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Title: Industrial applications of high energy proton microscopy

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Form 836 (7/06)

Industrial Applications of High Energy Proton Radiography

Fesseha G. Mariam

Abstract

Proton radiography has been used at Los Alamos to study dynamic processes requiring time resolutions of order of nanoseconds to microseconds. In the past few years we have also devoted some time to exploring the use of proton radiography for the study of slow or static phenomena, some with industrial applications. This presentation explores industrial uses of proton radiography at even higher energy.

Industrial Applications of High Energy Proton Radiography

Fesseha G. Mariam
(for the LANL PRAD Team)

Presented at the High Energy Proton Microscopy Workshop, Darmstadt, Germany
(August 24 to 25, 2009)

Common Radiographic Tools

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

X-Rays

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

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

Neutrons

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

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

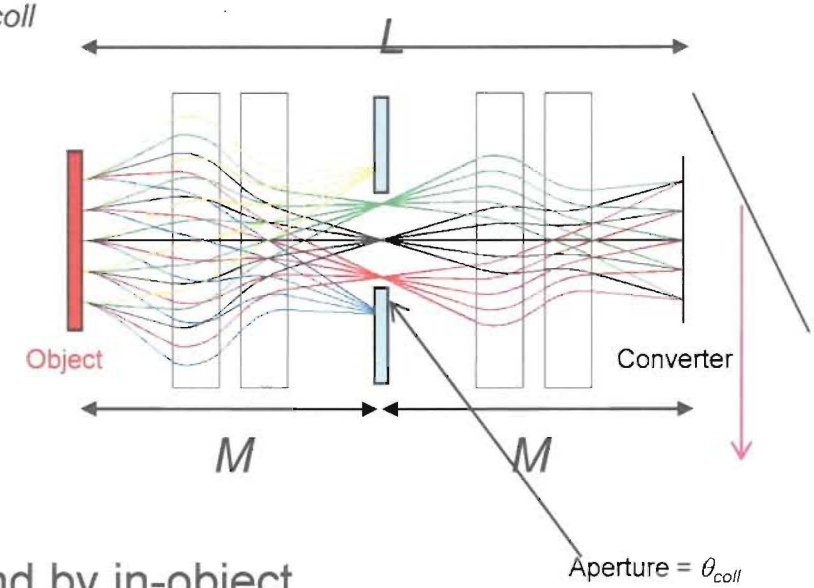
$\lambda_{Nuclear}$ is greater than X_0 for all elements Z>6
In addition to attenuation, both X-rays and neutrons scatter and loss energy. The scattering can result in poor resolution unless the image sensor or converter is close to the object.

Proton Radiography (pRad) - Matched Lens (Mid 1990's)

For protons of momentum p [MeV/c] and velocity $\beta = v/c$ through an imaging lens with aperture θ_{coll}

$$T_{PRAD}(X) = e^{-\frac{X}{\lambda_{Nuclear}}\left(1 - e^{-\frac{\theta_{Coll}^2 X_0}{2\alpha^2 X}}\right)}$$

$$\alpha = \frac{14.1}{p\beta}$$



Resolution is limited mainly by chromatic blur and by in-object scattering both of which diminish with increasing proton energy

For protons in the GeV range and above, the object to image (or converter) distance L is typically ~10 meters or higher.

Optimizing the Radiography

- Maximize resolution

$$\delta x = T_{126} \vartheta_{Coll} \frac{\delta E}{E}$$

- Maximize contrast to enhance density reconstruction

$$C(X, \vartheta_{Coll}) = \frac{\partial Trans(X, \vartheta_{Coll})}{\partial X} \frac{\delta X}{Trans(X, \vartheta_{Coll})} = g(X, \vartheta_{Coll}) \delta X$$

- Minimize statistical error

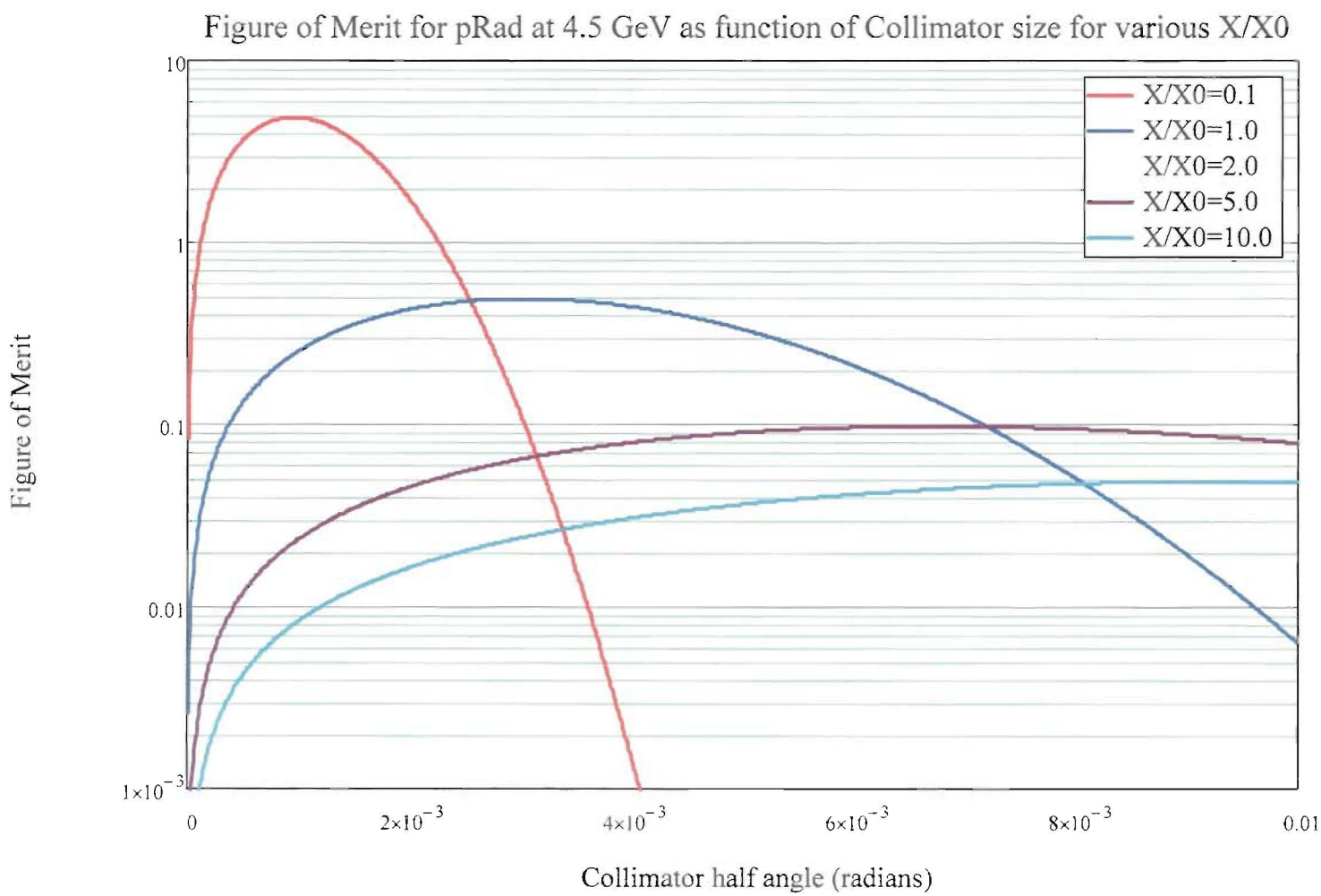
$$\frac{1}{\sqrt{Trans(X, \vartheta_{Coll})}}$$

- Figure of Merit

$$Q(X, \vartheta_{Coll}) = g(X, \vartheta_{Coll}) \sqrt{Trans(X, \vartheta_{Coll}}$$

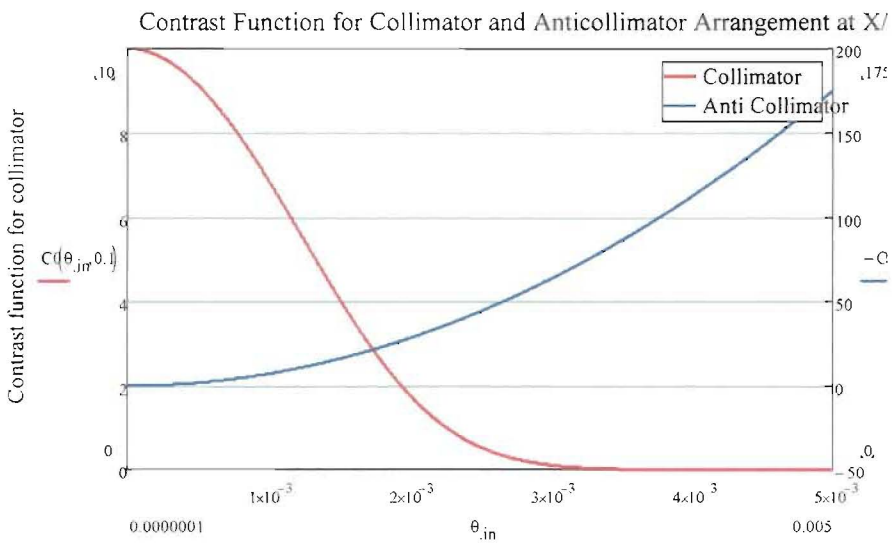
One can optimize the figure of merit for density reconstructions by choosing the right collimator for the right object thickness

