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Title: Study of Spatial and Density Resolution of the 800MeV pRad Magnifier

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Study of Spatial and Density Resolution of the 800MeV pRad Magnifier

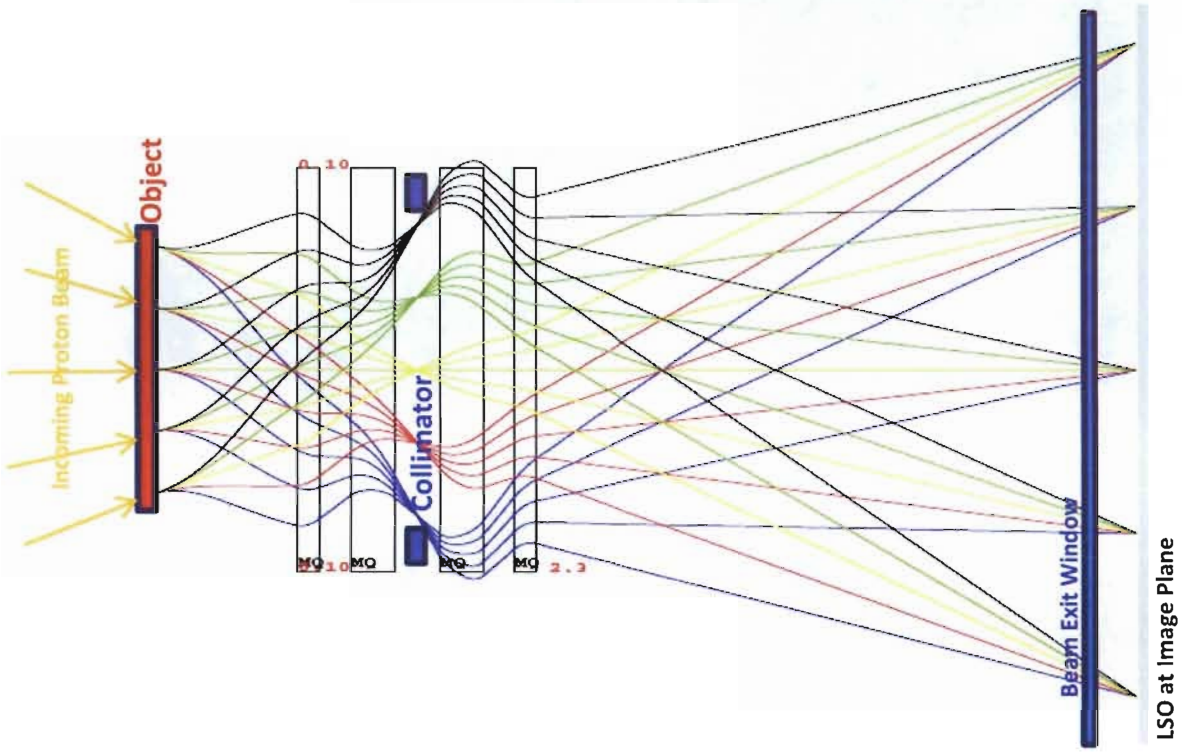
ABSTRACT

Proton radiography uses magnetic quadrupoles arranged in the Russian quadruplet fashion with an aperture restriction (collimator) at a Fourier plane of the imaging lens. Simple models predict that, for a fixed object thickness, it is possible to achieve vanishingly small spatial resolution by restricting the collimator opening, ie. at the expense of flux. The resulting reduction in flux may be unsustainable for dynamic experiments and we are forced to use some optimum collimator opening to get reasonable resolution and statistics. However, in the radiography of static objects it seems plausible that one can simply compensate for the reduced flux by longer exposure times. However, there are several factors that can potentially contribute to limit the achievable spatial and density resolution in proton radiography. We embarked on the study of these factors and their respective contributions, using simulations and measurements using the x3 magnifier at the LANSCE prad facility. Standard targets and collimators were built to facilitate the planned experiments. We have also built GEANT4 simulations that may help to explain present and future measurements. In this presentation we will give a brief description of the x3 magnifier at pRad, the experimental and simulations plans and the results achieved so far. We will also discuss a path forward for future development efforts.

