Applications of 800 MeV Proton Radiography

Frank Merrill, for the pRad collaboration

800 MeV Proton Radiography at Los Alamos is the result of contributions of many scientists, engineers and technicians over the past decade.

The pRad Collaboration

National Security Technologies
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Heather Leffler

WX-6
Wendy Vogan McNeil,
Robert P. Lopez,
Joel Heidemann,
Michael Archuleta,
Pam Scott,
Joe Strotman,
Gary McMath,
Isaac P. Martinez

LANSCE-NS
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AOT-ABS
Rodney McCrady,
Chandra Pillai

P-23
Nick King,
Kris Kwiatkowski,
Frank Merrill,
Paul Nedrow,
Josh Tybo,
Carl Wide

P-25
Camilo Espinoza,
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Fesseha Mariam,
Christopher Morris,
Deborah Morley,
Matthew Murray,
Alexander Saunders,
Amy Tainter,
Frans Trouw,
Dale Tupa

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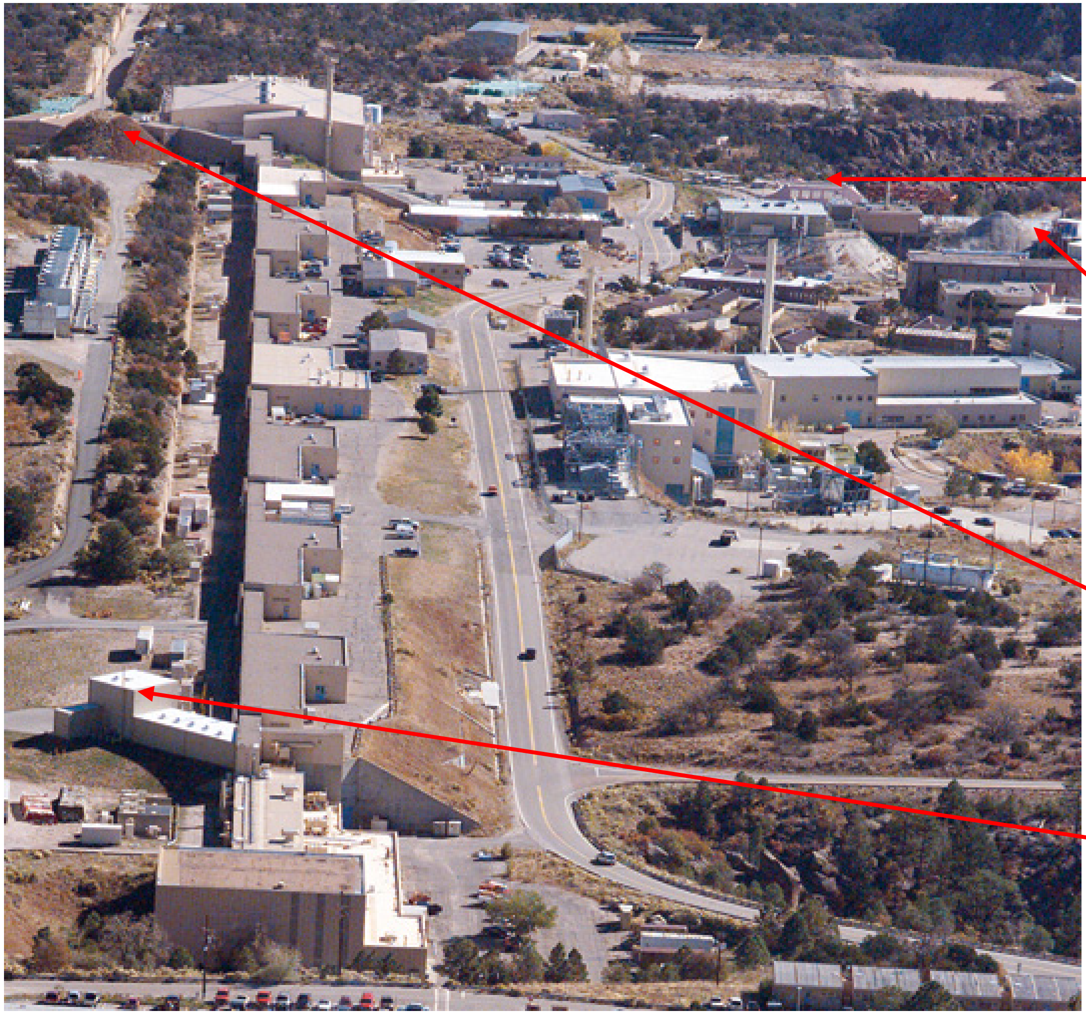
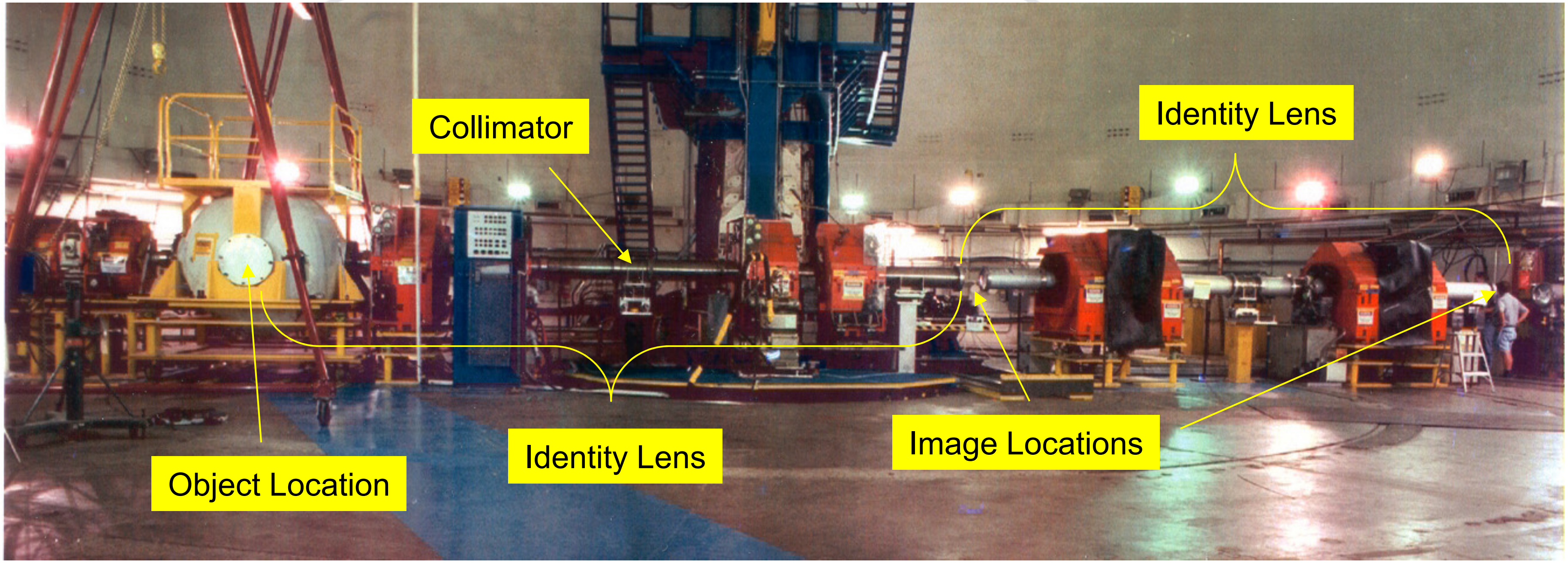
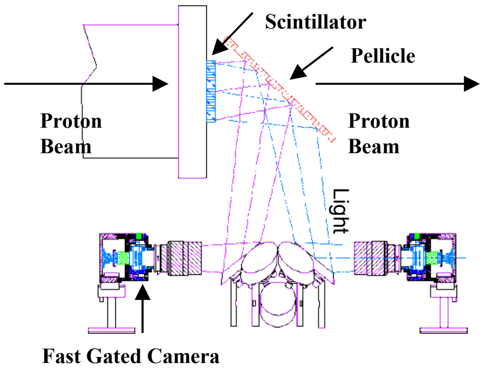
LANSCE Accelerator Delivers beam to Several Experimental Areas

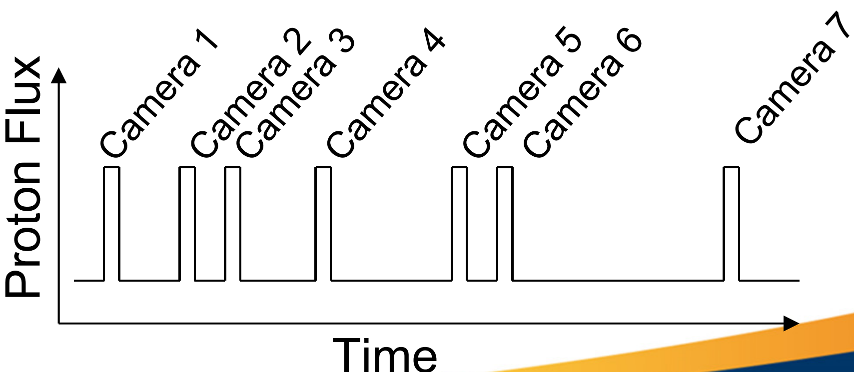


- Lujan Center
  - ***Materials, bio-science, and nuclear physics***
  - ***National user facility***
- Neutron research
  - ***Nuclear Physics***
  - ***Neutron Irradiation***
- Proton Radiography
  - ***Dynamic Materials science,***
  - ***Hydrodynamics***
- Isotope Production Facility
  - ***Medical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

