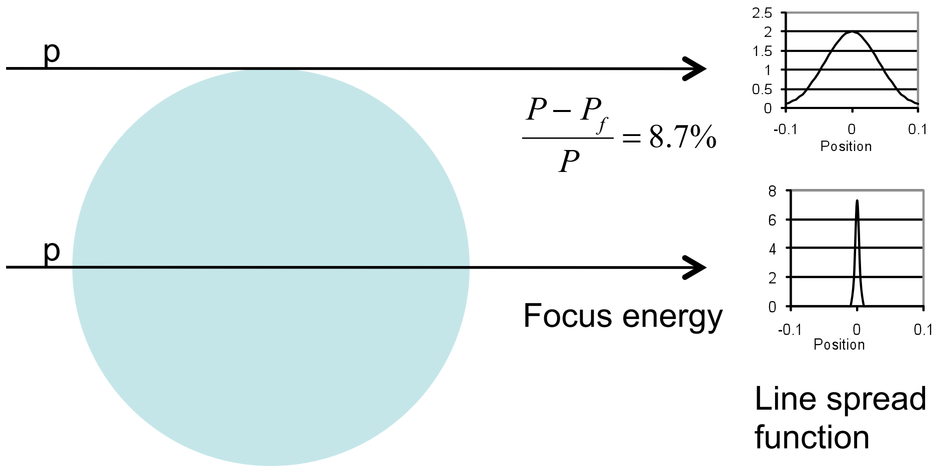
Bethe-Bloch Energy Loss for 800 MeV Protons

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2\right] \approx 1.5\frac{MeV}{g/cm^2}$$

$$K = 4\pi N_A r_e^2 m_e c^2 = 0.307\frac{MeV}{g/cm^2}$$

$$T_{\max} = \frac{2m_e c^2\beta^2\gamma^2}{1 + 2\gamma m_e/M + \left(m_e/M\right)^2}$$

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

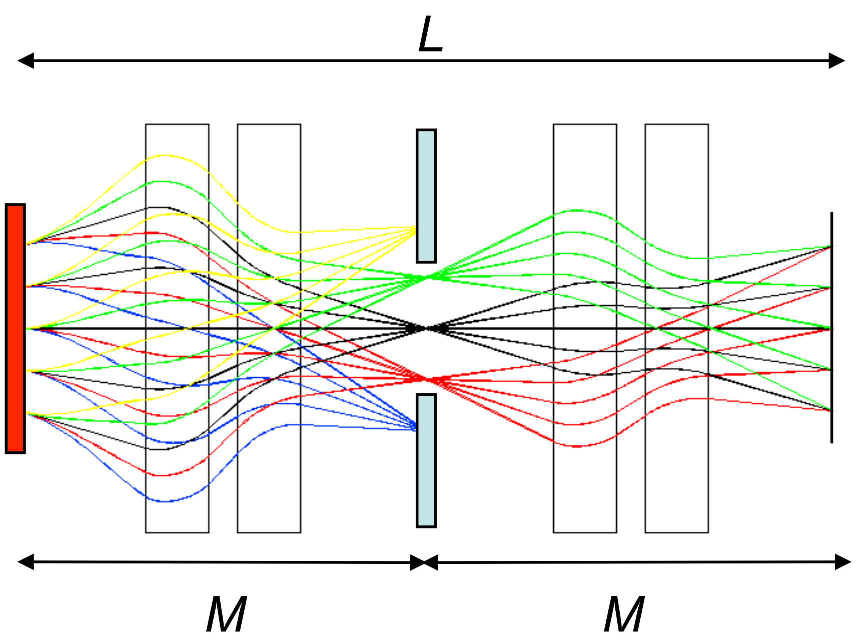


Line spread function

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

copper

Correcting Second Order Chromatic Aberrations



x_o, x_o' - position and angle at object
x_{fp} - position at midpoint of lens
x_i - position and angle at image
δ - $\Delta p/p$
M - Transport matrix for doublet
L - First order Transport matrix
T - Second order Transport tensor

$$L = M^2 = -I$$

Form identity lens from identical doublets

Resolution

$$x_i = L_{11}x_o + L_{12}x_o' + T_{116}x_o\delta + T_{126}x_o'\delta$$

$$x_i = -x_o + T_{116}x_o\delta + T_{126}(wx_o + \phi)\delta$$

$$w = \frac{-T_{116}}{T_{126}} = \frac{-M_{11}}{M_{12}}$$

$$w = \frac{-M_{11}}{M_{12}}$$

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

Inject beam with position-angle correlation to form Fourier plane at center of lens.