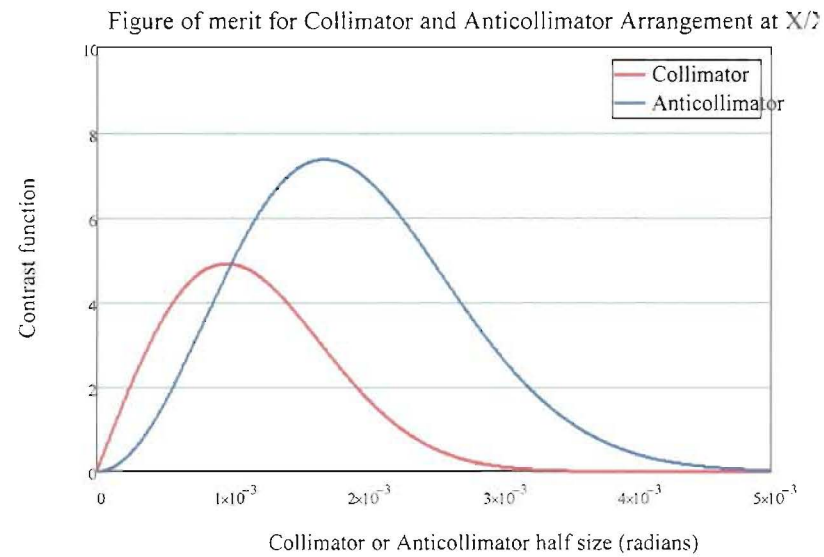
4.5 Gev pRad Density Reconstruction Figure of Merit

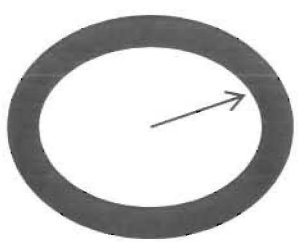


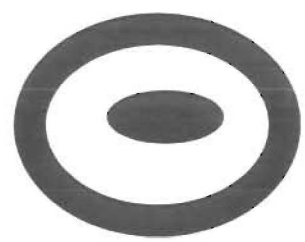
Anticollimator for Contrast Enhancement

For thin objects with small area density variations such as gas targets the contrast can be enhanced by using anticollimators instead of collimators









Typical Uses of pRad

pRad is especially well suited for:

a) where radiographic requirements are such that the object to converter (detector) distance is large such as the radiography of radioactive samples

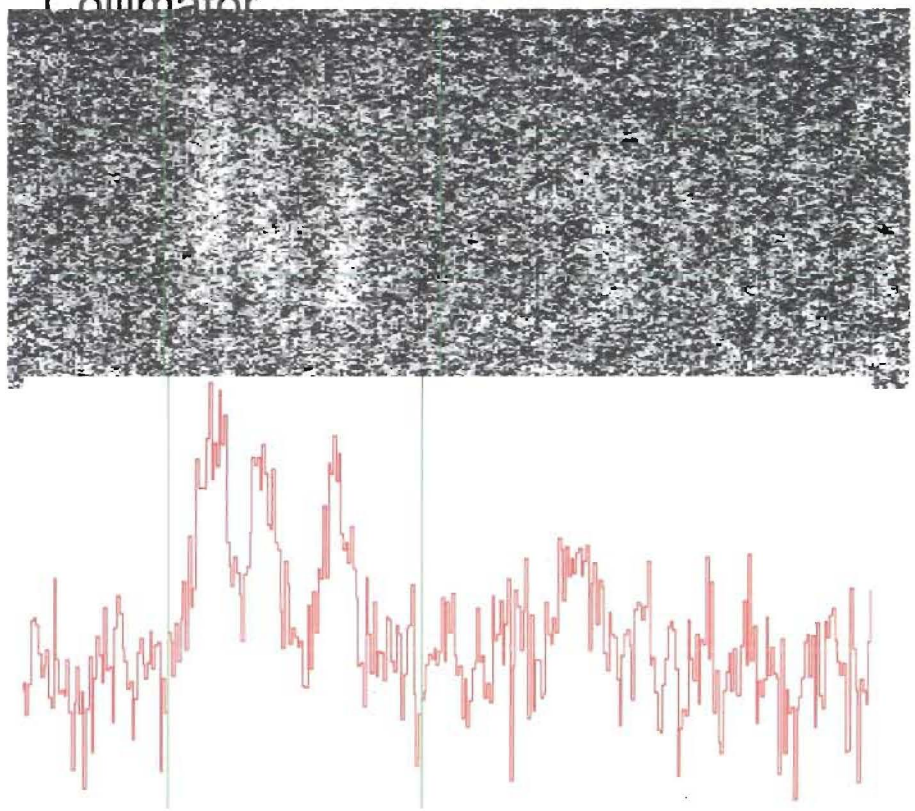
b) Multi frame imaging of fast (10^{-3} to 10^{-6} s) dynamic processes.

Fuel Cells:

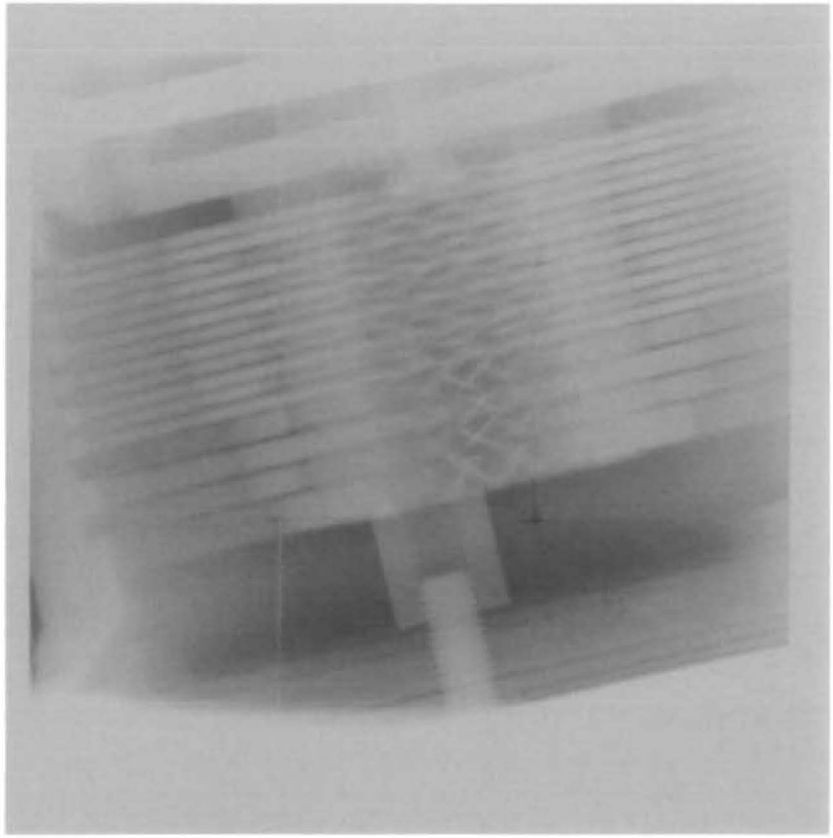
The rate of reaction needs to be optimized by adjusting the ratio of the fuel (hydrogen) to the oxidant . This is observed by monitoring the rate of water formation in the channels.

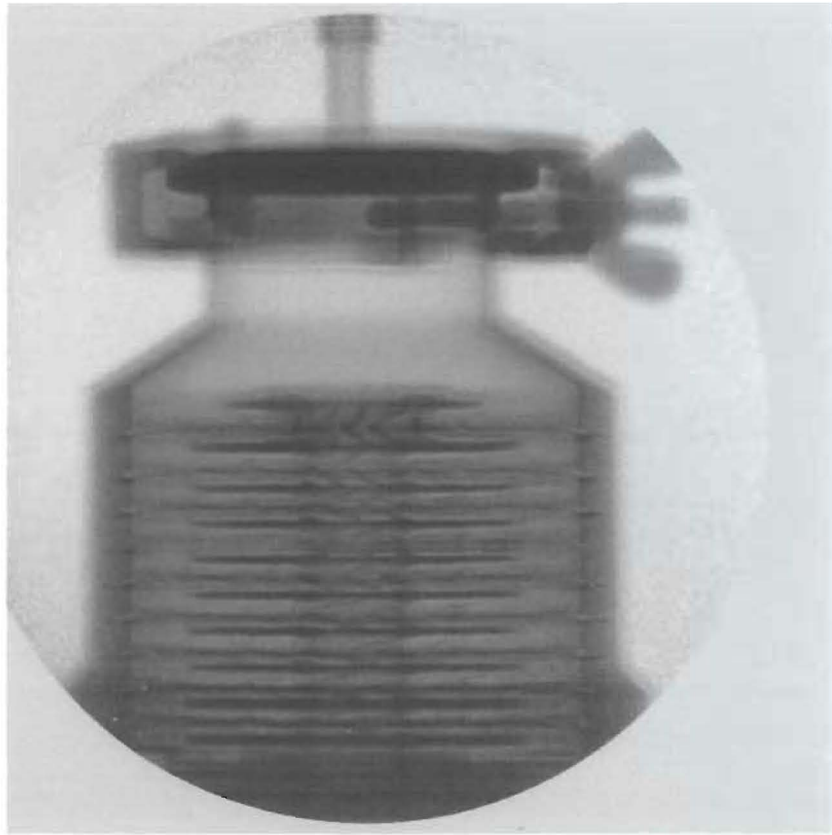
Radiograph using the LANSCE –I lens with a 5 mradianFerm Collimator

Two grooved graphite discs separated by polymer electrolyte membrane (PEM)



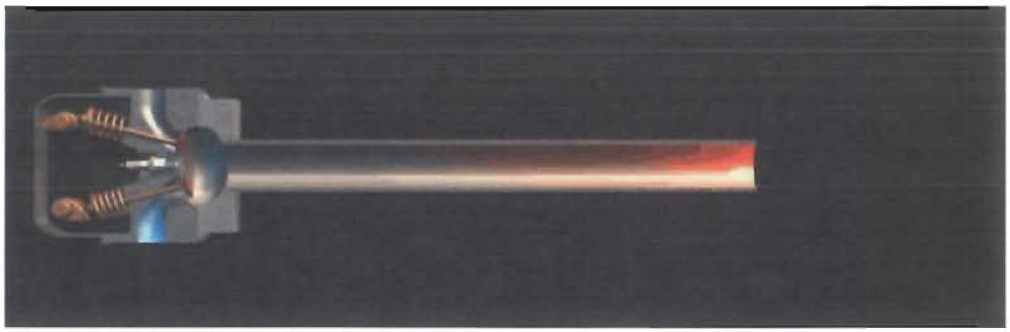
P-Rad of Turbo Pump at 7.5 and 1.46 GeV/c