Study of Spatial and Density Resolution of the 800MeV pRad Magnifier

Fesseha G. Mariam
And
John Perry
(for the pRad team and Andy Saunders)
2011 High Energy Proton Microscopy Workshop
LANL
10/27 to 10/28, 2011

Introduction/Motivation



$$\Delta x = (T_{116}x + T_{126}\delta\theta)\frac{\delta p}{p}$$

MATCHING

Inject beam with position-angle correlation is such a way that the T_{116} (position dependent) term is eliminated or minimized The remaining blur is then:

$$\Delta x = T_{126}\delta\theta\frac{\delta p}{p}$$

Controlled by size of collimator

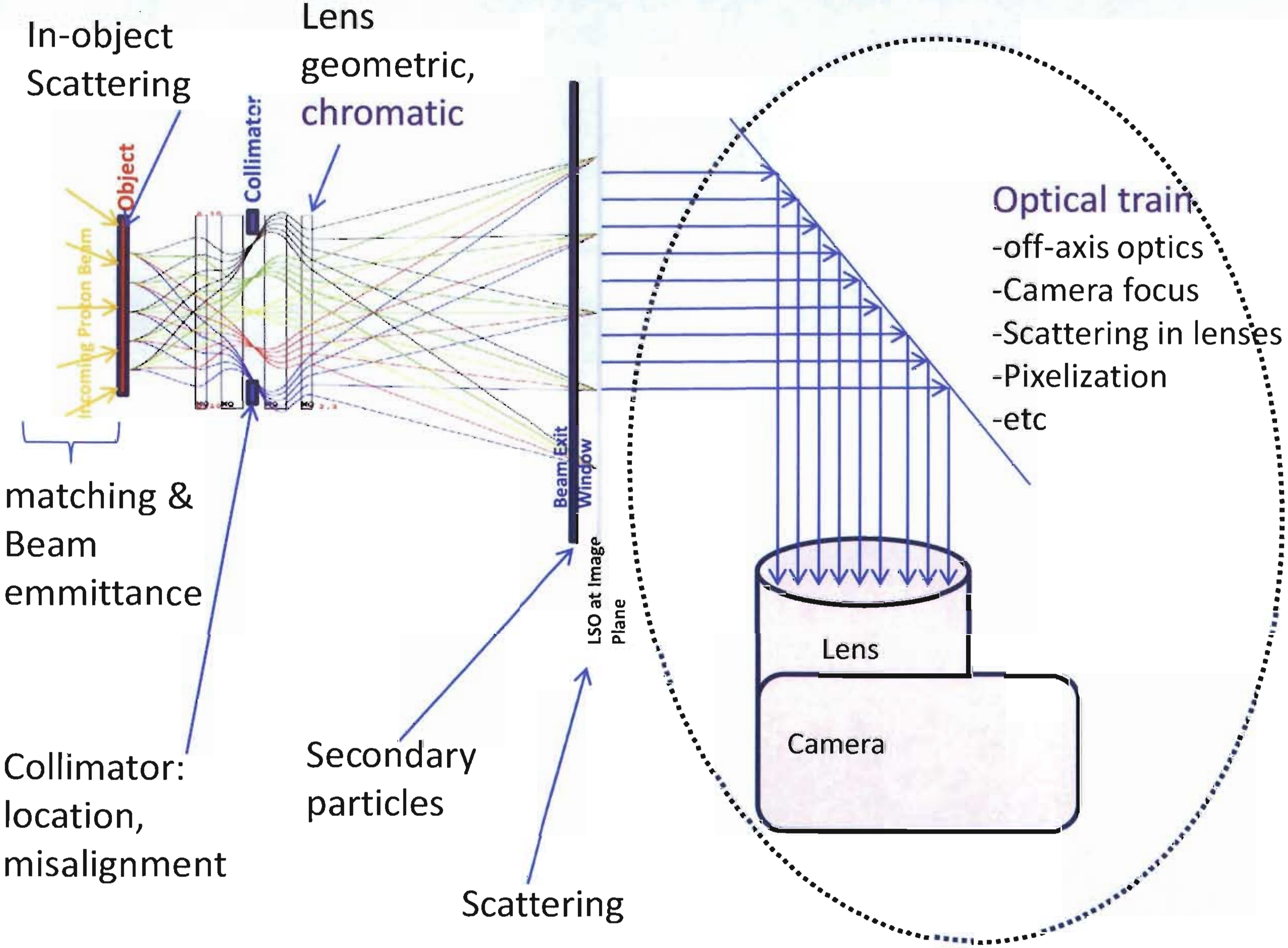
Density resolution is depends on transmission and the collimator controls transmission

In both spatial and density resolutions, the collimator size plays an important role.