Momentum spread and chromatic length determine the resolution

Fourier Plane

$$x_{fp} = M_{11}x_o + M_{12}x_o'$$

$$x_o' = wx_o + \phi$$

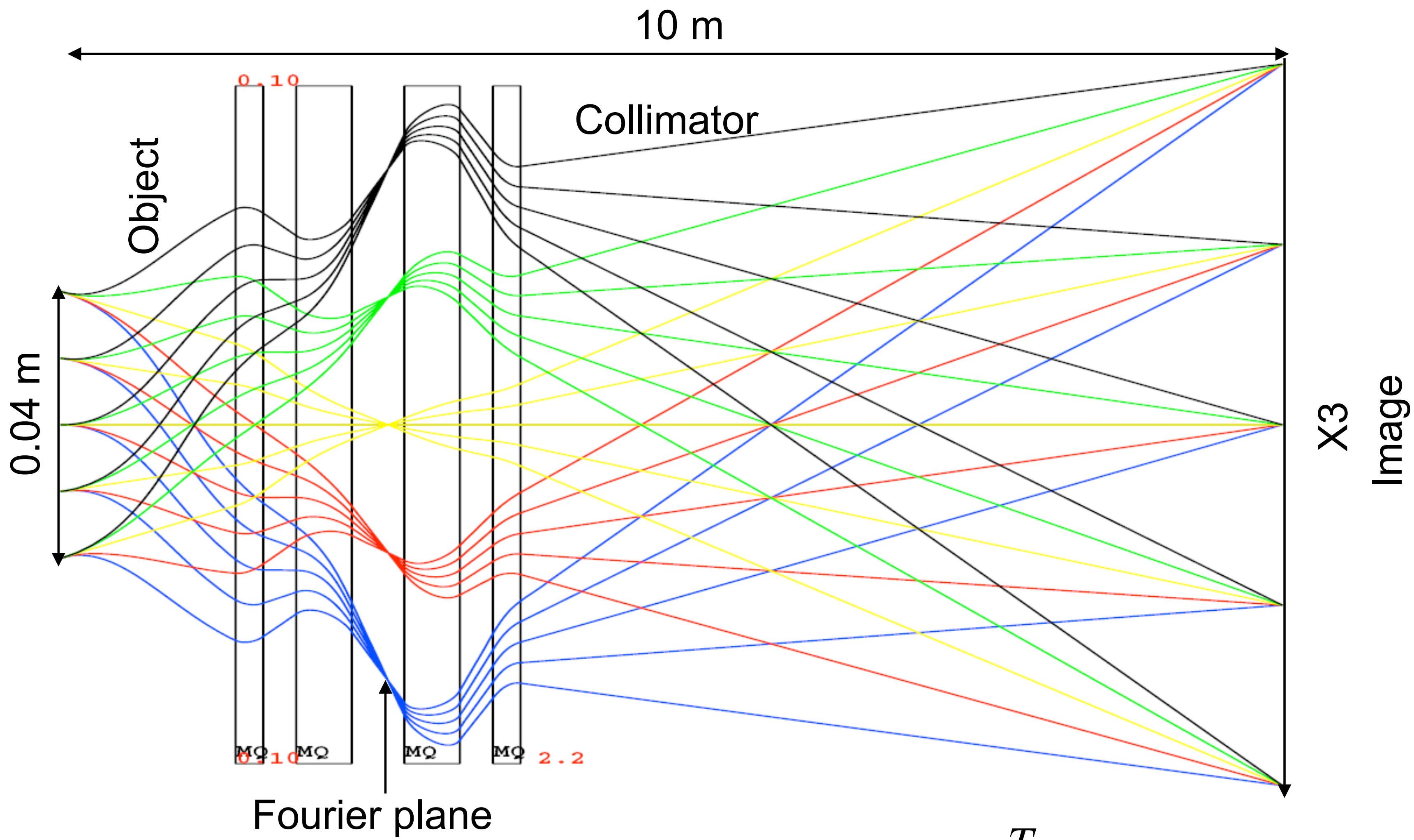
$$x_{fp} = M_{11}x_o + M_{12}\left(wx_o + \phi\right)$$

$$w = \frac{-M_{11}}{M_{12}}$$

$$x_{fp} = M_{12}\phi$$

Same position-angle correlation which forms a Fourier plane at the center of the lens also cancels second order chromatic terms.