Multi-frame radiograph can be used to measure the blade deflections at various rotational speeds and under various loads

Pulse Detonation Engine – Next Technological Revolution in Airplane Engines



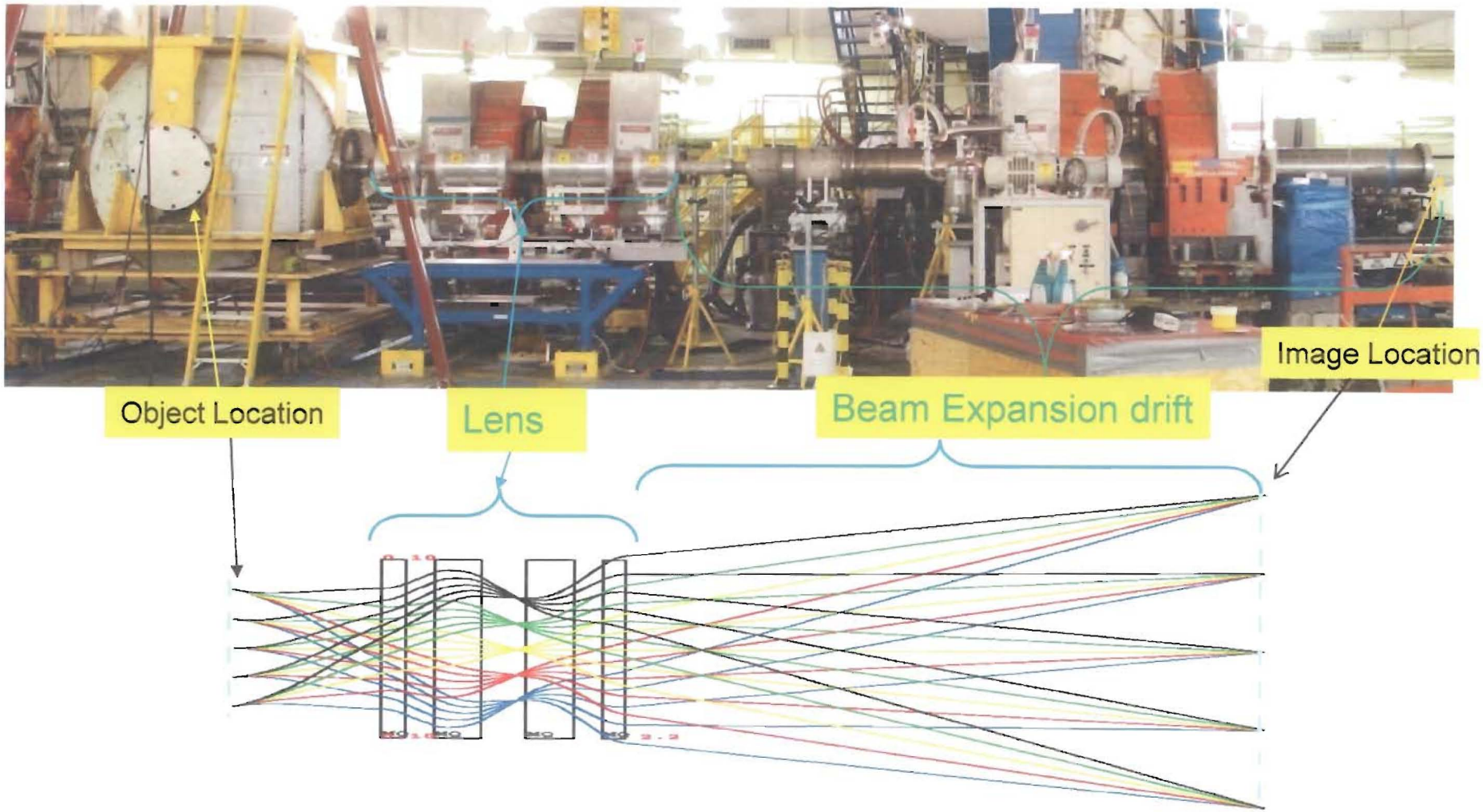
Courtsey of Dr. Fred Schauer
Head,
Air Force Research Laboratory
Wright-Patterson AFB

Cycle

- **Intake valve - premixed fuel & air (green)**
- **Detonation and blow down (red/orange)**
- **Exhaust valve – purge cycle (blue)**

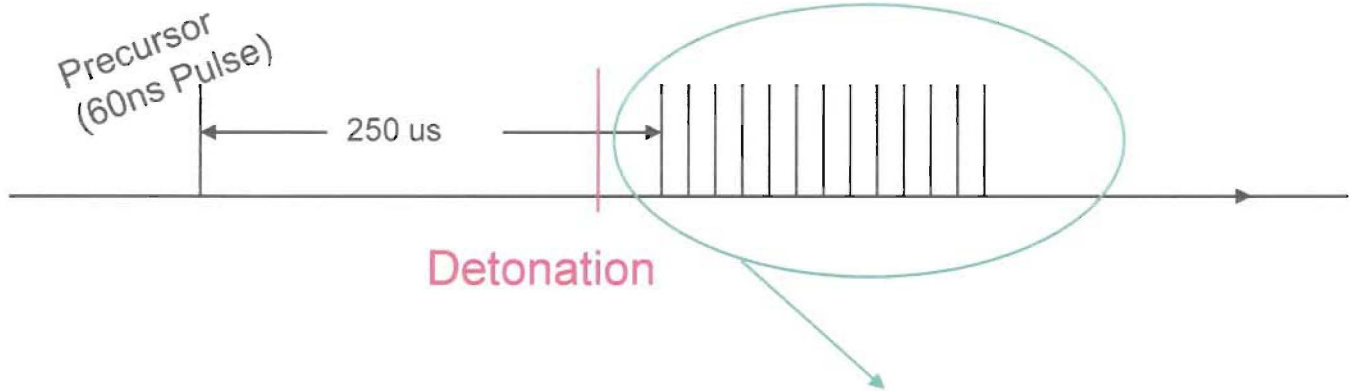
Motivation: Develop airplane engines with much fewer moving parts such as compressors and turbines in present-day jet engines.
There is great need in validating computed fluid dynamics that is employed in this technological research.
-Deflagration to detonation transition regions have very small dx, and the flash radiography problem is hard.

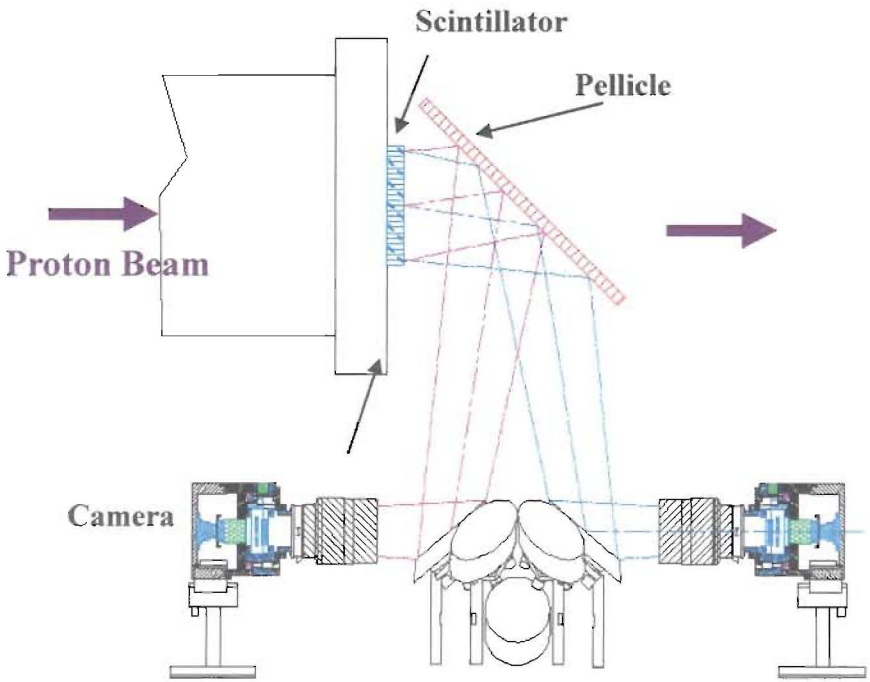
x3 Magnifier (PMQs)

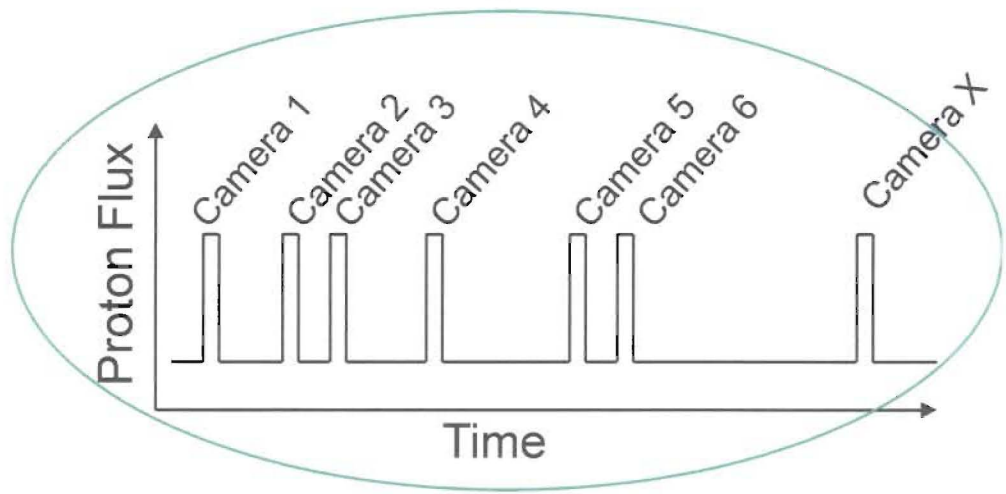


Made up of four 4" bore permanent magnet quads.