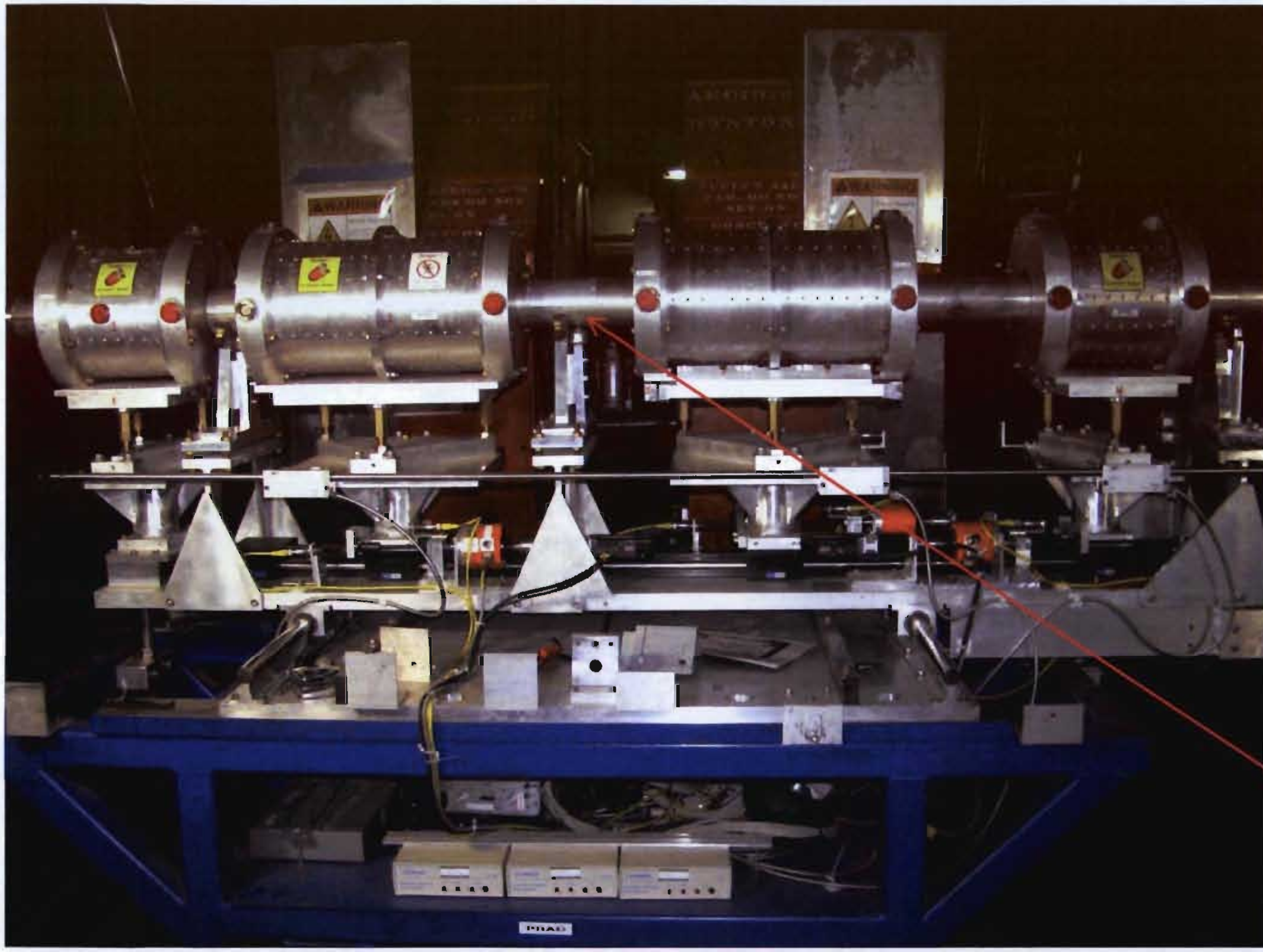
➔So we embarked on the study of both parameters as function of collimator size using simulations and measurements.

Is there a limit to the achievable resolution?