800 MeV pRad Facility at LANSCE







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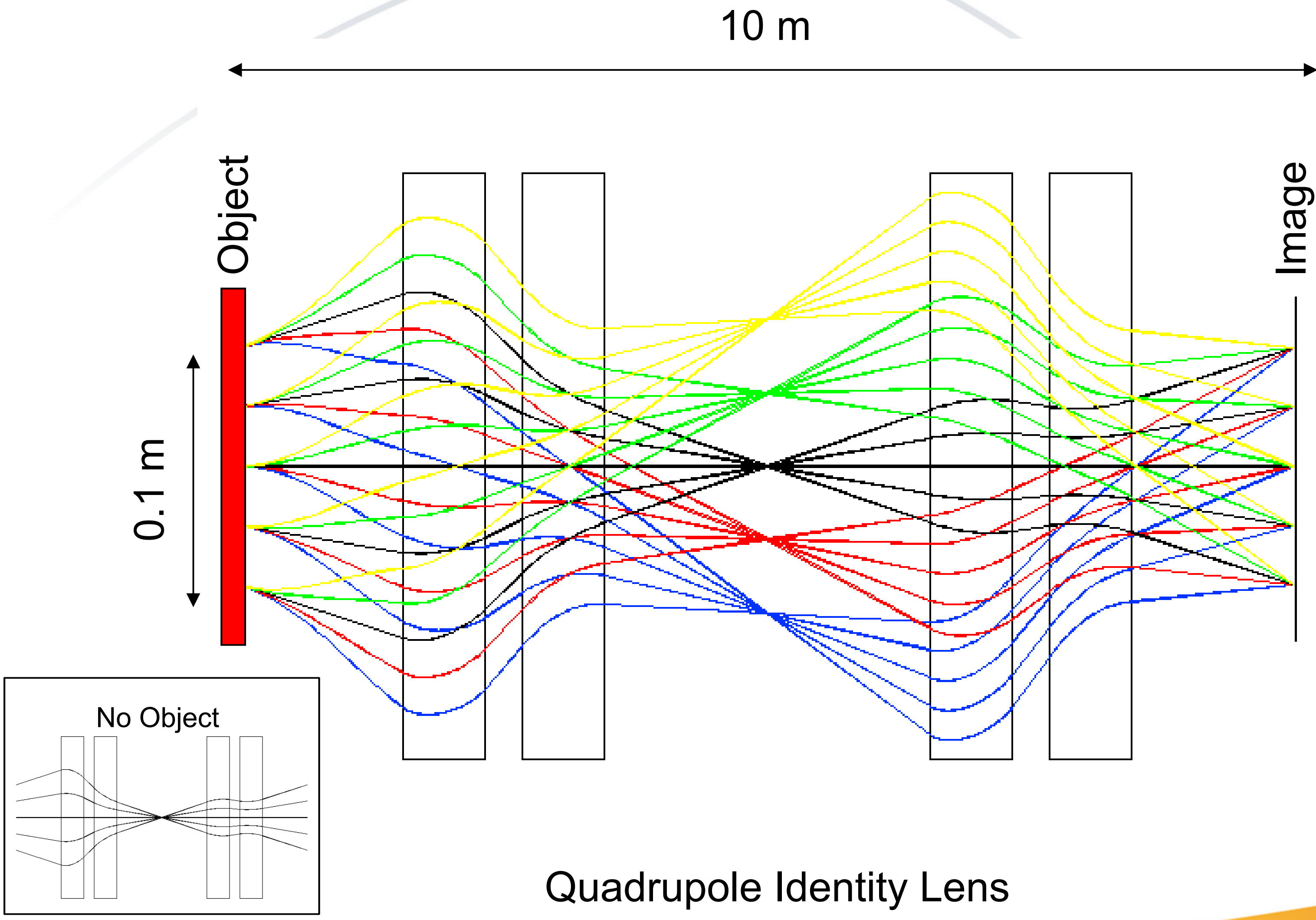
Magnetic Imaging Lens provides precise control of proton beam (down to 20 μm)



Quadrupole Identity Lens

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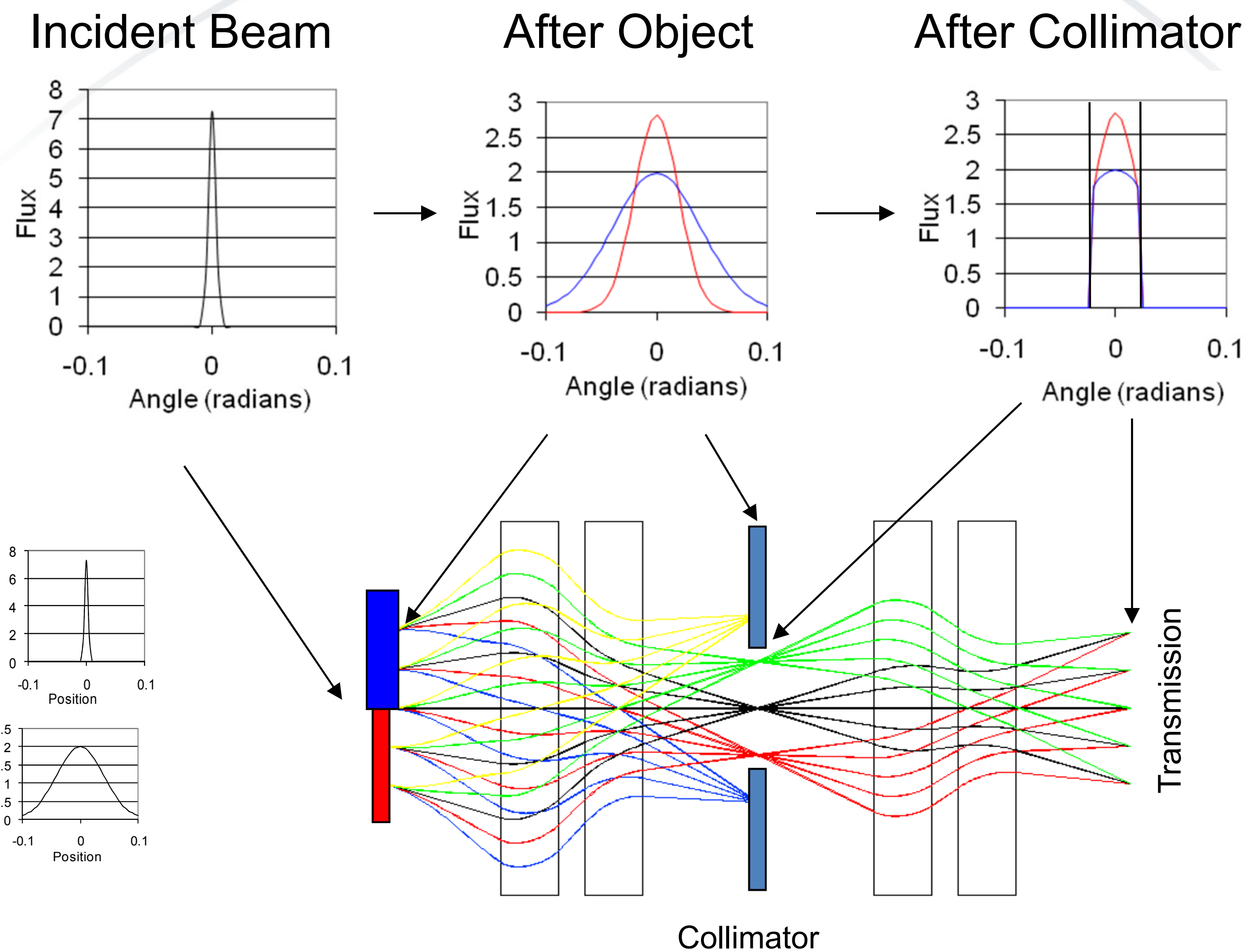
Contrast from Multiple Coulomb Scattering



Measured transmission provides information of object thickness

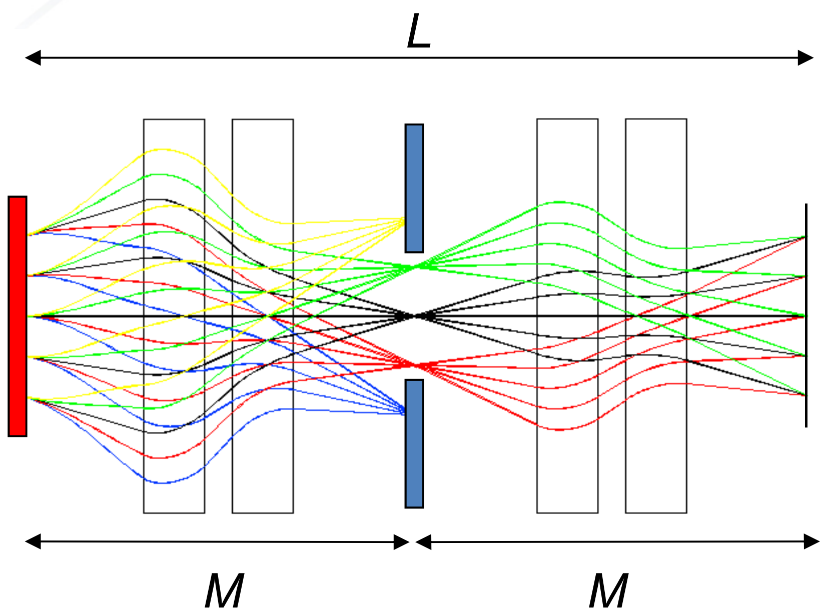
Transmission

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

Handling Second Order Chromatic Aberrations

Form identity lens from identical doublets

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



Resolution

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

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

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

$$w = {-M_{11}}/{M_{12}}$$

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

Dominates Blur

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

800 MeV proton radiography provides 42 images with better than 100 μm spatial resolution and 1% density resolution

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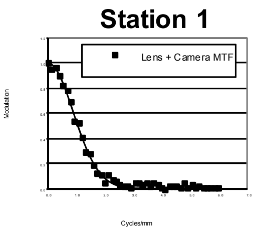
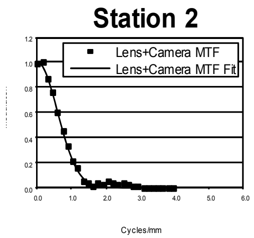
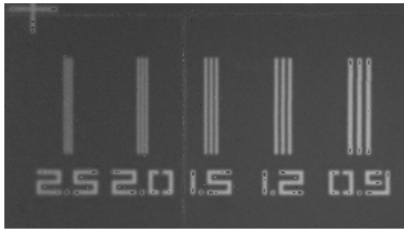
Identity Lens