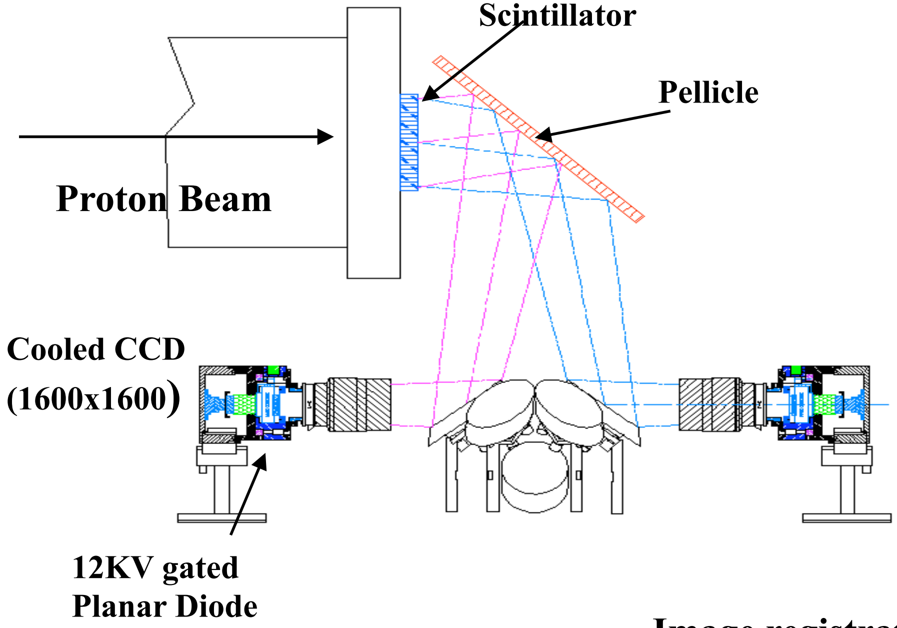
800 MeV x3 Magnifying Imaging Lens

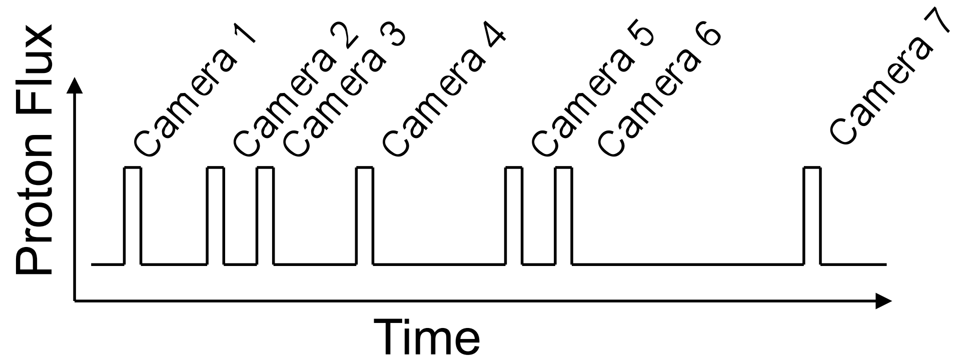


Resolution $\Delta x_i = \frac{T_{126}}{M_{12}} \phi\delta$

Temporal Resolution

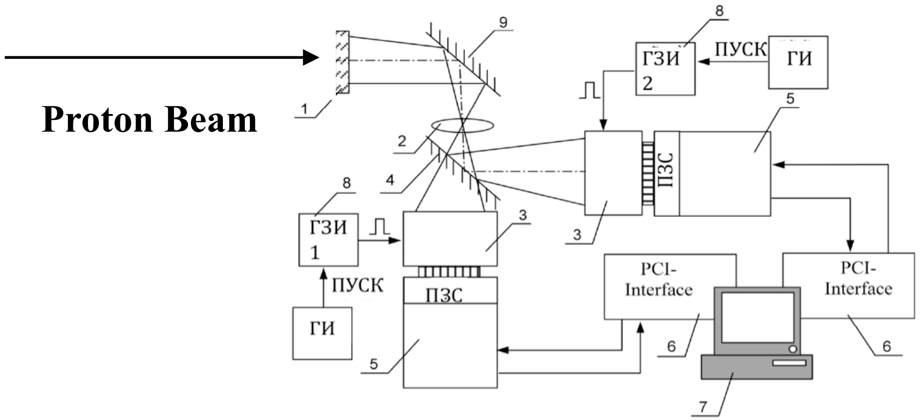
pRAD LANCE image registration system

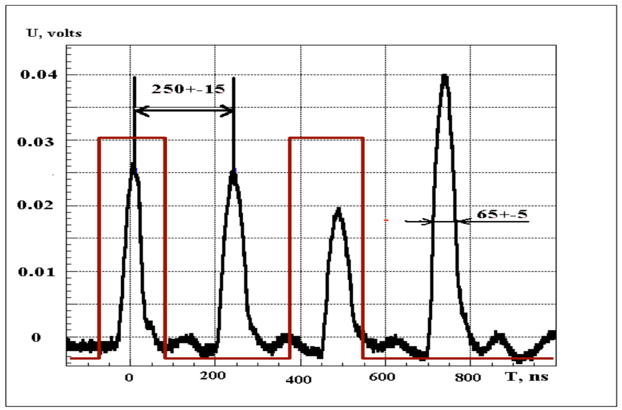




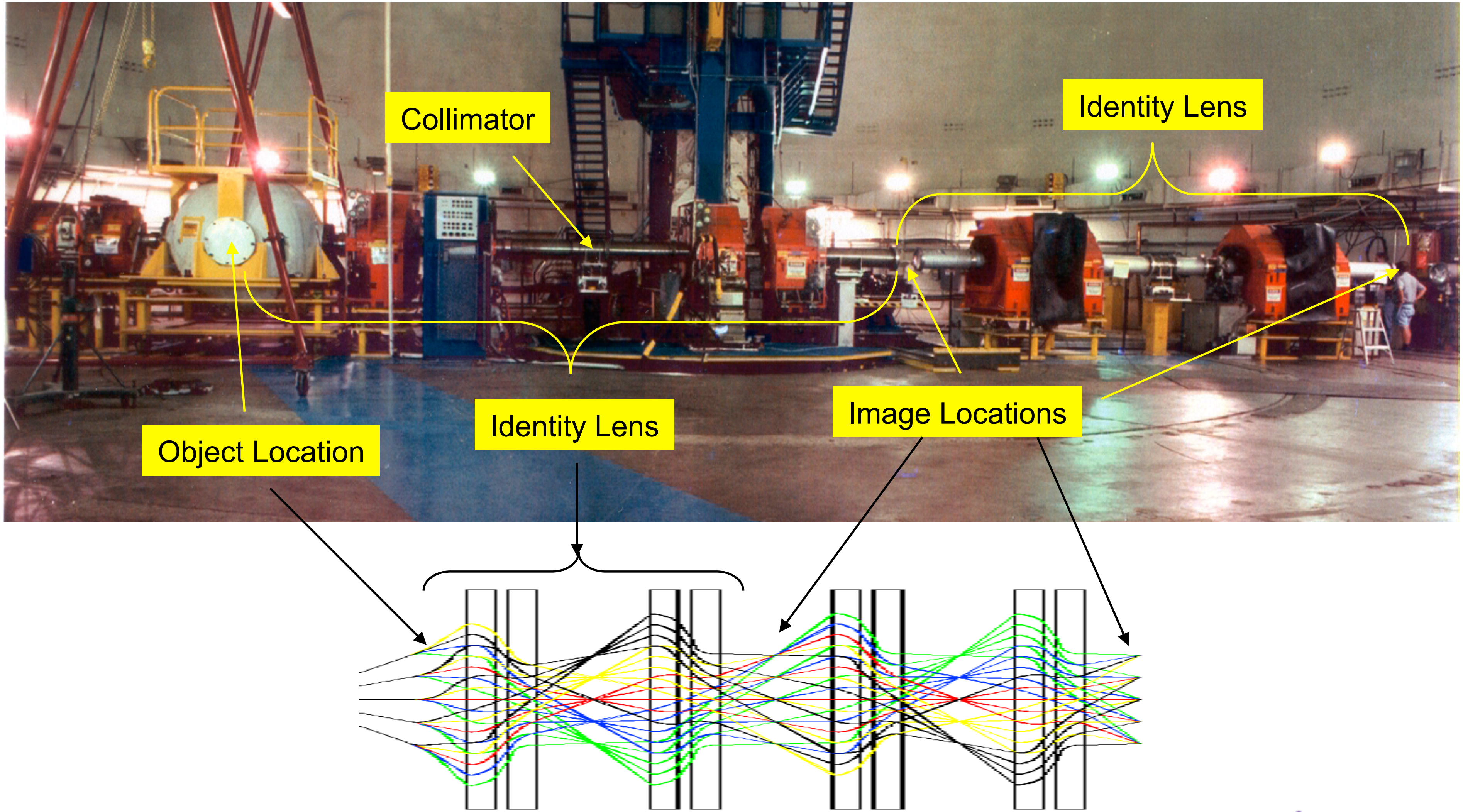
- 19 images at first station
- 22 images at second station
- Typically 100 ns exposure times