Possible sources of blur and systematic errors

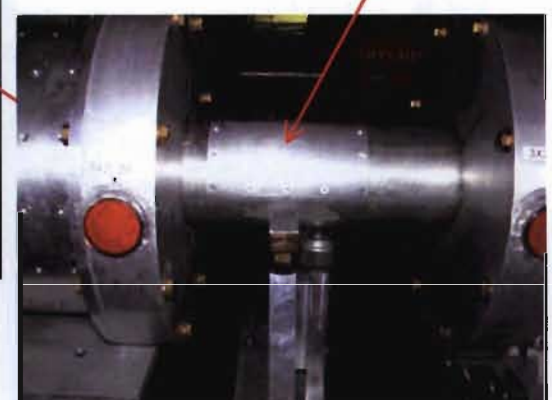


The x3 pRad Magnifier and its collimator

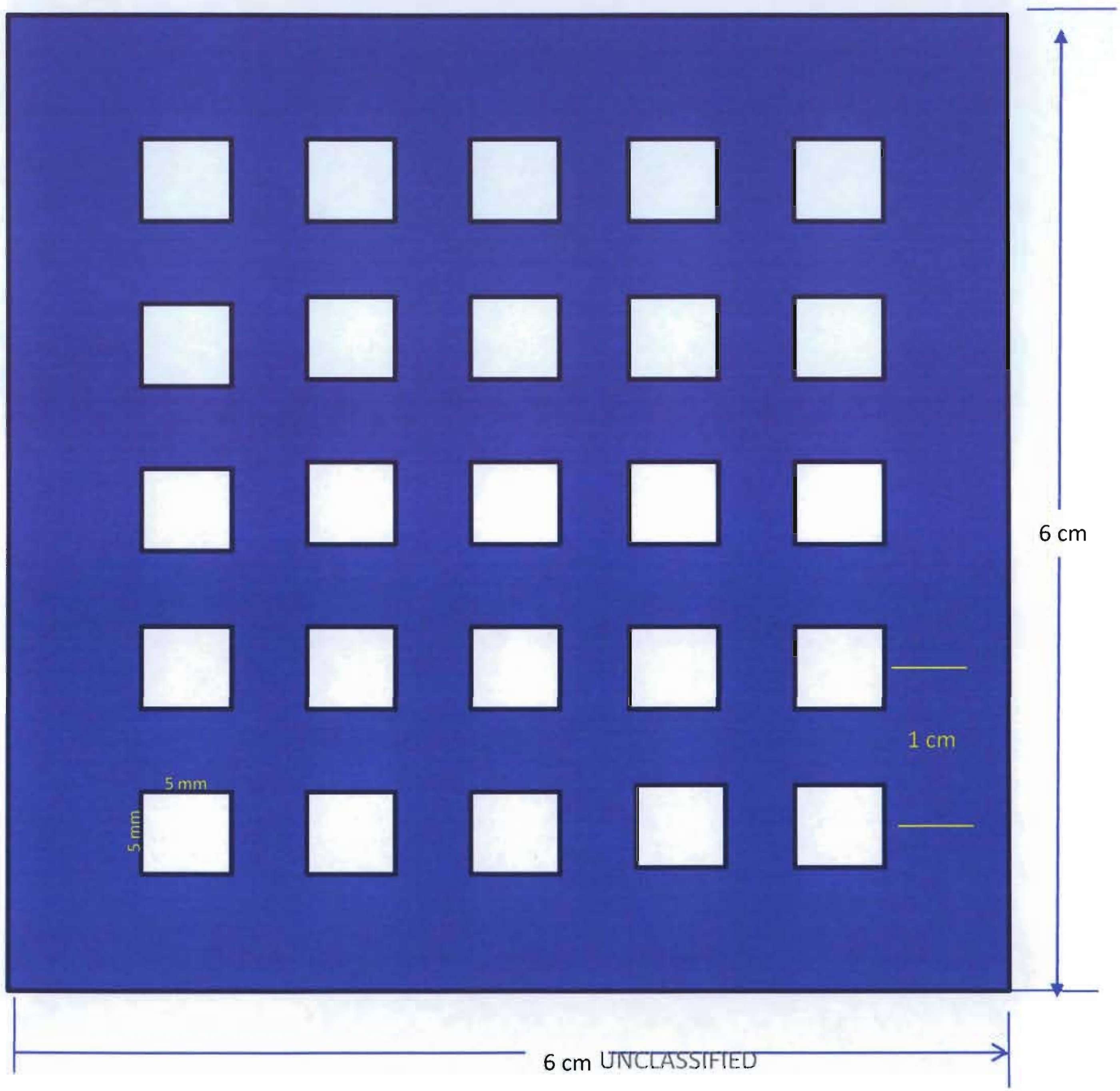


Special beam pipe facilitates rapid change of collimators

Collimator port