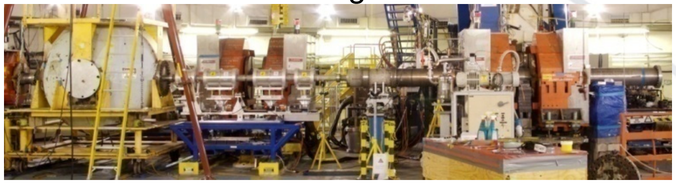


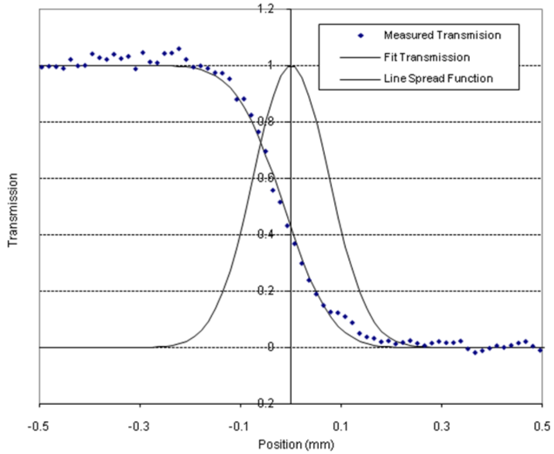




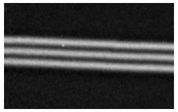
- 12 inch lens
- Station 1: 180 μm
- Station 2: 280 μm
- 120 mm field of view

X3 Magnifier



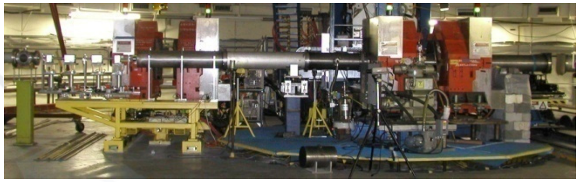


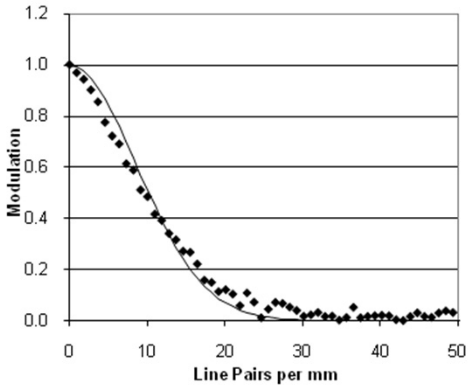
2.5 lp/mm



- 4 inch lens
- Station 1: 60 μm
- 44 mm field of view

X7 Lens





- 1 inch lens
- Station 1: 30 μm
- 17 mm field of view

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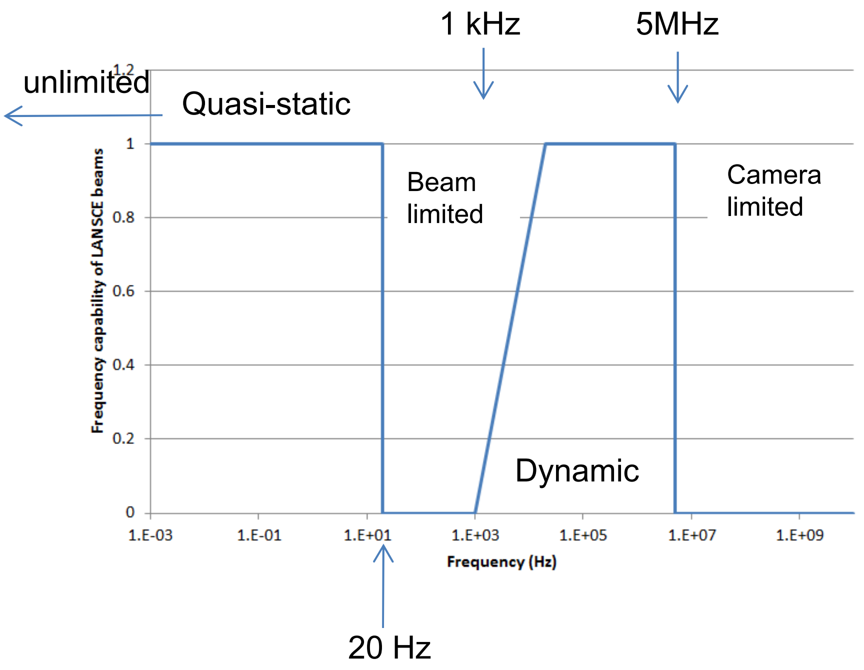
The temporal flexibility of the LANSCE Linear accelerator provides opportunities for quasi-static measurement as well as fast dynamic experiments.

- LANSCE accelerator runs at 60 or 120 Hz
- Fast kicker directs the beam to the proton radiography facility
- Fast kicker limits beam to 20 Hz.
- Each pulse lasts ~1 ms.
- A flexible time structure is available in this 1 ms window
- Cameras and scintillator can handle a 200 ns spacing between frames.
- RF of the accelerator imposes a 201 MHz time structure on the beam (5 ns).
- This enables the study of fast systems (MHz frame rates) as well as
- Quasi-static systems (10 Hz frame rates).



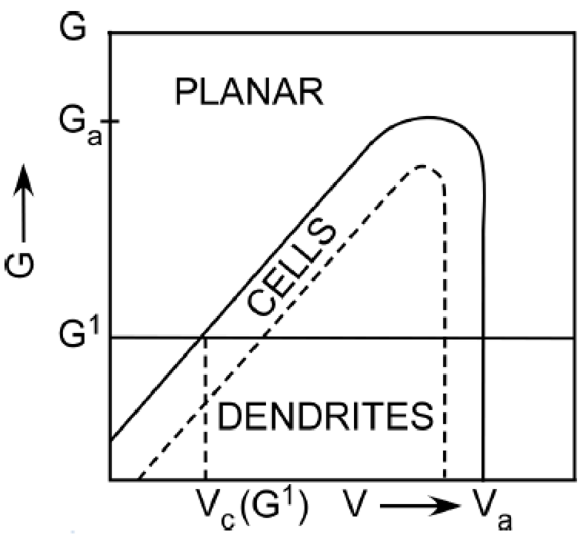
Penetration of protons allows the study of processes in thick systems.

The effects of magnetic field on casting processes were studied to compare the effects on the initial stages of casting.

Amy Clarke, Seth Imhoff, Paul Gibbs, Jason Cooley, Martha Barker

Thermal Gradient G and Interface Velocity V affect interface stability in castings

Melt and subsequent solidification of Al-In alloys

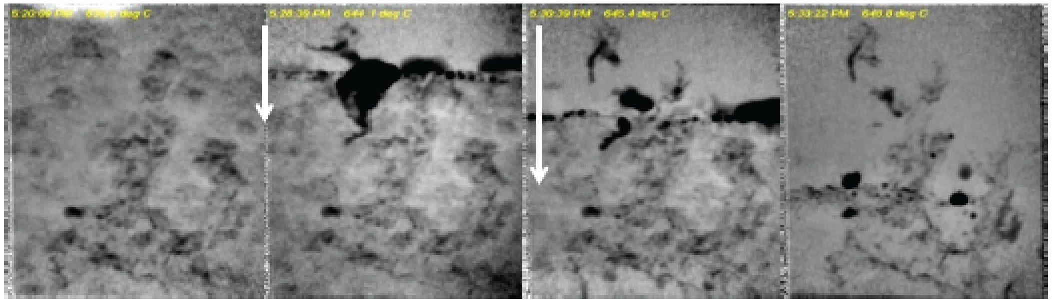


- Management of G and V to control morphology and microstructure evolution during processing.
- Integration of experiments/modeling (e.g. phase field) to predict microstructure and segragration as a function of processing parameters.

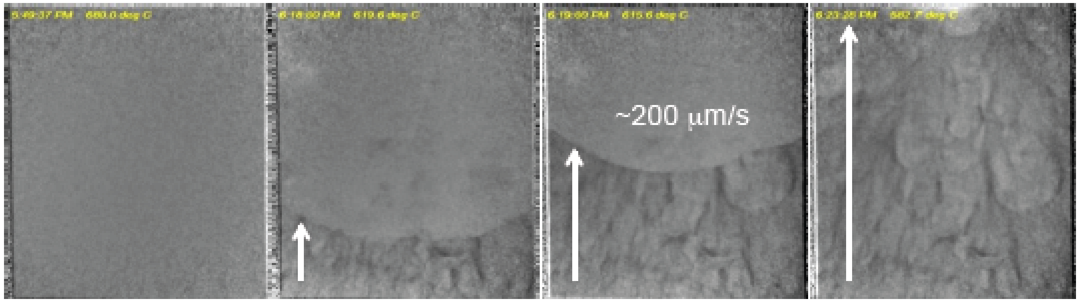
Amy Clarke, Seth Imhoff, Paul Gibbs, Jason Cooley, Martha Barker

Thermal Gradient, G, and Interface Velocity, V, affect interface stability in castings