Camera System and Standard Timing

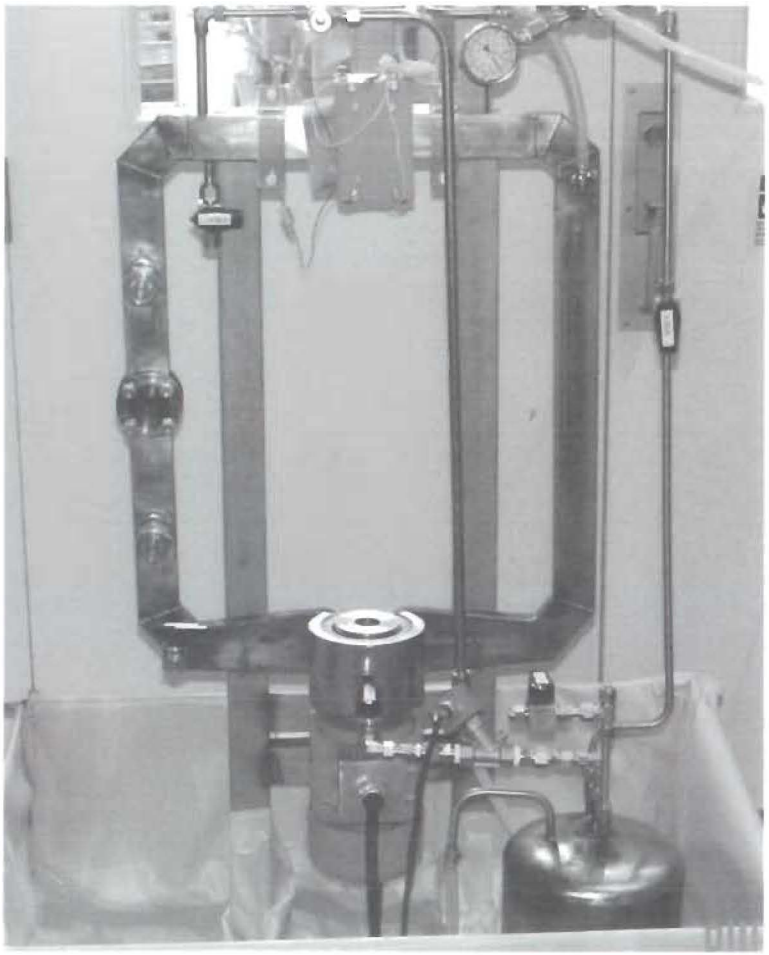






- 19 images at first station (IL1)
- 22 images at second station (IL2)
- Typically 50 to 200 ns exposure times

PRAD in support of SNS Hg Target Development

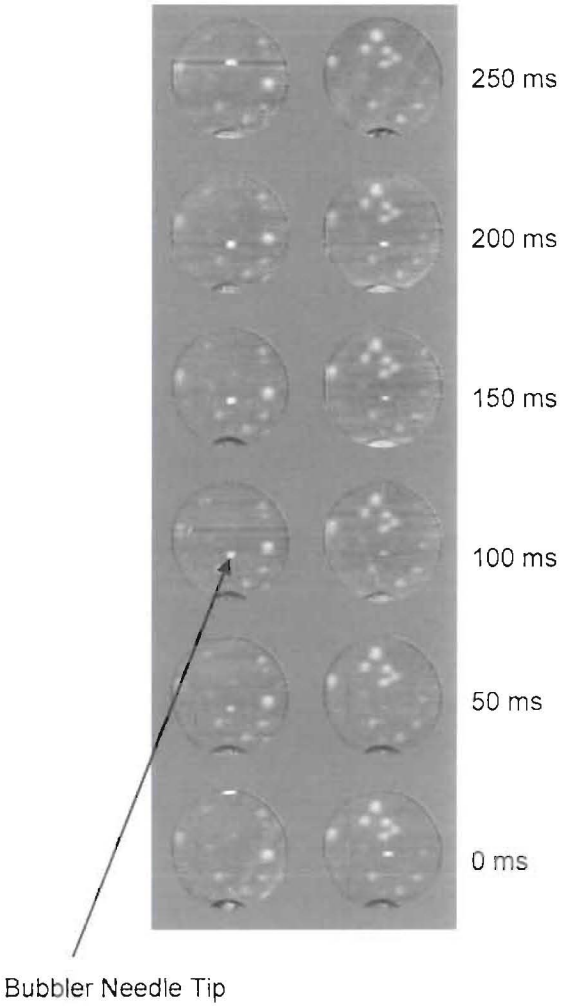


SNS uses a self cooling Hg target for spallation neutron source. Concern is (was): high peak and short proton pulses induce cavitations in the Hg and set up a strain wave resulting in high velocity jets of liquid Hg that pits the target windows reducing the life time of the windows. The proposed solution was to introduce small helium bubbles to scatter the strain waves and reduce their impact on window degradation. They performed several experiments at the LANCE WNR line, but did not have any idea of the He/Hg ratio as well as the distribution of bubble sizes. Hence the use of PRAD to determine these important parameters.

SETUP: 6" Hg, with different Hg flows and He bubbler configurations. Use the x3 magnifier to image He bubbles in Hg and observe their formation, migtration and size distribution

- This is a quasi static study of slow phenomena. One set up was in movie mode at 20Hz

Quasi Static Systems (msec to seconds): Dynamic studies of He Bubble formation in Hg in Support of the SNS High Current Target Development



He bubble formation in stagnant (left) and flowing (right) mercury.

In the case of the stagnant Hg, the bubbles form, grow in size and break off in about ¼ sec. When the Hg is flowing, the bubbles break off at much faster time scales.

Thousands of such pictures were taken with the Rockwell cameras in movie mode at 20Hz under various He and Hg flow rates.

Static Objects Surrogate Fuel Rods

X3 magnifier has T126 ~ 3 meters

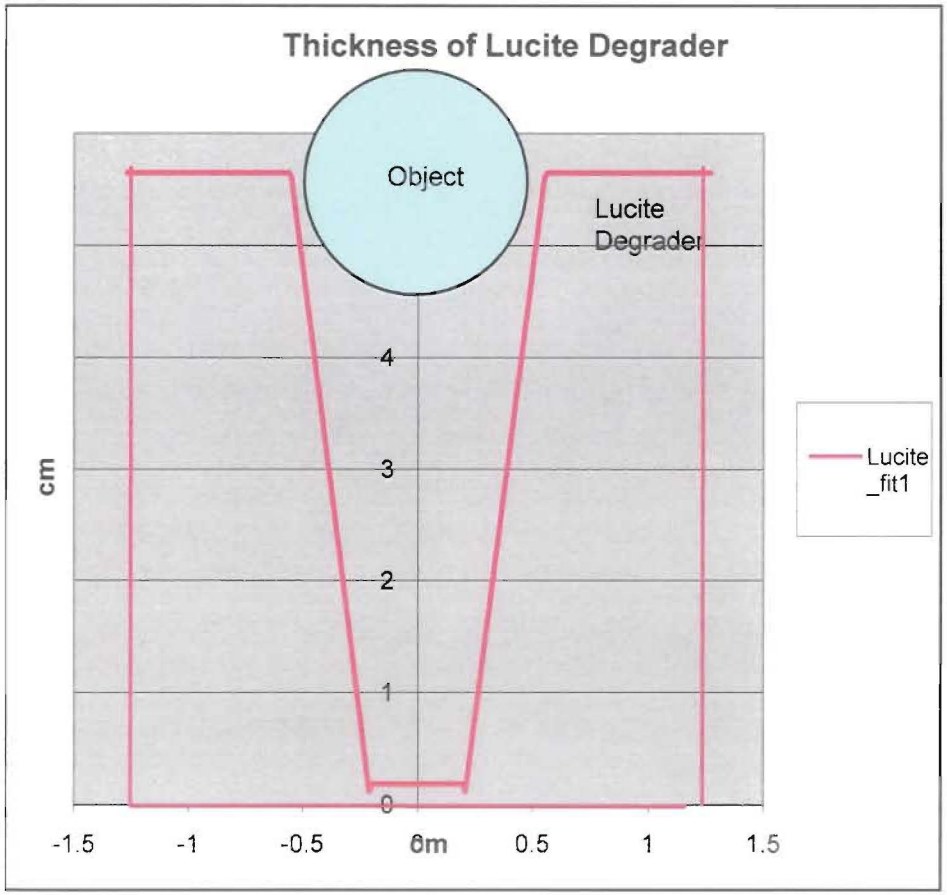
E-Loss through object center ~ 13 MeV ➔resolution ~ 0.5mm at center

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

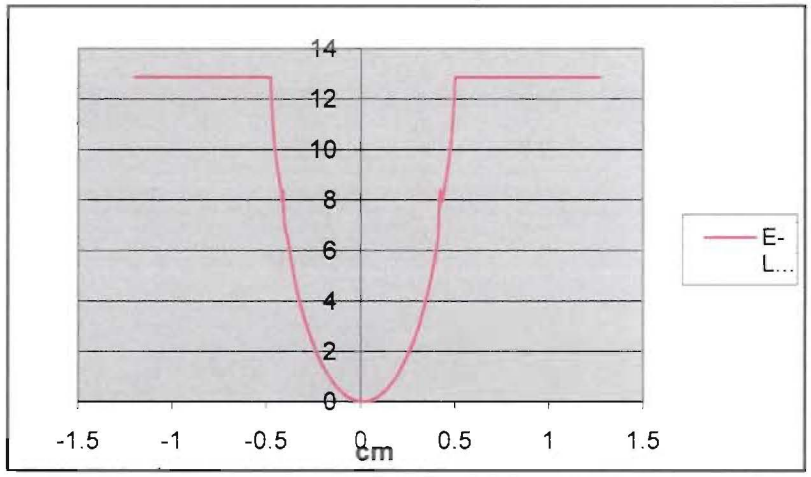
For Static Objects One can reduce chromatic blur by use of "Graded Degraders"