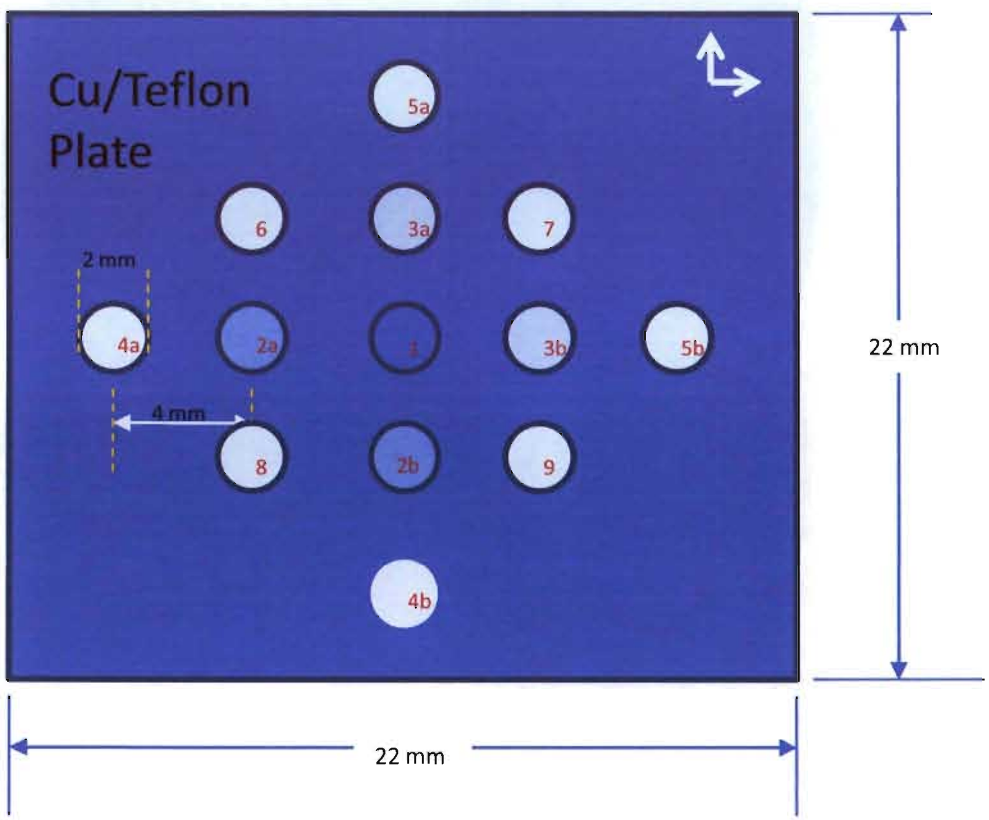


Position-dependent Spatial Resolution Object



3mm-thick tungsten plate with equally spaced machined square holes allows measurement of edge resolution as function of position with respect to the beam optic-axis