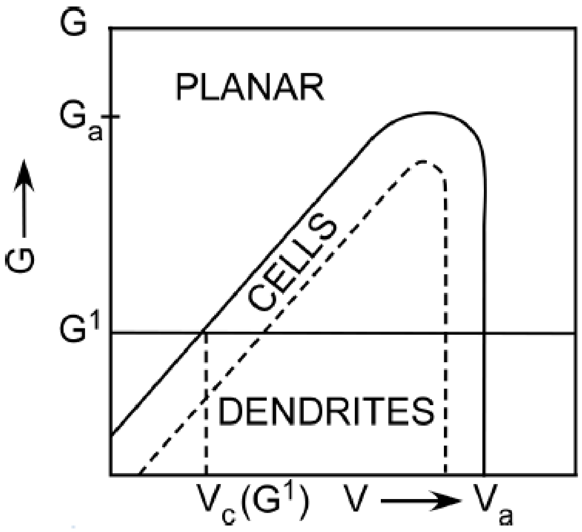
Melting, Increasing Time



Solidification, Increasing Time



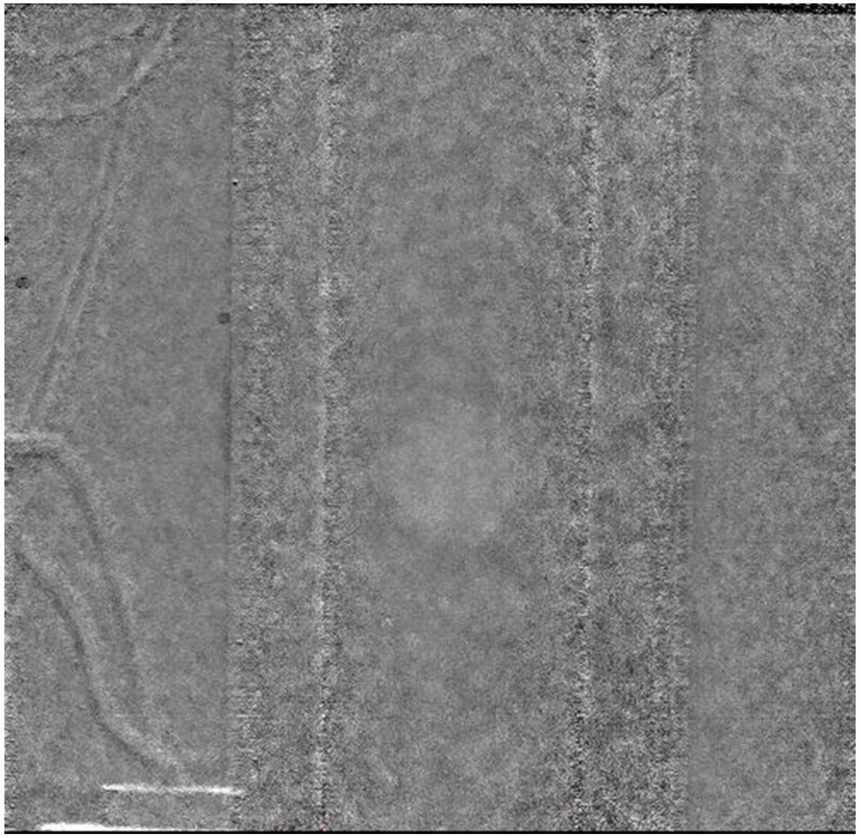
Melt and subsequent solidification of Al-In alloys



Management of G and V to control morphology and microstructure evolution during processing.

Integration of experiments/modeling (e.g. phase field) to predict microstructure and segragration as a function of processing parameters.

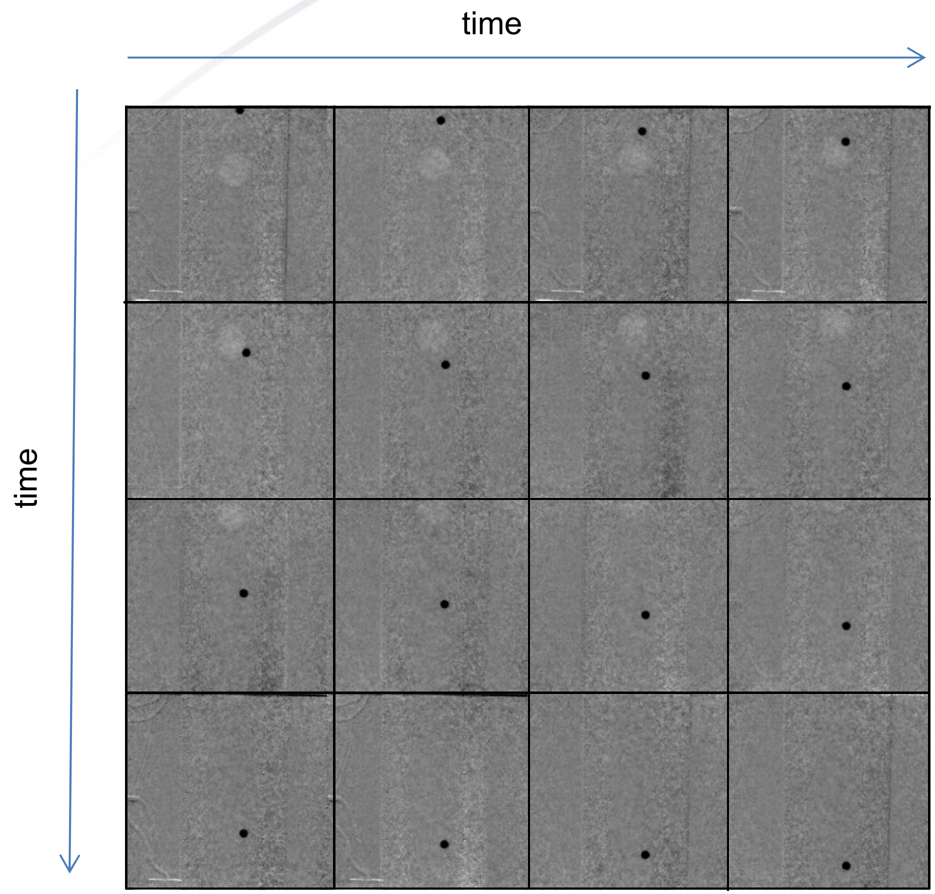
Penetration of opaque materials allows the classic measurement of viscosity for novel materials.



The measurement of the terminal velocity of the bubble and the steel sphere provides a measure of viscosity of the fluid.

The penetrating power of the proton beam allows the measurement of viscosity of opaque materials that require significant support equipment surrounding the material (containment, crucible…).

Penetration of opaque materials allows the classic measurement of viscosity for novel materials.

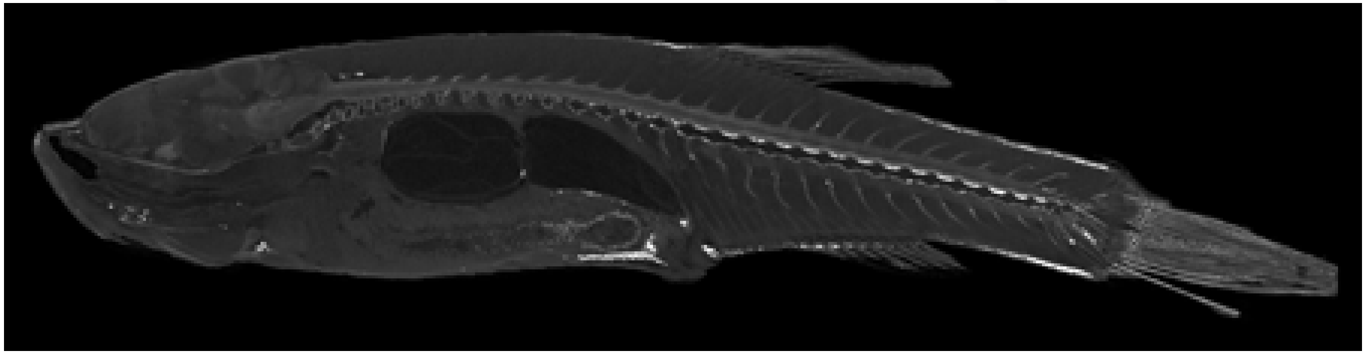


The measurement of the terminal velocity of the bubble and the steel sphere provides a measure of viscosity of the fluid.

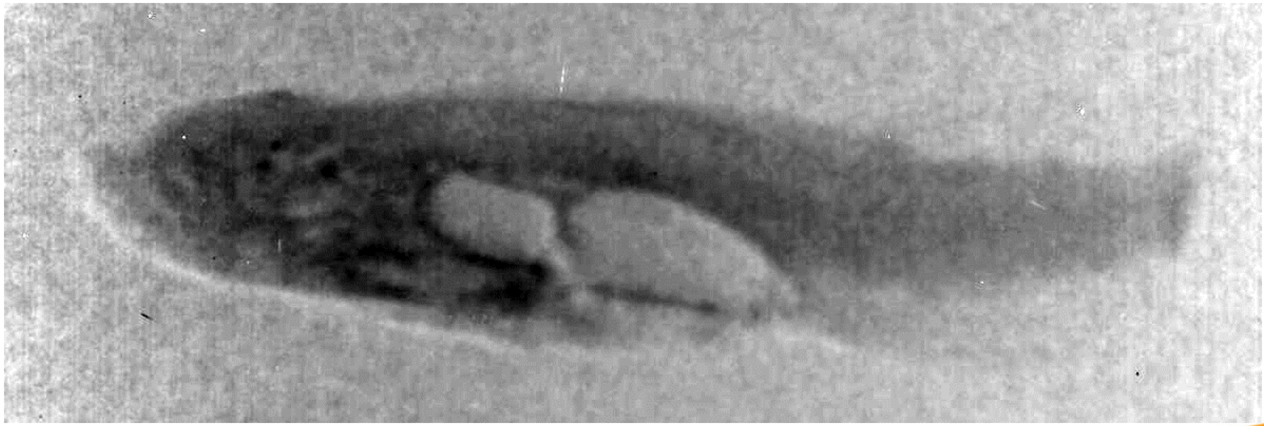
The penetrating power of the proton beam allows the measurement of viscosity of opaque materials that require significant support equipment surrounding the material (containment, crucible…).

We are investigating the potential for biological applications. Protons are not the ideal probe for thin low Z objects, but show promise for measurements in support of proton cancer treatment.

X- rays



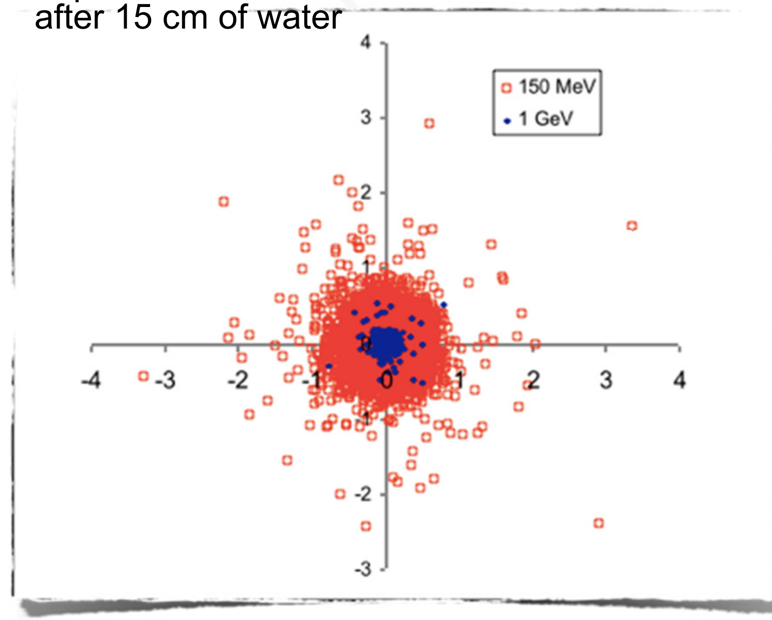
Protons



M. Durante, C. La Tessa, L. Shestov, P. M. Lang, F. Merrill, D. Varentsov, M. Prall

IGSpRS – Image-Guided Stereotactic Particle Radiosurgery

Spatial distribution of proton beams after 15 cm of water



“+” very small lateral scattering (remote scalpel)

“+” simultaneous imaging (on-line radiography) with the same beam.