Image registration system on proton synchrotron TWAC-ITEP





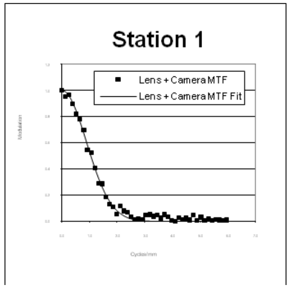
800 MeV pRad Facility at LANSCE

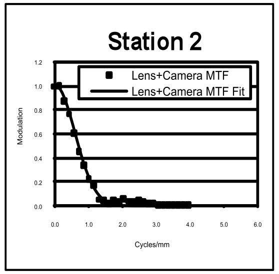


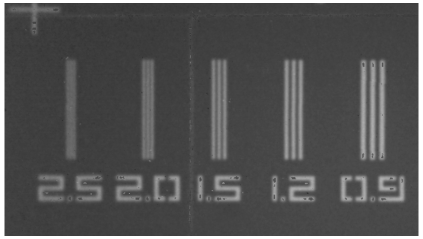
800 MeV pRad Facility at LANSCE

Chromatic Aberration and Resolution

Identity Lens

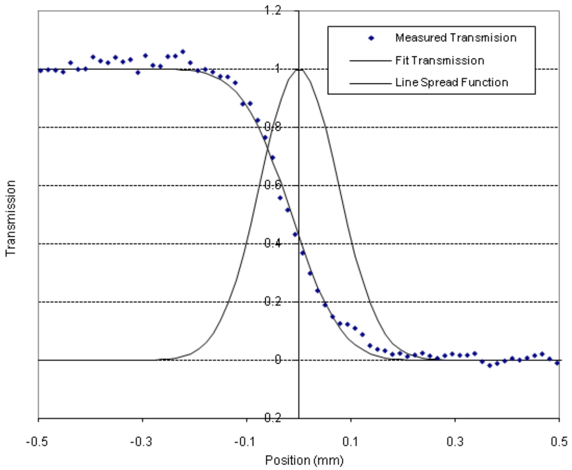




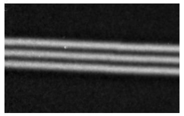


- 12 inch lens
- Station 1: 178 μm
- Station 2: 280 μm
- Gaussian blur function.
- 120 mm field of view