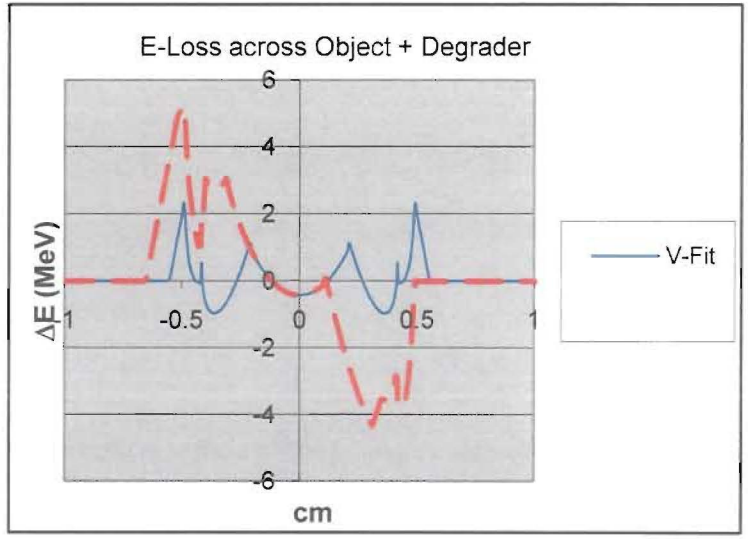
Mitigating Chromatic Blure: E-Loss Flattening Scheme

Chromatic term (T126) = 3m*δθ*(dE/E)

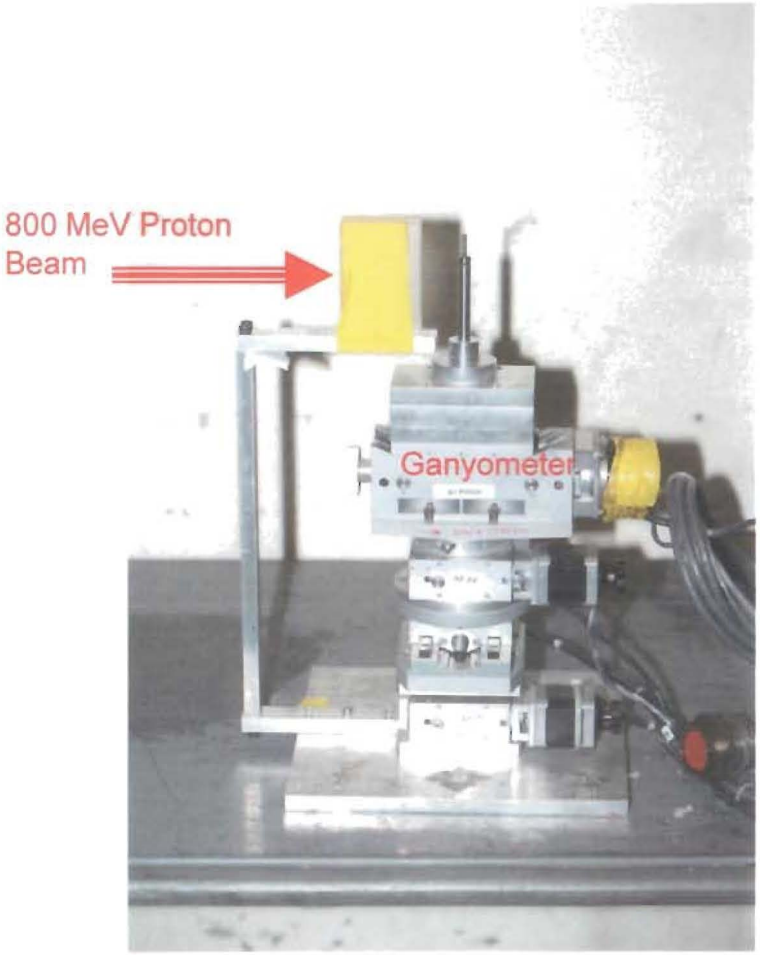


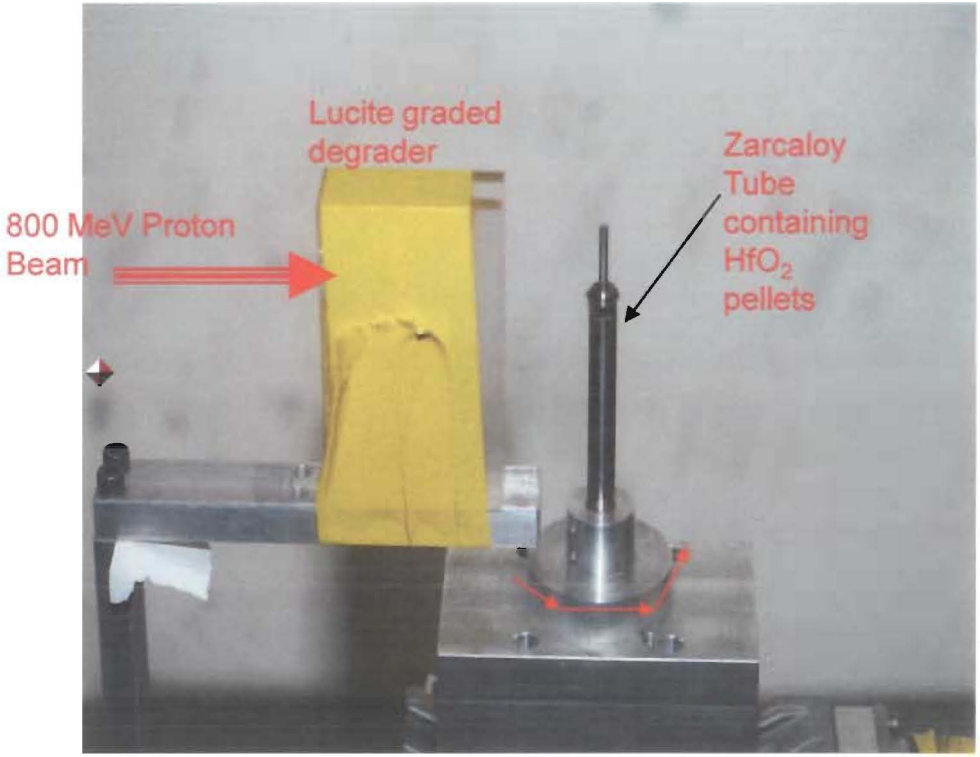
E-Loss across Bare Object





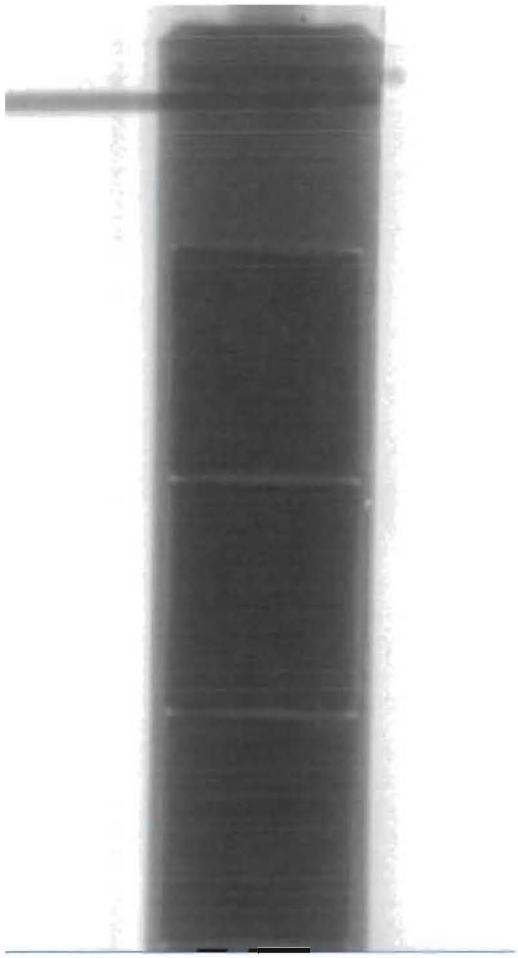
The Set up





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

Transmission Image to Areal Density Transformation



Transmission Image, T(X)

Transmission T,

$$T(X) = e^{-\frac{X}{\lambda}}\left(1 - e^{-\frac{\theta_{Coll}^2 X_0}{2\alpha^2 X}}\right)$$

α is a kinematic factor given by $\alpha = \frac{14.1}{p\beta}$

p = beam momentum [MeV/c]