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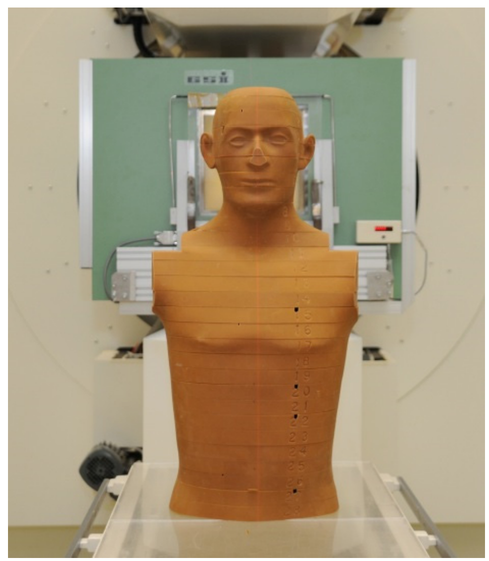
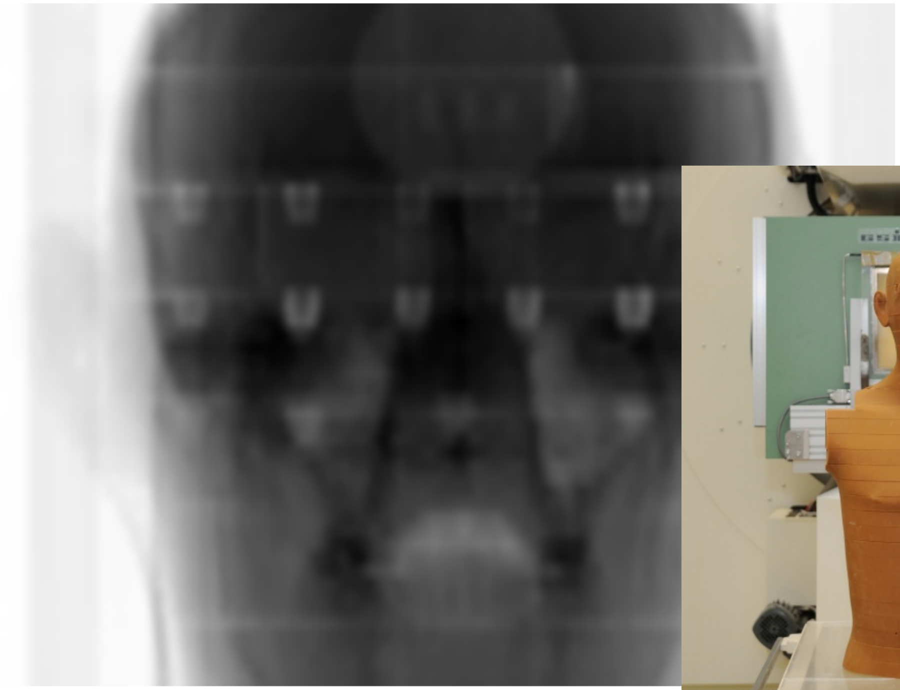
pRad – Radiography of an anthropomorphic Phantom



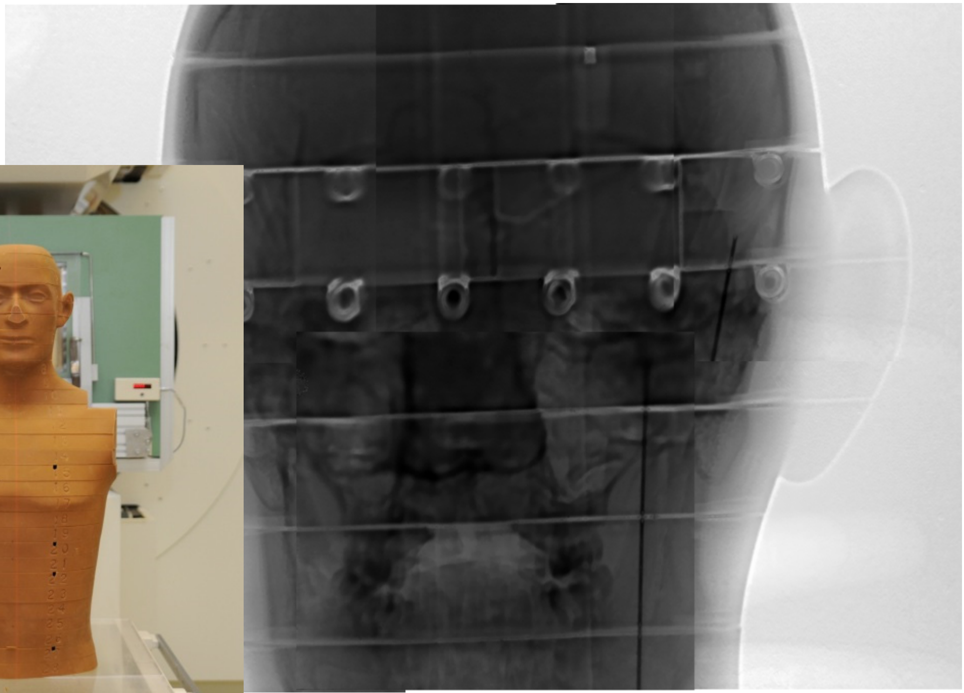
M. Durante, C. La Tessa, L. Shestov, P. M. Lang, F. Merrill, D. Varentsov, M. Prall

pRad – Radiography of an anthropomorphic Phantom

CT-scan



Proton radiography



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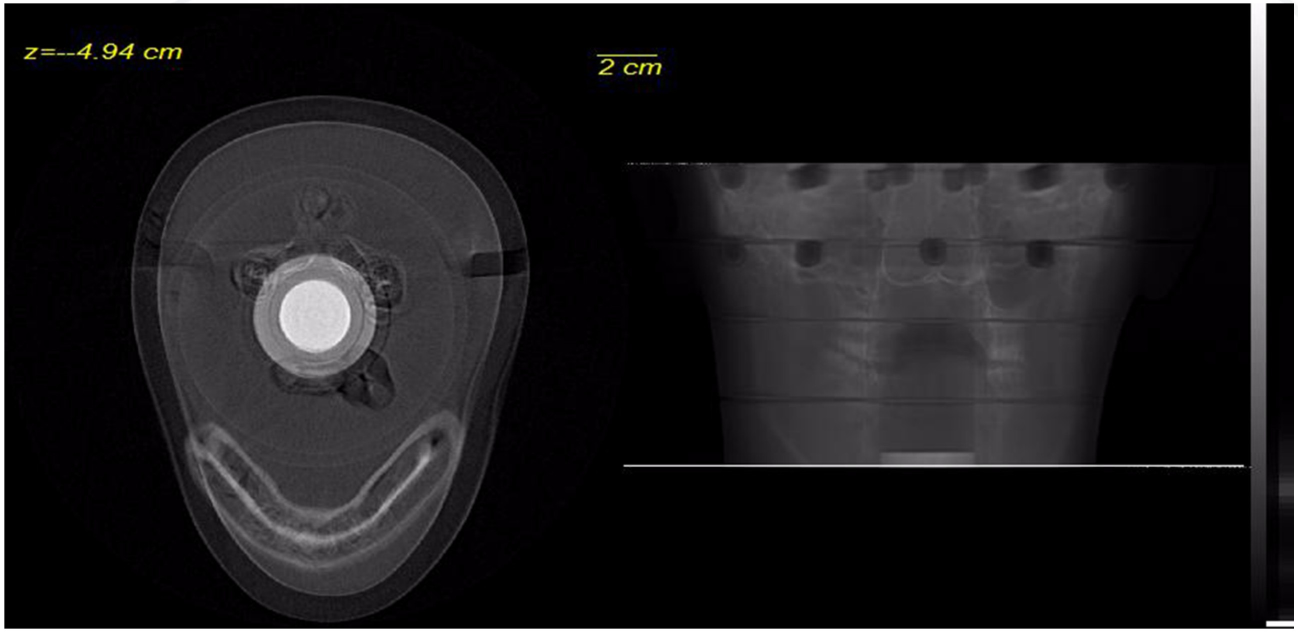
Multiple View Proton Radiography Allows Proton Computed Tomography



Our measurements show remarkable sensitivity to soft tissue contrast.