X3 Magnifier

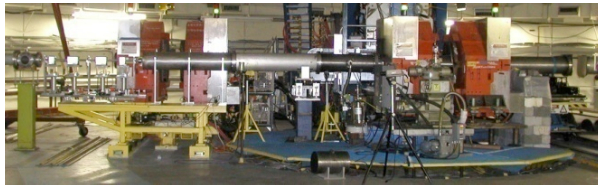


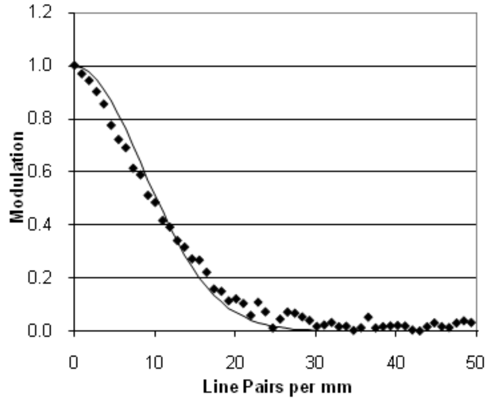
2.5 lp/mm



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

X7 Lens

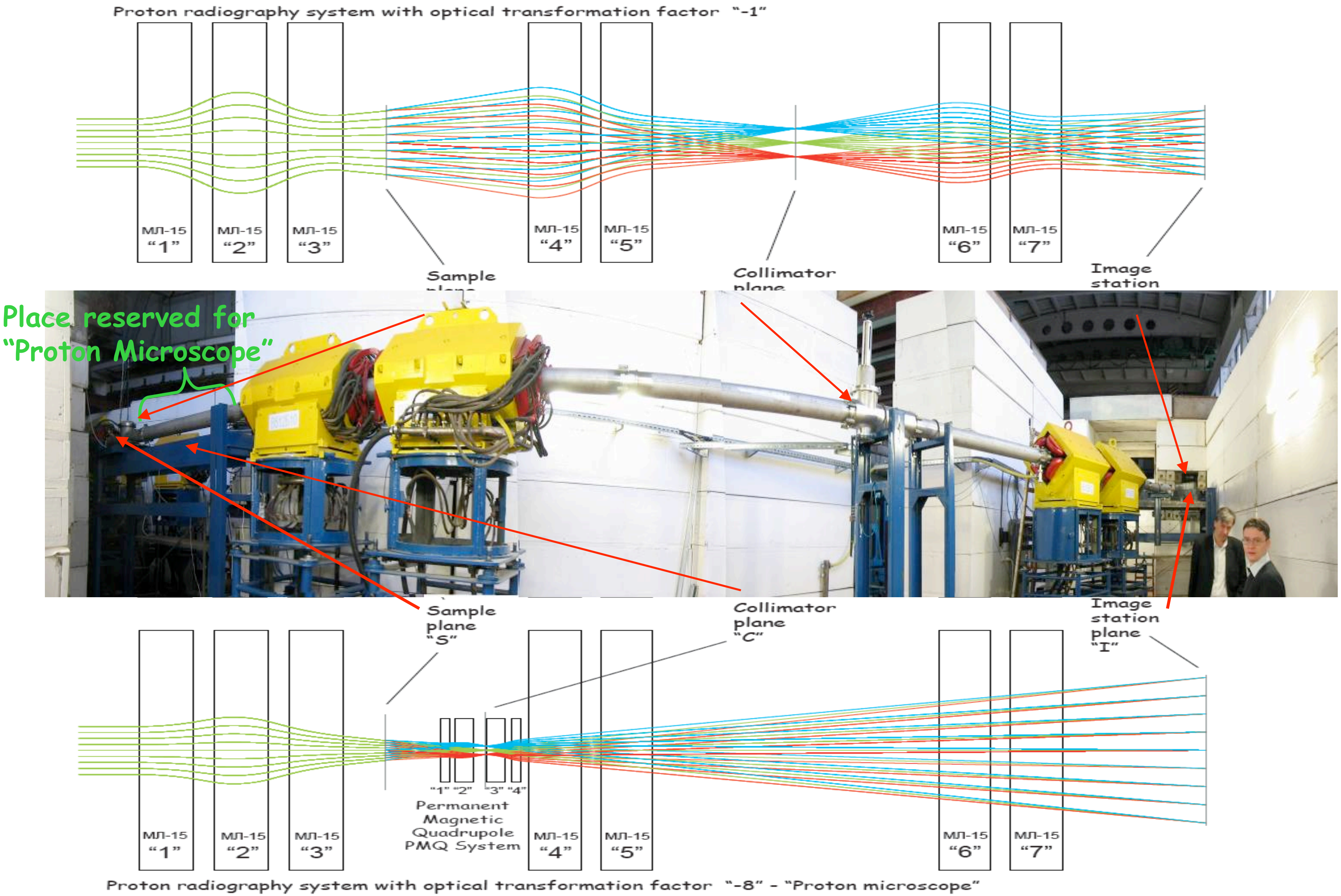




- 1 inch lens
- Station 1: 30 μm
- Gaussian blur function.
- 17 mm field of view

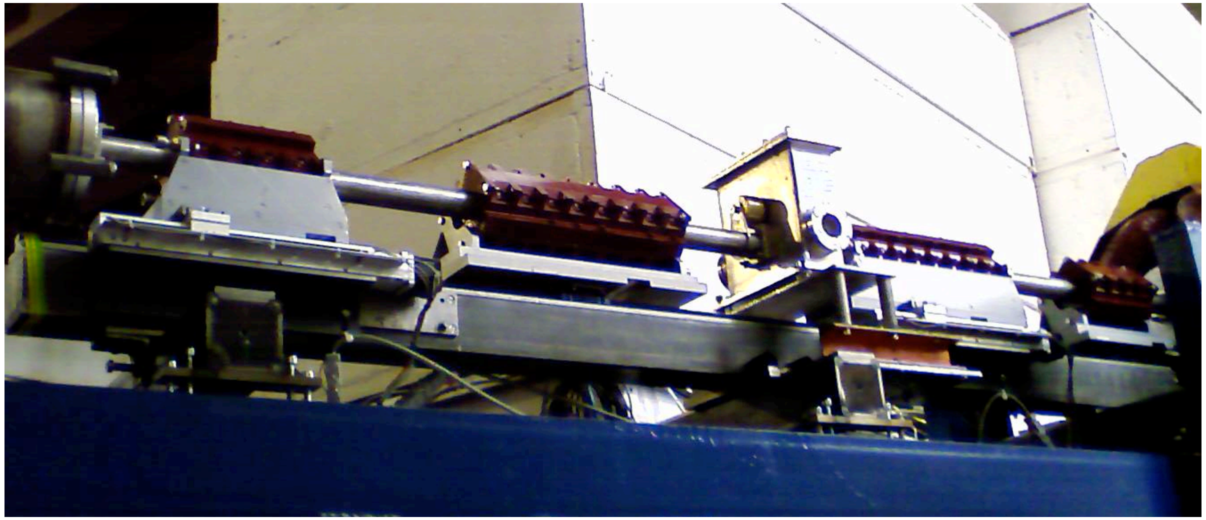
NNSA Los Alamos

Proton Radiography Set-up at ITEP-TWAC Facility



Proton Radiography Set-up at ITEP-TWAC Facility

E = 800 MeV
Magnification X = 7.82
Field of view < 10mm
Spatial resolution σ ~ 50um



Magnification X = 3.92
Field of view < 22 mm
Spatial resolution σ ~ 60um

Magnification X = 1.0
Field of view < 40 mm
Spatial resolution σ ~ 300um

Beam structure – 4 bunches (FWHM=70ns) in 1 us

Protective Target Chamber:

- up to 80 g TNT
- Pumped down to 10^{-3} Torr
- Active ventilation system
- Fiber for optical diagnostics (VISAR)

Summary

Proton radiography (PR) is a novel technique for probing the interior of thick and dense objects in dynamic experiments by monoenergetic beams of fast protons from accelerator.

Special system of magnetic lenses is used for imaging and aberrations correction.

Density measurements with sub-percent accuracy;
few micrometers spatial resolution over several centimeters-wide field of view;
nanosecond-scale temporal resolution.

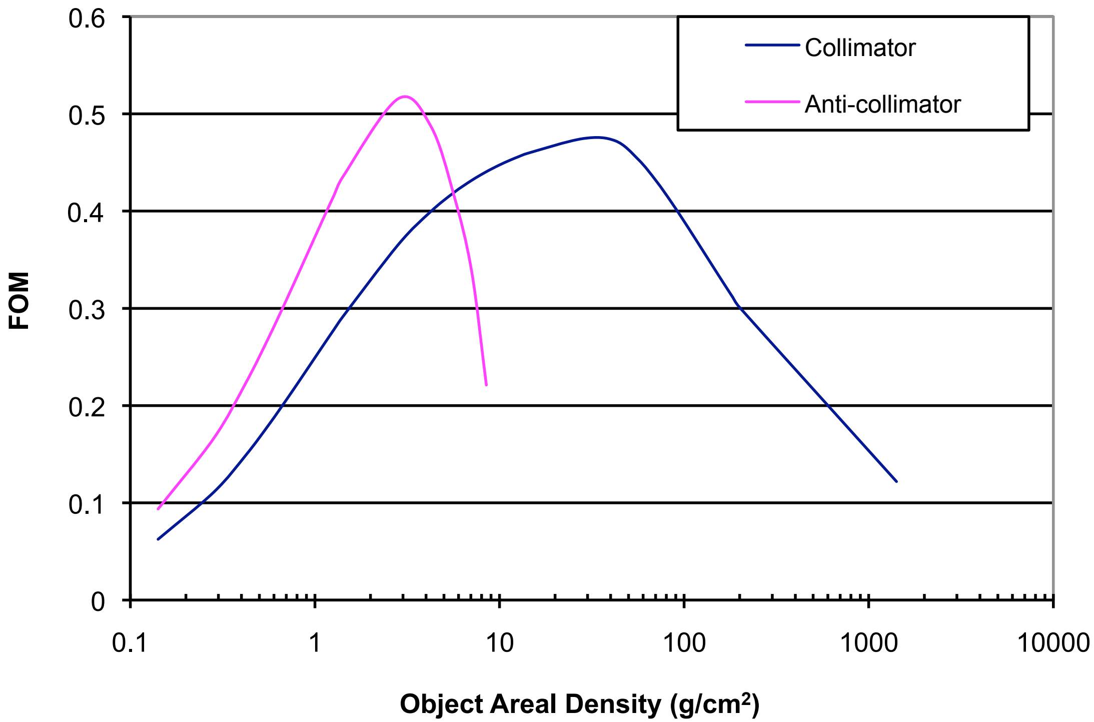
PR is one of the most valuable and versatile single technique available to interrogate the hydrodynamic and equation of state aspects of high energy density physics (HED) and material research.