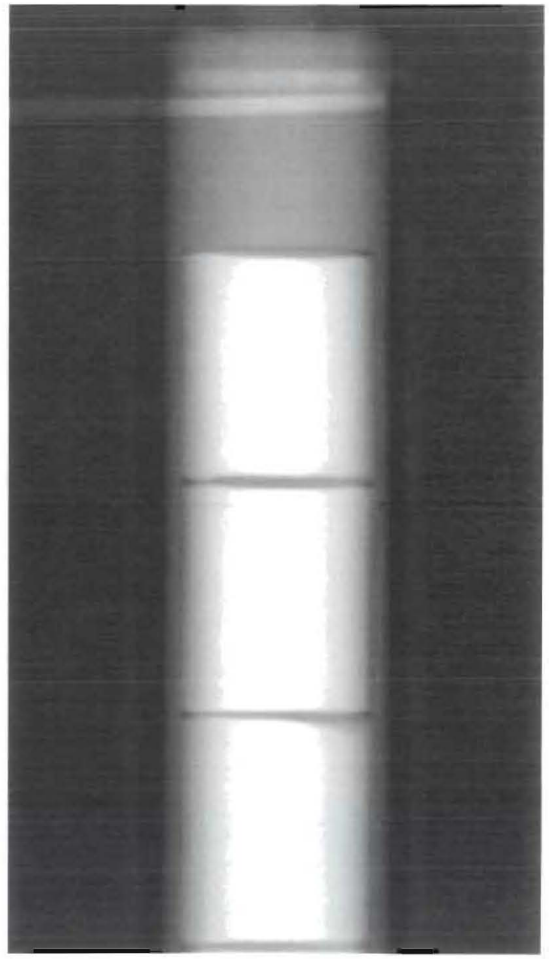
X = Areal density

λ=Nuc. Interaction Length

X_0 = Radiation Length

θ_{coll} = Collimator size

Pixel by pixel inversion of the transmission equation



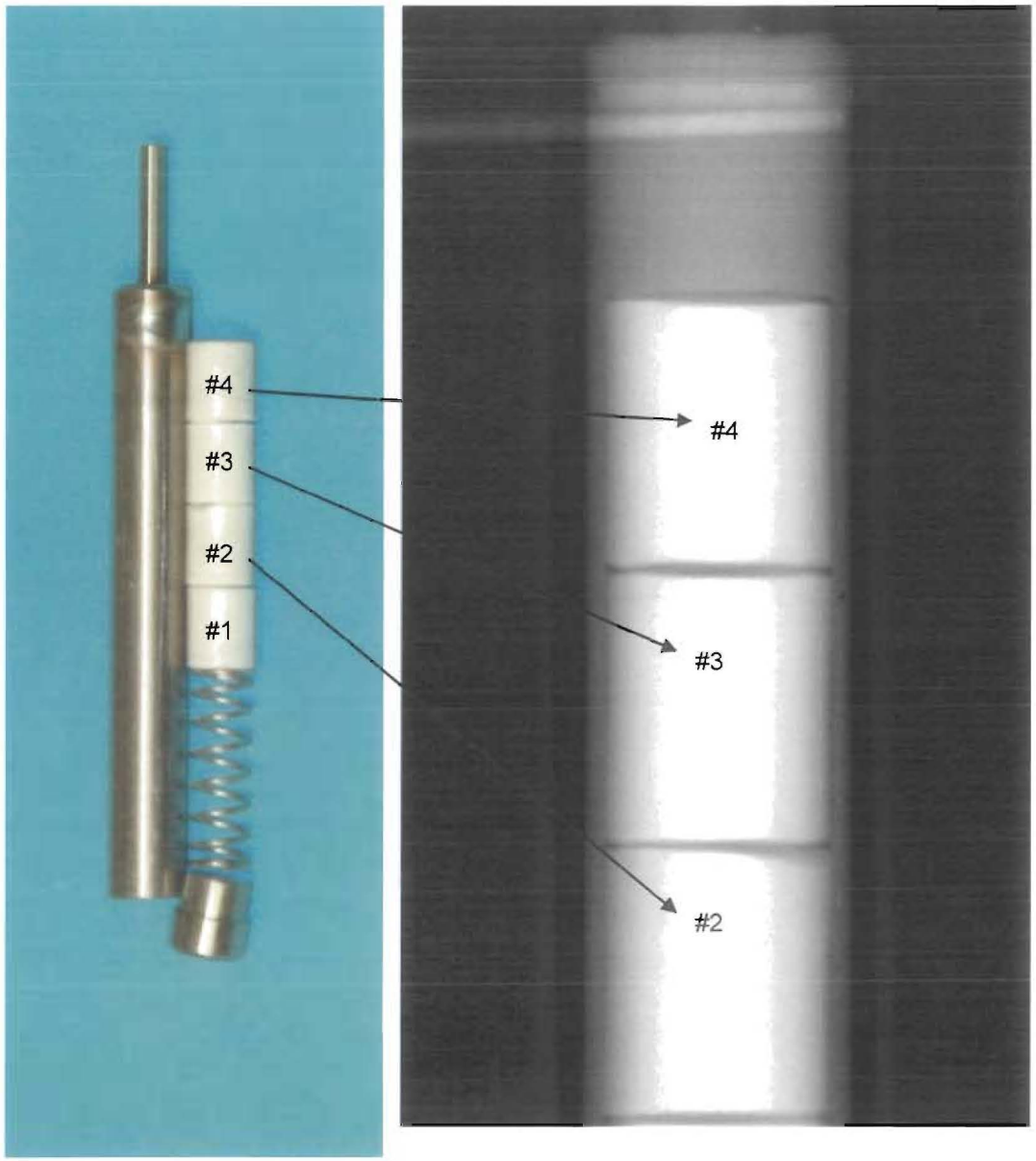
Areal density Image, X(T)

Nuclear Fuel Cells

Neutron Radiography of a hot fuel rod

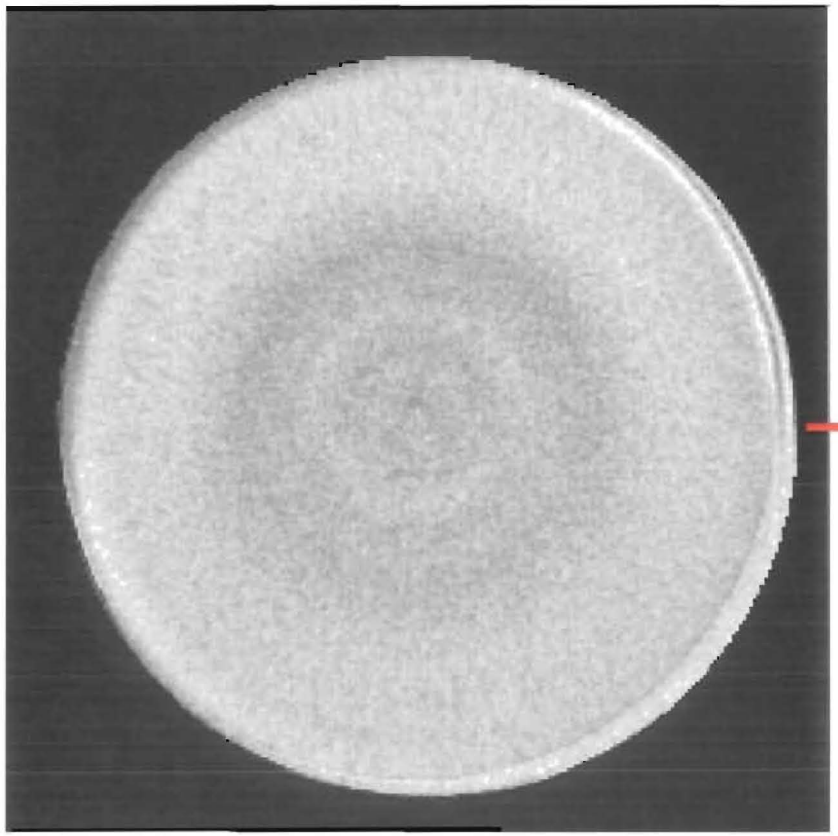
Neutron Radiography of a hot fuel rod from Eberhard Lehmann, et al, NIM A 531, (2004), 228-237 SINQ

Areal Density

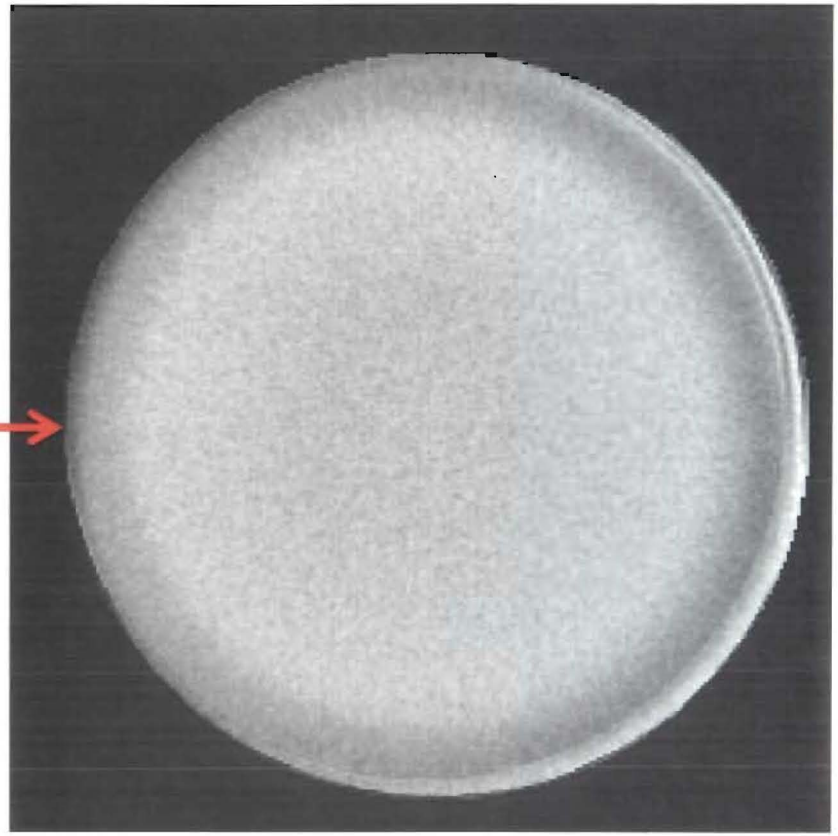


CT Reconstrusction: Minimize ring artifacts by assuming that the zarcaloy portion of the images is homogeneous and therefore has no ring structure in the density