M. Durante, C. La Tessa, L. Shestov, P. M. Lang, F. Merrill, D. Varentsov, M. Prall

Russia has developed two pRad facilities and are pushing the technology forward

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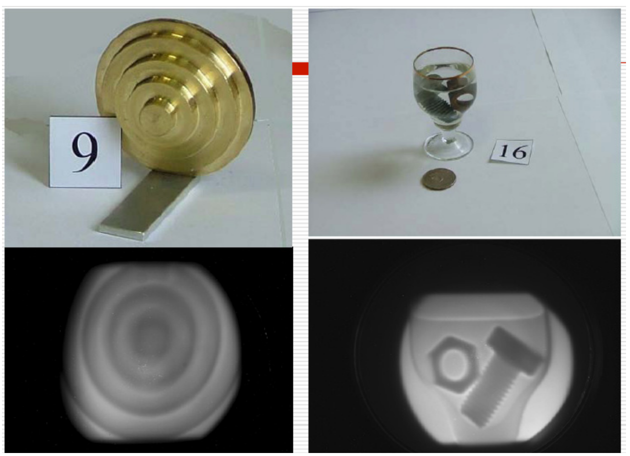

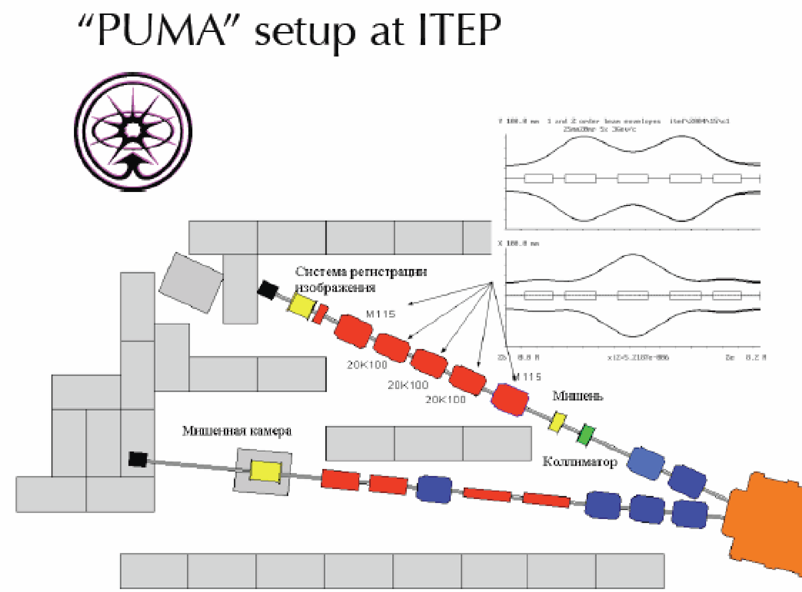

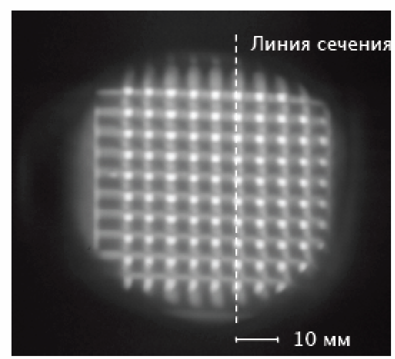

An accelerator built in Protvino, Russia for high energy physics experiments in the '70s is the "dream machine" for hydro test radiography and Russia is developing and publishing beautiful results from this radiographic capability.

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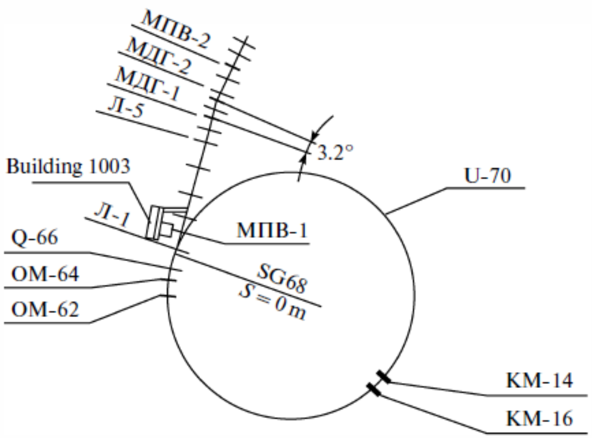
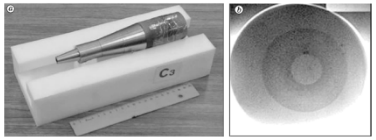


Fig. 1. Schematic diagram of the U-70 accelerator ring at the entrance into the injection line: (U-70) accelerator ring, (KM-14, KM-16) kicker magnets located in the straight gaps SG14 and SG16 of the accelerator, (OM-62, OM-64) extraction magnets located in the straight gaps SG62 and SG64 of the accelerator, (Q-66) lens for preliminary focusing of the proton beam in the SG66, (Л-1—Л-5) IL lenses, (МПВ-1, МПВ-2) bending vertical magnets, and (МДГ-1, МДГ-2) dispersion horizontal magnets; the IL input is in the SG68.



300 g/cm^2 test object.

NUCLEAR EXPERIMENTAL TECHNIQUES

A Radiographic Facility for the 70-GeV Proton Accelerator of the Institute for High Energy Physics

Yu. M. Antipov[a], A. G. Afonin[a], A. V. Vasilevskii[†a], I. A. Gusev[a], V. I. Demyanchuk[a], O. V. Zyat'kov[a], N. A. Ignashin[a], Yu. G. Karshev[†a], A. V. Larionov[a], A. V. Maksimov[a], A. A. Matyushin[a], A. V. Minchenko[a], M. S. Mikheev[a], V. A. Mirgorodskii[a], V. N. Peleshko[a], V. D. Rud'ko[a], V. I. Terekhov[a], N. E. Tyurin[a], Yu. S. Fedotov[a], Yu. A. Trutnev[b], V. V. Burtsev[b], A. A. Volkov[b], I. A. Ivanin[b], S. A. Kartanov[b], Yu. P. Kuropatkin[b], A. L. Mikhailov[b], K. L. Mikhailyukov[b], O. V. Oreshkov[b], A. V. Rudnev[b], G. M. Spirov[b], M. A. Syrunin[b], M. V. Tatsenko[b], I. A. Tkachenko[b], and I. V. Khramov[b]

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Received September 1, 2009

CONCLUSIONS

A unique proton radiography irradiation facility capable of forming images of samples with a diameter of 60 mm and an optical (mass) thickness of >300 g/cm^2 at an energy of 50 GeV has been developed by the IHEP with the use of the available infrastructure. The optical resolution of this facility is 0.25 mm. The ways for improving the parameters of the proton beam and the facility are currently being considered.

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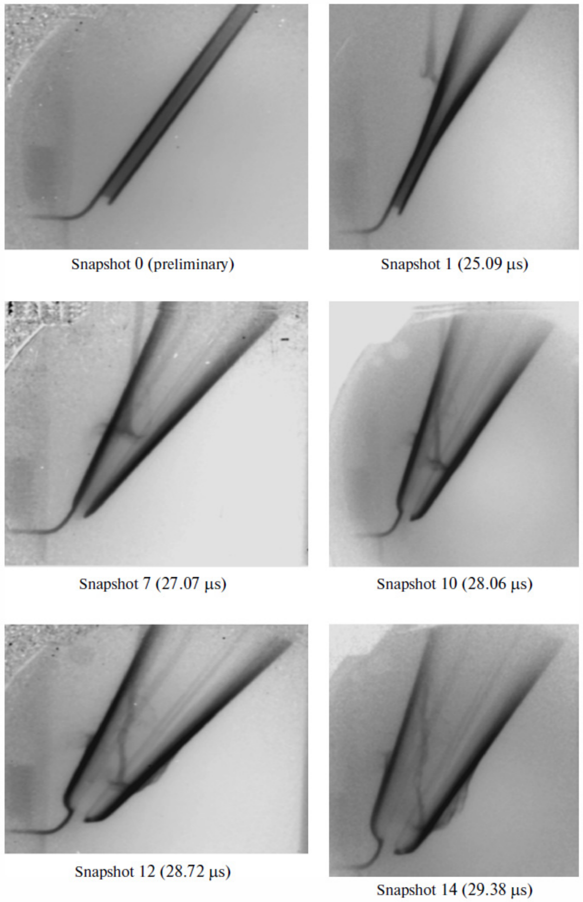
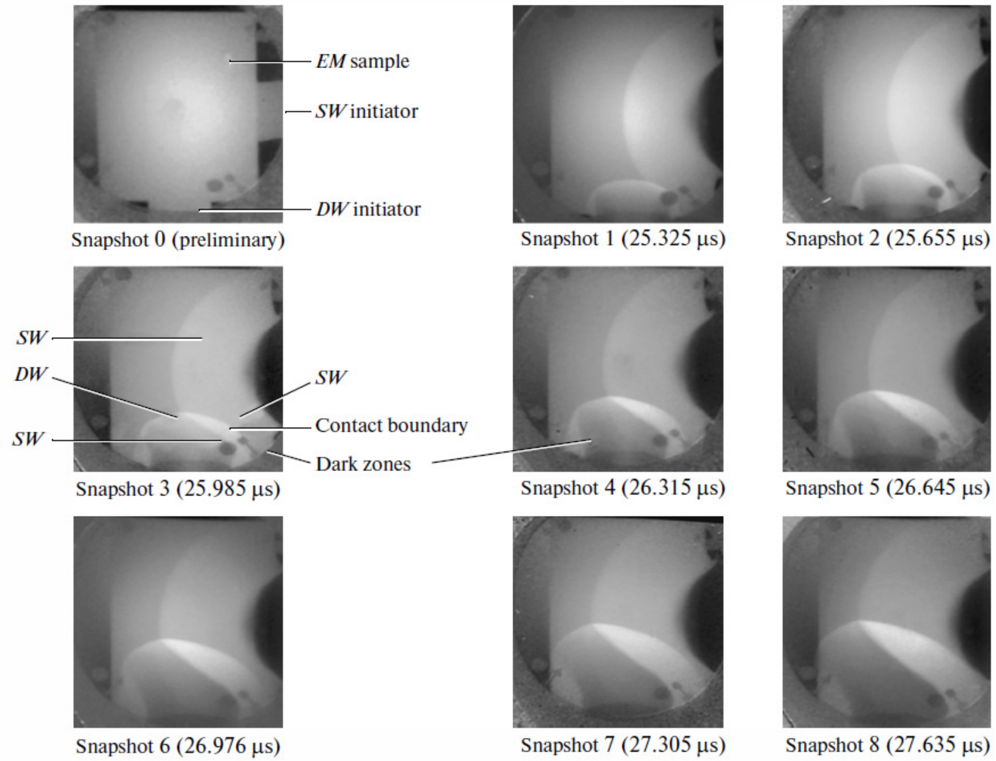
Recent publications of data collected from the Protvino facility show interesting results in armor studies and explosives science.