Dynamic Range of 800 MeV Proton Radigraphy

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

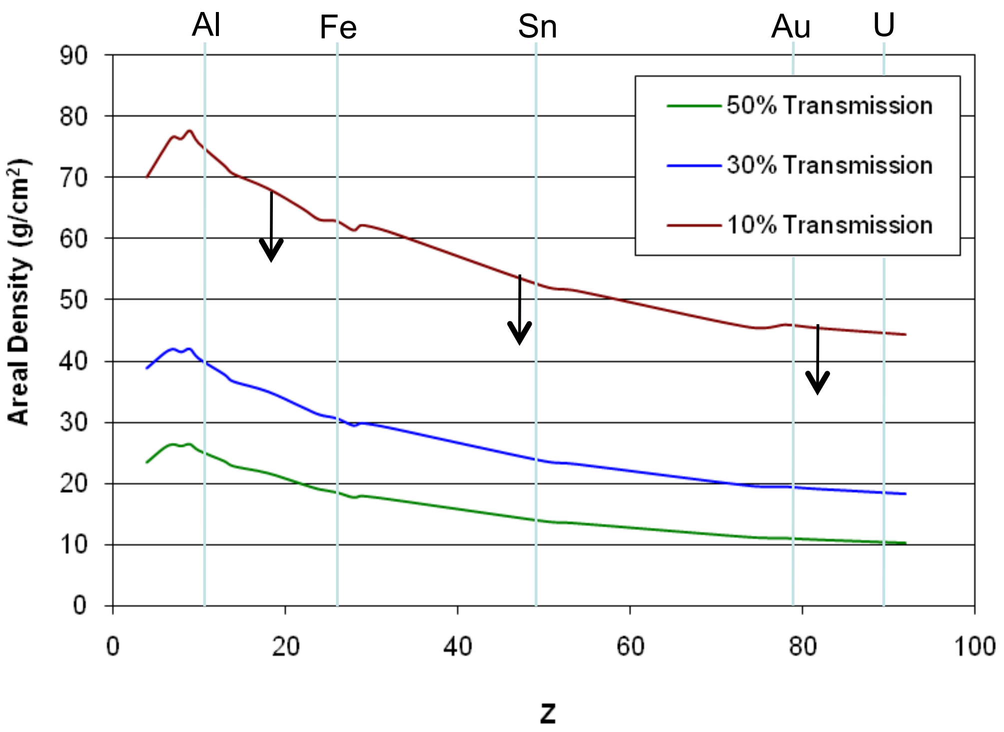
Signal to noise

Fractional change in thickness



- 800 MeV proton radiography ranges from 1 g/cm^2 up to 70 g/cm^2 of iron

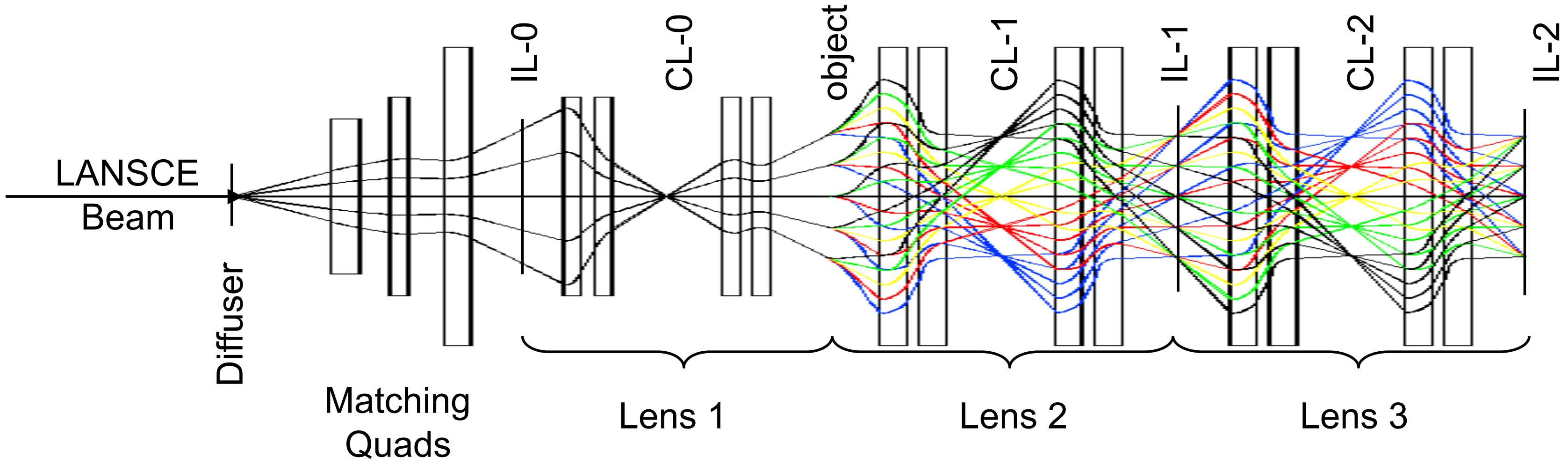
When is an object too thick?