Dafault ring removal parameter

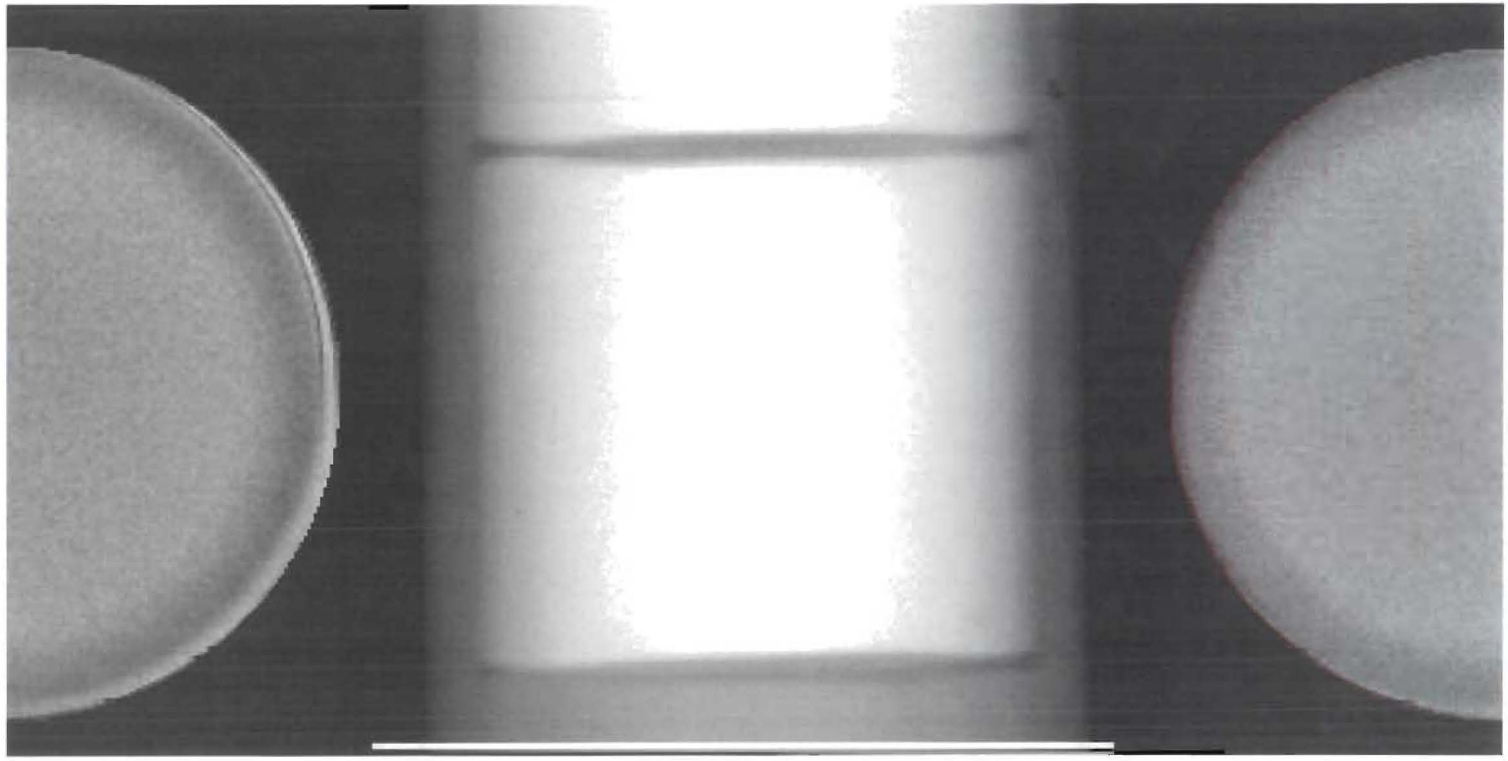


Increased ring removal parameter



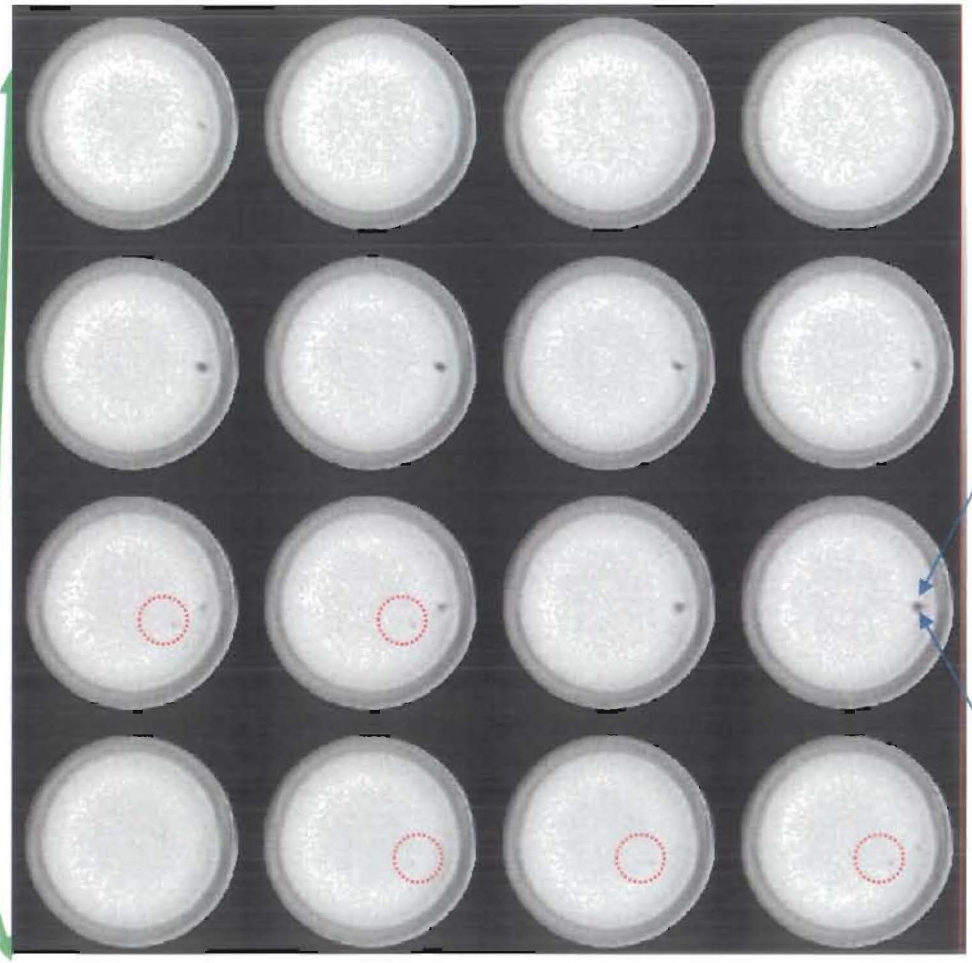
CT Reconstructed Slices:

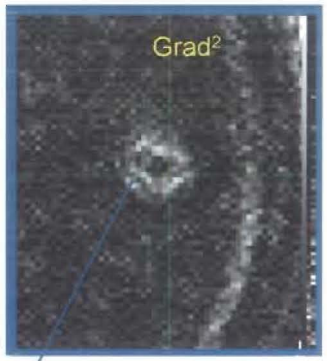
Interesting Regions: Part of Zarcaloy portion, all of Pellet#4, Part of Pellet#3

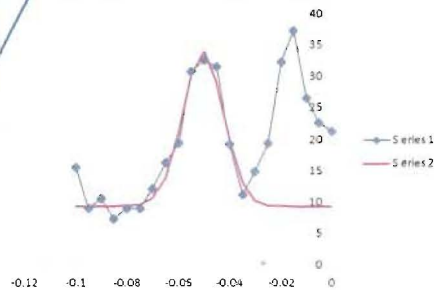


Filtered Back Projection:

Defects in Pellet #4, Slices 78 to 93



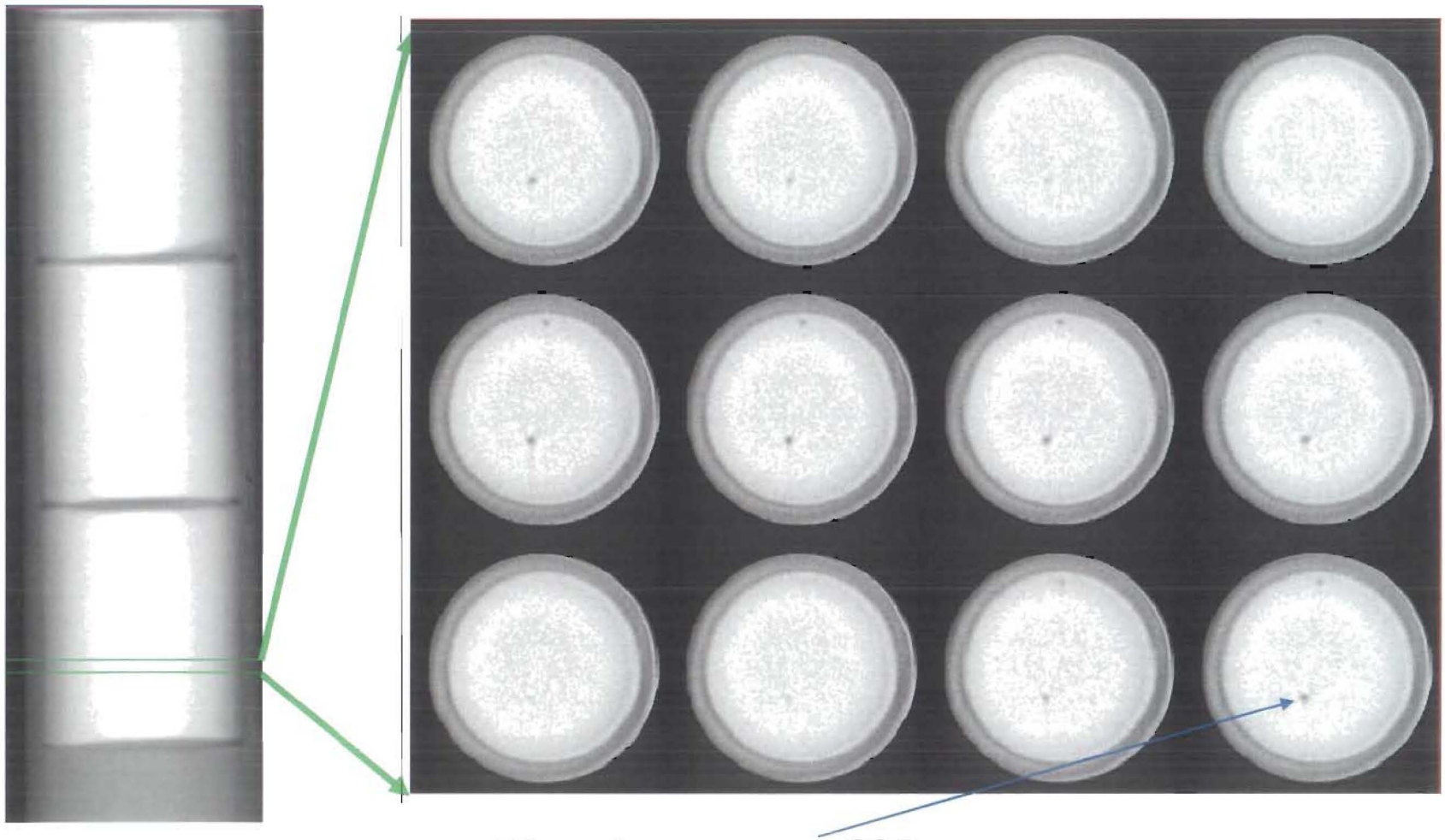




Resolution	~ 80 μm
$\text{Diameter}_{\text{Inclusion}}$	~ 350 μm
$\text{Length}_{\text{Inclusion}}$	~ 550 μm

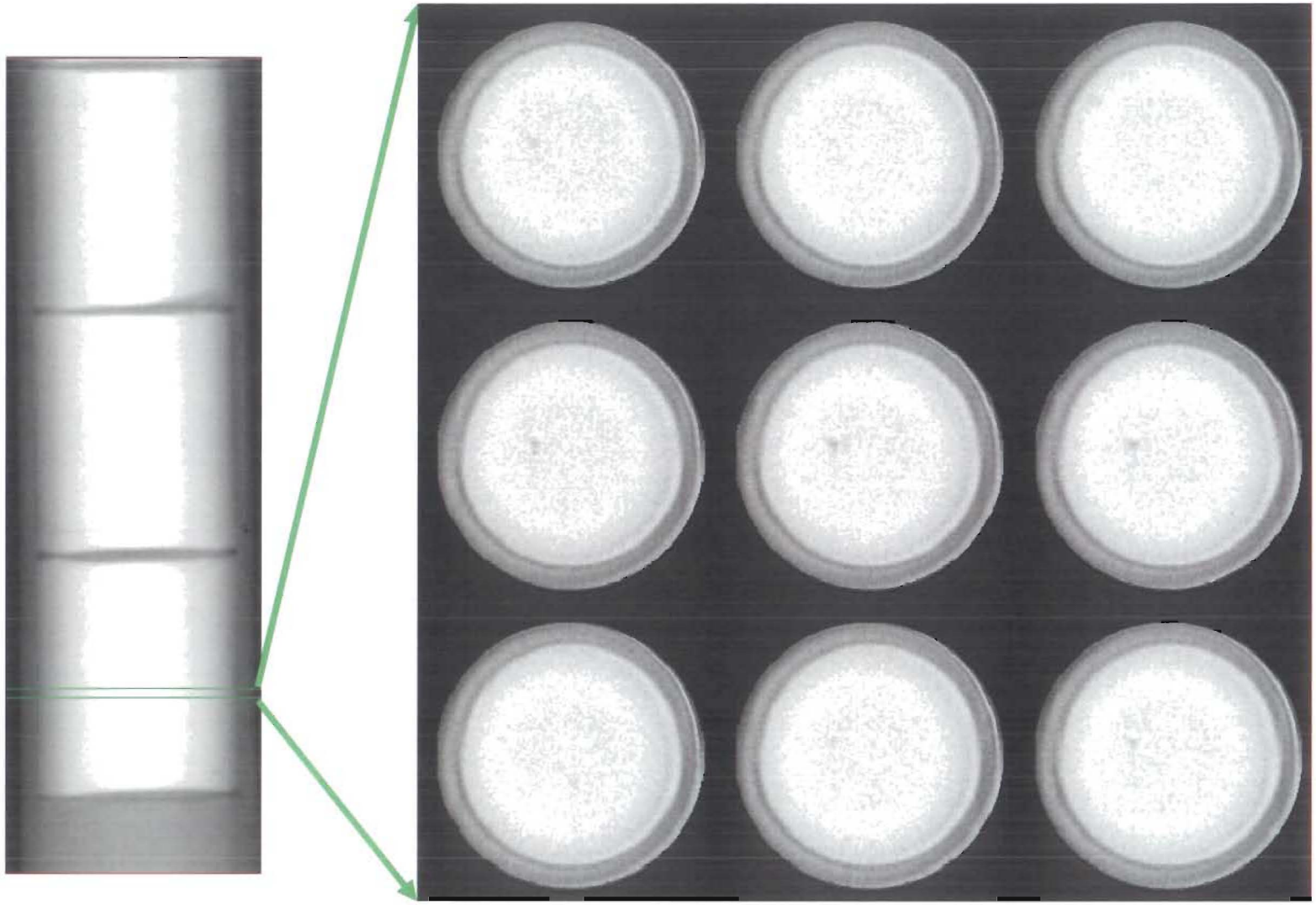
Fainter 250 μm long by ~150 to 200 μm diameter inclusions are shown in the circles

More Defects in Pellet #4: Slices 131 to 142



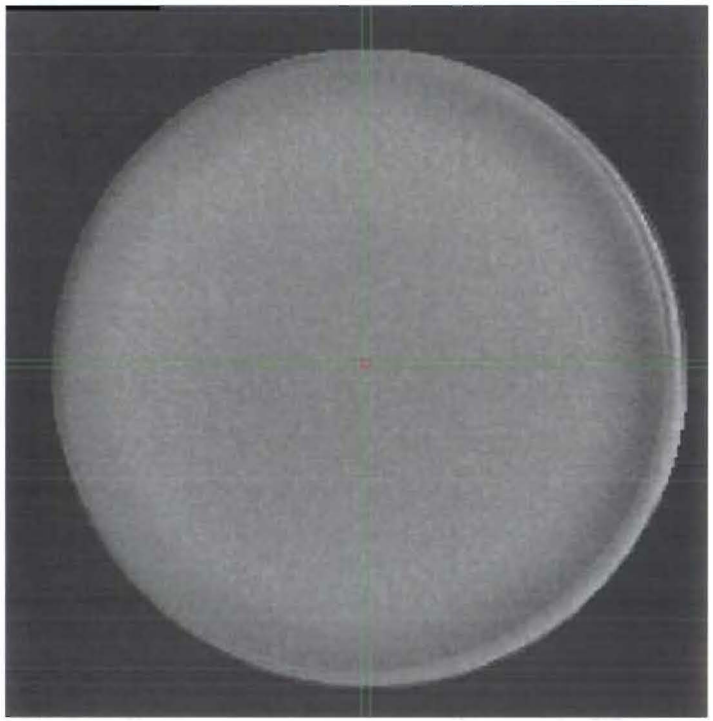
$Diameter_{Inclusion}$ ~ 225 μm
$Length_{Inclusion}$ ~ 450 μm

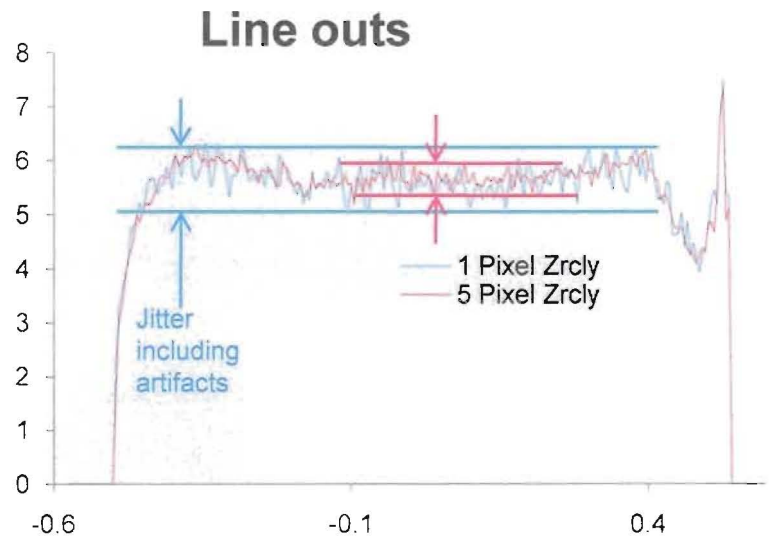
More Defects in Pellet #4: Slices 152 to 160



Density reconstruction uncertainties from reconstructed Slices;

A slice thru the zircaloy section





Single Pixel rms Jitter ~ 4%
Five Pixel rms Jitter ~2%

Bad pixels due to tile boundary contribute to reconstruction artifacts above
This can be avoided in future measurements
Better CT algorithms can be used

Concluding Remarks:

Industrial Materials of Interest:

a) PDE deflagration to detonation transition studies (hard problem but requires development)

b) Fuel cells – fuel ingredient ratio optimization

c) Nuclear fuel rods – can benefit from the high energy at GSI

b) Material strength and EOS studies with HE or powder gun drivers

c) Quasi static phenomena such as fluid flow through engine parts

Each of the above is unique enough in its own right that, they require specific optimization such as the selection of appropriate collimators to maximize contrast and minimize statistical and systematic errors.

GSI should strive toward multiple camera systems matched to the specific FOV and magnification and requisite resolution