Yu. M. Antipov et al., "A radiographic facility for the 70 GeV proton accelerator of the institute for high energy physics", Nuclear Experimental Techniques, *2010, Vol. 53, No. 3, pp. 319–326*

China is designing a 20 GeV proton radiography system

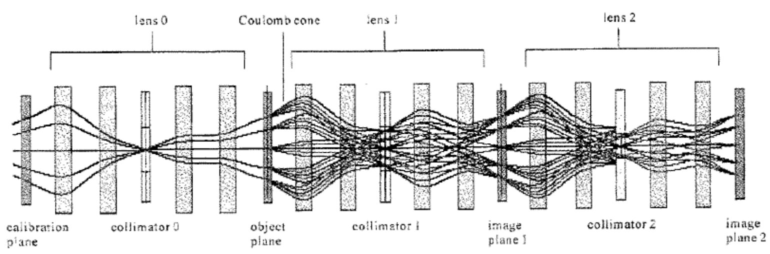


Fig. 1 Schematic of using magnetic lenses to image the protons in proton radiography

图 1 LANL 质子照相磁透镜成像示意图

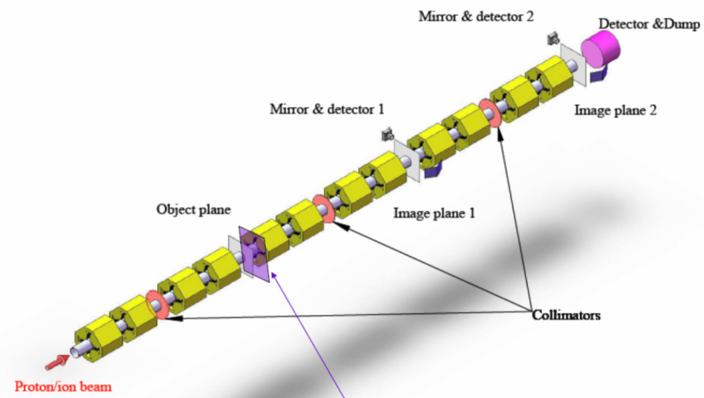
律也可用(1)式表示，其中的 N_0，N 分别为入射到被测物体上的质子通量和穿过被测物体的质子通量。质子在第 i 种材料内的平均自由程可表示为

$$\lambda_i = \frac{1}{n_i\sigma_i} \approx \frac{A^{1/3}}{0.032} \quad (\mathrm{g/cm^2}) \tag{2}$$

式中：A 为原子量；n_i 为原子数密度；σ_i 为核反应截面，$\sigma_i=\pi r_i^2$，$r_i\approx 1.3\times 10^{-13}A^{1/3}$ cm。

质子与原子核的库仑力作用发生多库仑散射，使得质子方向发生小的变化。多次散射可以近似用高斯分布表示

Proton or Ion Radiography (PIRG) at Lanzhou



Totally 25m in length; first try putting Image Plane just behind the Object.

A lattice scenario for a proton radiography accelerator

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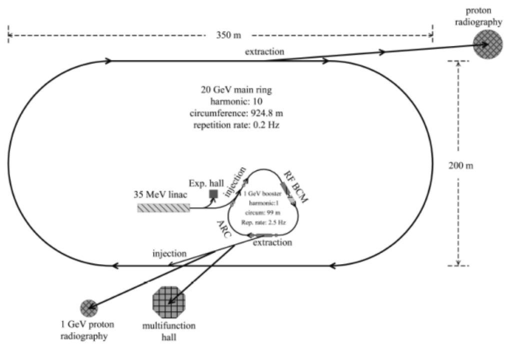
ZHANG Zhuo(张卓) WANG Shao-Heng(王少恒) YANG Zhen(杨振) LI Wei-Feng(李伟峰)
LI Hong(李洪) YANG Xing-Lin(杨兴林) WANG Min-Hong(王敏洪) SHI Jin-Shui(石金水)
ZHANG Kai-Zhi(张开志) DENG Jian-Jun(邓建军) ZHANG Lin-Wen(章林文)

Chinese Academy of Engineering Physics, Mianyang 621900, China

Abstract A proton radiography system is an accelerator-based facility. Especially high-energy proton radiography is an advanced hydrodynamics diagnostic tool, and it is the trend of radiography technology development. In this paper, a 20 GeV accelerator complex scenario, including a 35 MeV linac, a 1 GeV booster and a 20 GeV main ring, is introduced. The overall physics design of the proton radiography accelerator is described, including the design of each part of the accelerator and the choice of the main parameters.

Key words proton radiography, accelerator, lattice



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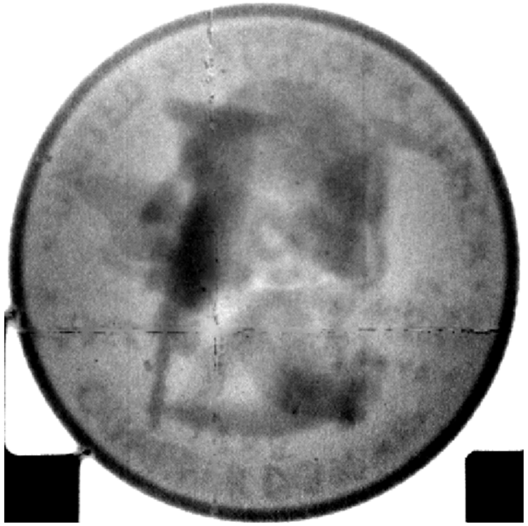
Both collaboration and competition are often good…

Heavy ion radiograph of a Russian 10 Kopek coin Collected at ITEP in Moscow.

Proton radiograph of a US quarter collected at LANSCE.



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Slide 27

The third High Energy Proton Microscopy workshop was held in October 2011, bringing this community together to identify exciting new capabilities and science opportunities.

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LA-UR-11-06791

2011 High-Energy-Proton Microscopy Workshop Summary Report
Los Alamos National Laboratory, October 27–28, 2011

Organizers and Theme Leads: *Cris W. Barnes, Frank Merrill, Kurt Schoenberg, Chris Morris, Markus Roth, David Teter, Dmitry Varentsov*

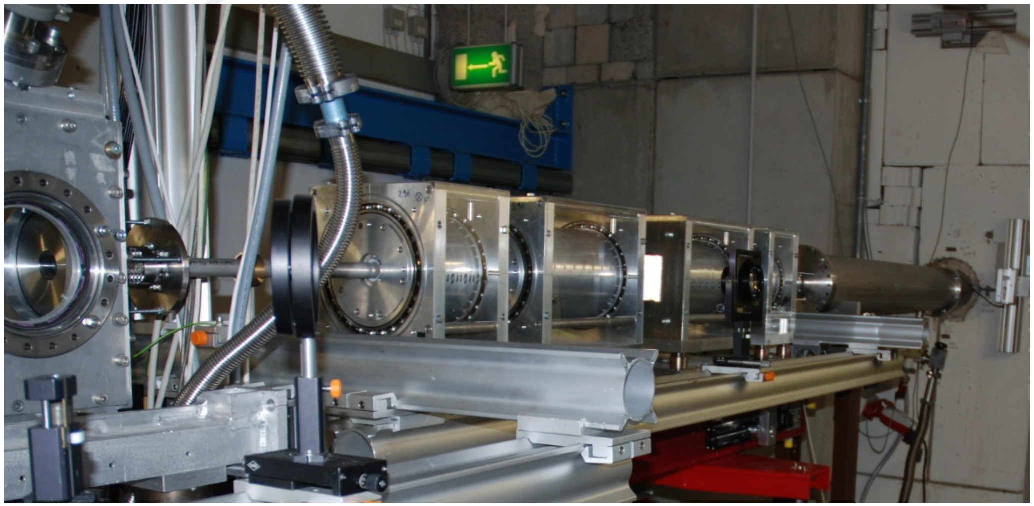
Overview

An international panel of collaborators met and discussed the topic of High Energy Proton Microscopy, its current status, technical specifications, the enablement of scientific experiments and future advances for the optimization of proton microscopy systems. This workshop[1] focused on defining a class of material science experiments that can effectively utilize high-resolution proton microscopy to achieve new scientific discoveries. Some of these experiments could be fielded at GSI in Darmstadt using the PRIOR microscope and some at the facilities of collaborators such as pRad and LANSCE at Los Alamos or at ITEP in Moscow.

The workshop was run to allow a flexible environment and encourage the discussion that occurred. The presentation set provides an excellent stocktake on pRad operations and operational issues and the current science being done.[2] It also identified future exciting directions such as dynamic materials processing and synthesis, simultaneous hadron therapy and radiography in medical applications, and the kinetics of phase transformations.

Three High Energy Proton Microscopy workshops are helping to define the development priorities and the scientific opportunities for higher energy proton microscopy around the world.

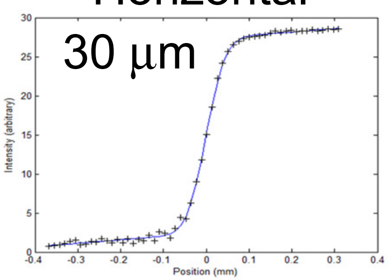
PRIOR Magnifier has been commissioned at GSI



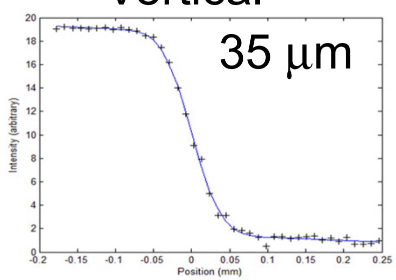
A German, US and Russian system has been installed and commissioned at GSI

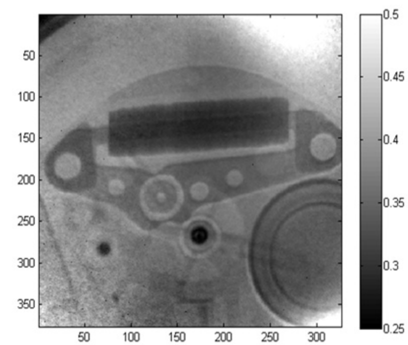
<u>Resolution</u>

Horizontal



Vertical



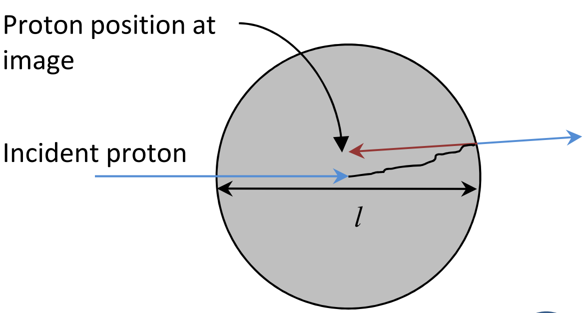


Resolution of Proton Radiography

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.