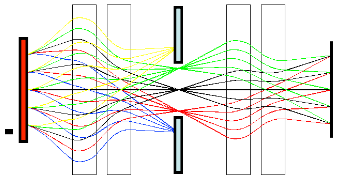
Areal density contours of constant transmission as a function of atomic number.

10% is near the lower limit of reasonable transmission.

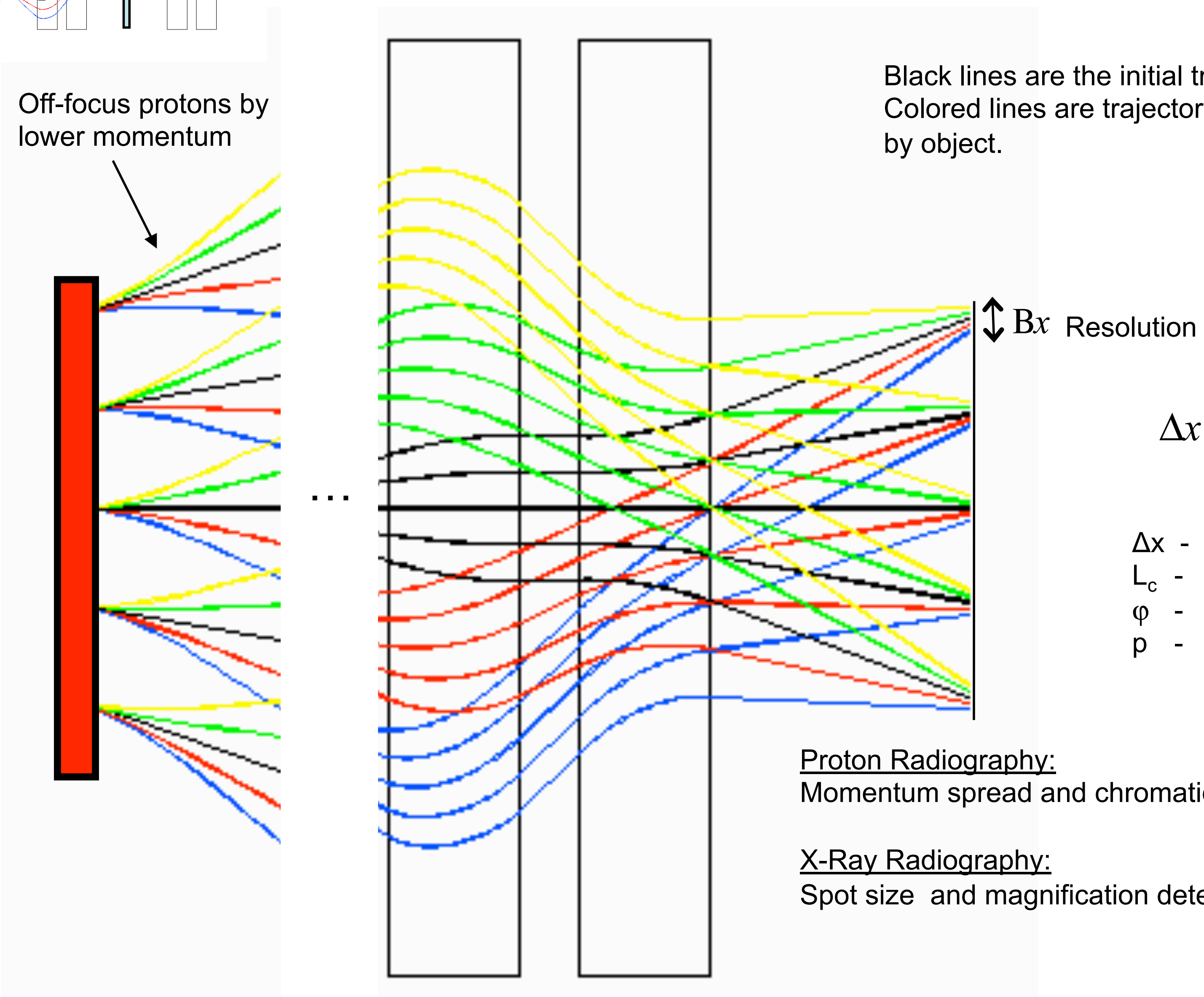
Full LANSCE System



- Diffuser sets illumination pattern at object.
- Matching quads establish position-angle correlation
- CL-0 has a 9.0 mRad collimator
- CL-1 and CL-2 can independently have 5-20 mrad collimators
- Lens 0 used for beam monitoring
- IL-1 has seven single-shot camera systems
- IL-2 has five single-shot camera systems and a 9-frame framing camera
- 21 images per dynamic event at up to 21 different times.



Chromatic Aberrations



Black lines are the initial trajectories of the protons.
Colored lines are trajectories of protons scattered by object.

$$\Delta x = L_c \phi \frac{\Delta p}{p}$$

- Δx - Resolution
- L_c - Chromatic Length
- φ - Scattering angle
- p - Momentum

<u>Proton Radiography:</u>
Momentum spread and chromatic length determine the resolution

<u>X-Ray Radiography:</u>
Spot size and magnification determine the resolution.