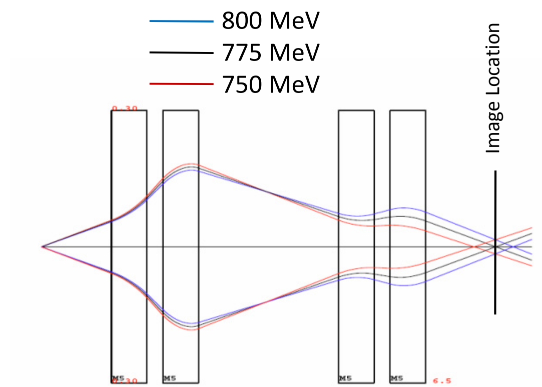
Assume detector development can keep up

Object Scattering



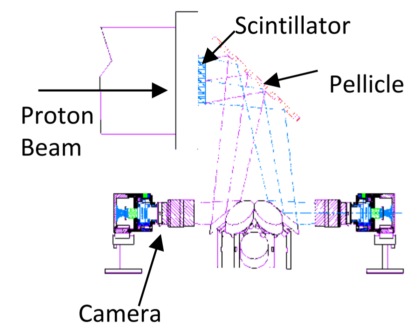
$$\sigma_o = \frac{1}{\sqrt{3}}\theta\frac{l}{2} = \frac{14.1}{\sqrt{6}}\frac{1}{P\beta}\sqrt{\frac{l^3}{x_o}} \propto \frac{l^{3/2}}{P}$$

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



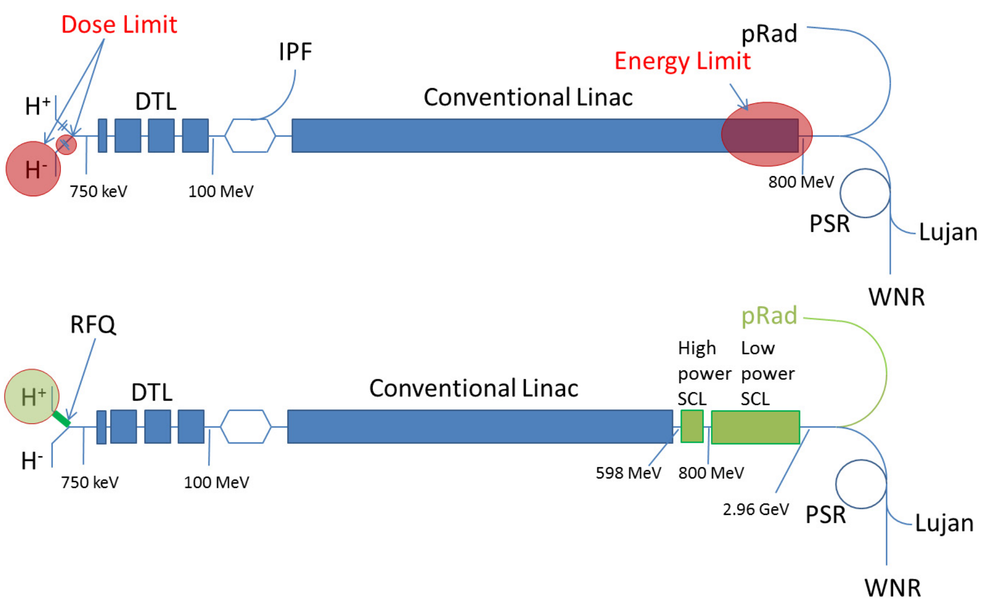
Scintillator

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

Camera

Resolution is independent of proton energy

A future upgrade to proton radiography would provide significant capability enhancements.



Replacing copper accelerating structures with superconducting structures increases the accelerating gradient by a factor of ~20, allowing higher energies to be achieved in the same real estate.

Replacing the Cockcroft-Walton injector with an RFQ provides a factor of ~3 increase in dose (protons/pulse)

Additional beam line magnets can transport the beam in existing tunnels

An imaging lens optimized for 3 GeV provides improved radiographic performance.

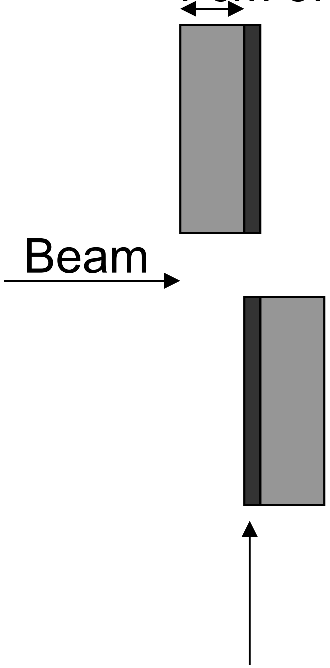
Conclusions

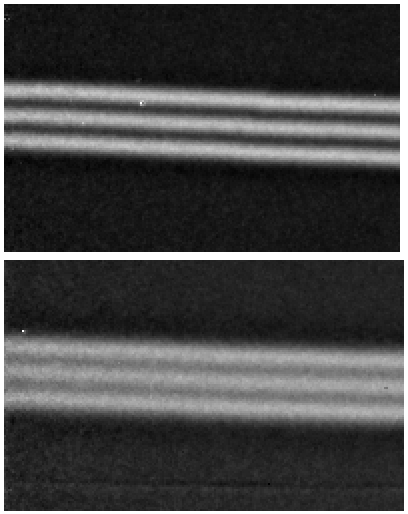
- 800 MeV proton radiography continues to provide new information to measure properties of dynamic materials.
- The temporal structure available from a linear accelerator provides unique opportunities in quasi-static measurements.
- The technique is being applied to a wide range of applications around the world.
- We have proposed a 3 GeV energy upgrade at LANSCE to enhance capabilities in diagnosing systems with improved resolution.
- Research will continue in improvements via achromats.

Object scattering blur is a fundamental resolution limitation

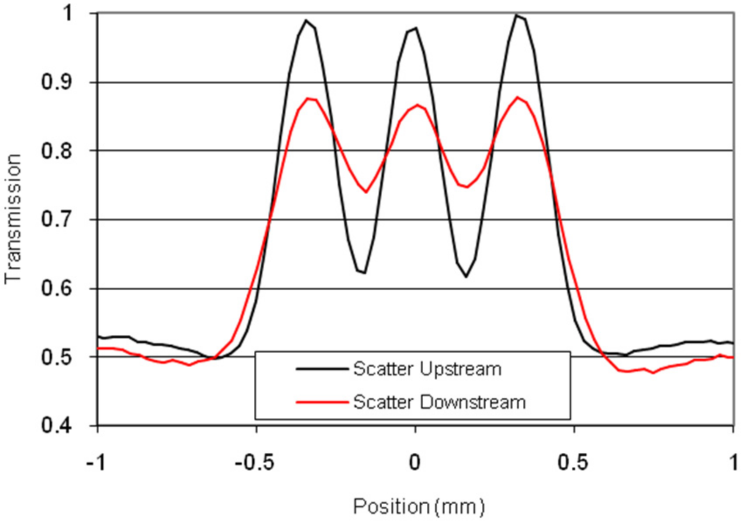
2.5 lp/mm

Sigma=0.061 mm





Sigma=0.150 mm



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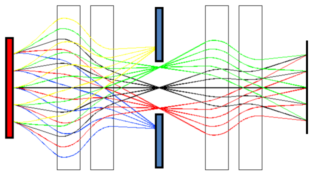
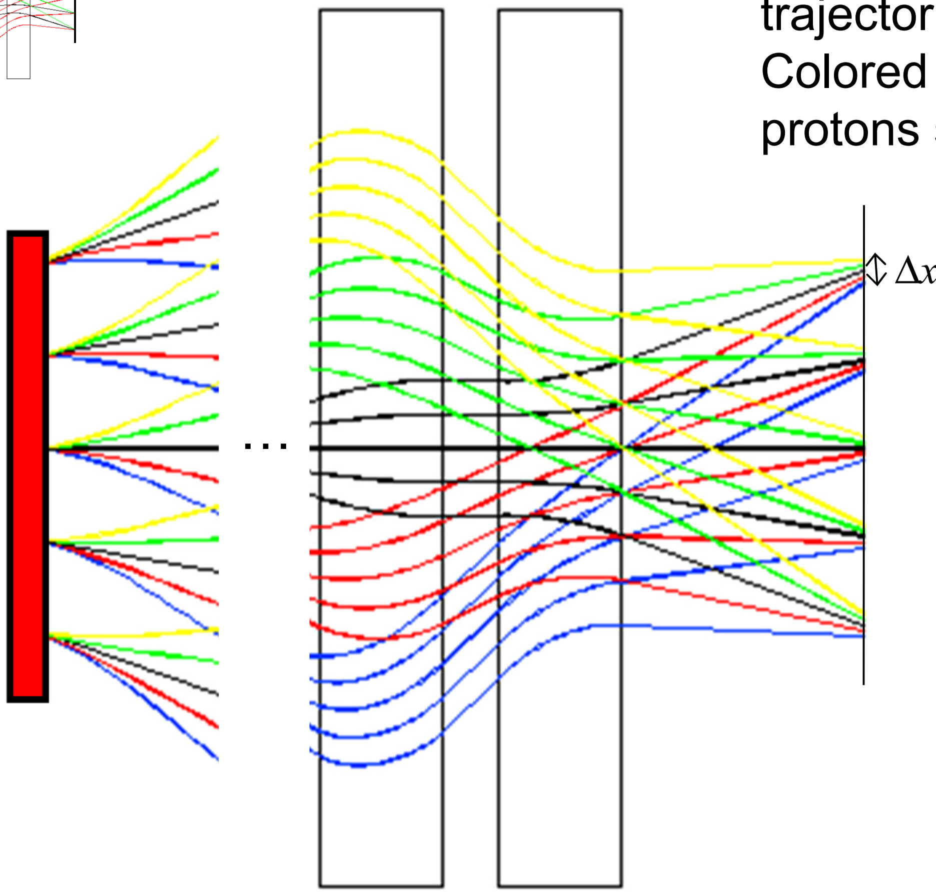
UNCLASSIFIED

We have been working to minimize the effects of chromatic aberrations





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

Resolution

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

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