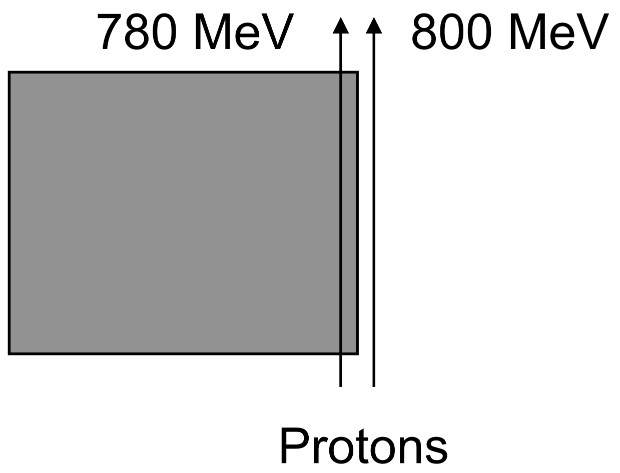
Chromatic Blur ⟶ Limbing

<u>Limb: To outline in clear sharp detail</u>

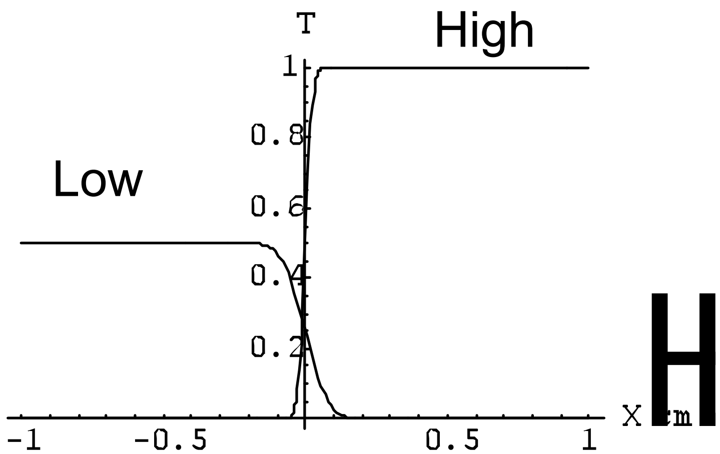
Like phase-contrast radiography:
- Useful to enhance edges
- Problem for density reconstruction

Resolution proportional to energy offset

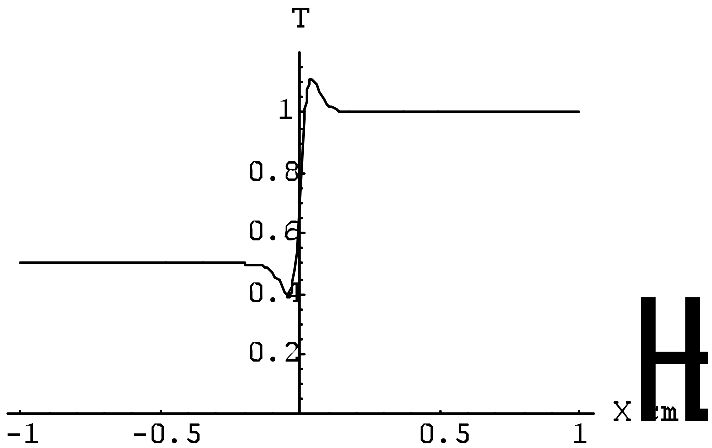
$$\sigma = \theta l_c \frac{E - E_f}{E_f}$$



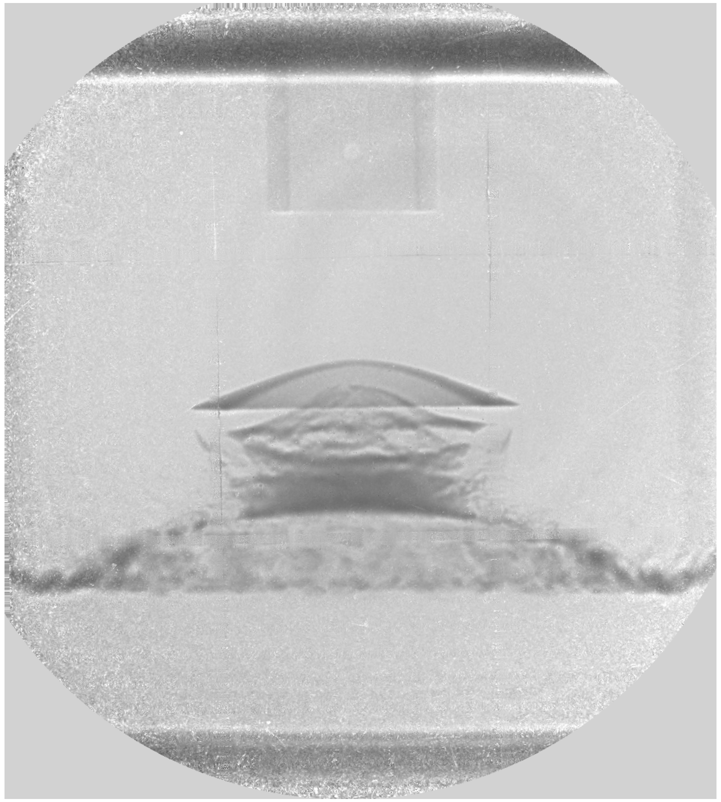
Focus on high energy protons



Low + High



Proton Radiography Primer



Frank Merrill, LANL

and the pRad collaboration

LA-UR 08-07298

pRad Collaboration

Bechtel Nevada

Stuart Baker, Alfred Meidinger, Richard Thompson, Josh Tybo

DE-2

Robert Hixson, Paulo Rigg, Darcie Dennis-Kohler

HX-3

Joe Bainbridge, Stephen Dennison, Eric Ferm, Robert Lopez, Mark Marr-Lyon, Carlos Montoya, Paul Rightley Wendy McNeil

LANSCE-1

Andrew Jason, Barbara Blind, Charles Mottershead

LANSCE-6

Leo Bittecker, Rodney McCrady, Chandra Pillai

P-23

William Buttler, David D. Clark, David Holtkamp, Nick King, Kris Kwiatkowski, Kevin Morley, Russ Olson, Paul Nedrow

P-25

Jeffrey Bacon, Bethany Brooks, Camilo Espinoza, Gary Hogan, Brian Hollander, Julian Lopez, Fesseha Mariam, Frank Merrill, Christopher Morris, Matthew Murray, Alexander Saunders, Richard Schirato, Larry Schultz, Cynthia Schwartz, Dale Tupa

S-7

Rodger Liljestrand

X-4

Langdon Bennett, John David Becker, Maria Rightley, Stephen Sterbenz