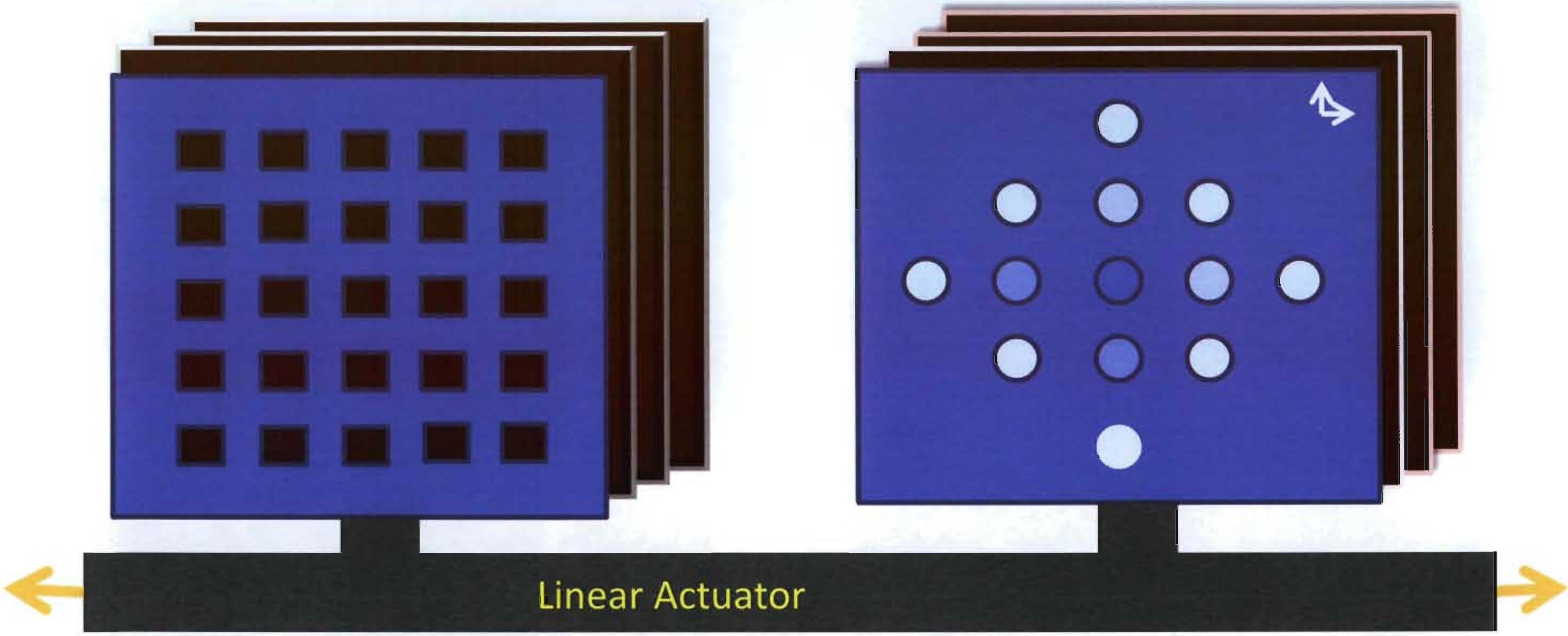
X3 Magnifier Density Resolution Objects (cu and Teflon)



Circles	Depth		Measured
#	[microns]	[mils]	[microns]
1	50	2.0	23
2a(b)	75	3.0	50(67)
3a(b)	100	3.9	63(80)
4a(b)	150	5.9	128(157)
5a(b)	200	7.9	147(184)
6	500	19.7	466
7	1000	39.4	971
8	2000	78.7	1997
9	3000	118.1	3002

Patterns of various depths are on a 3 mm-thick copper (and Teflon) plate would allow the observation of density resolution (contrast)

Experimental plan



a. Acquire images with various thickness of material (cu plates) stacked behind the basic spatial and density test objects with 10mradian collimator
b. Repeat (a) with 7.5, 5, 2.5 and 1mradian collimators

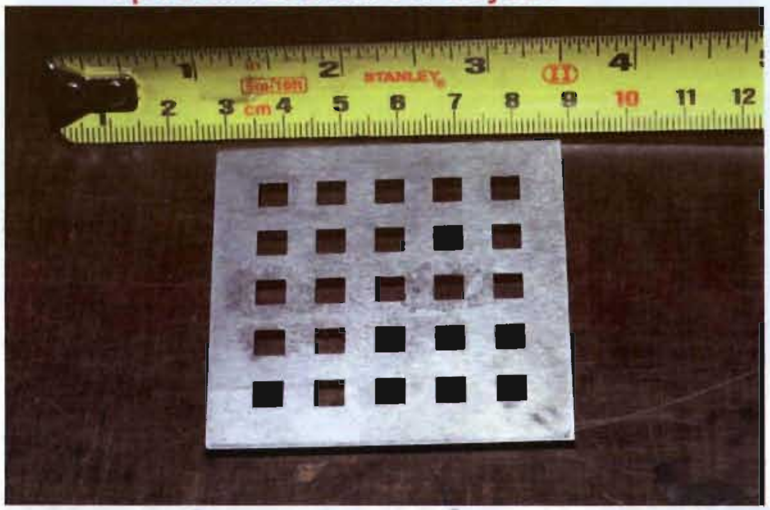
The result would be a four dimensional mapping of resolution $\sigma(X,\theta,x,y)$ and density reconstruction $\rho(X,\theta)$ down to the limits of the system.

Magnetic resolution can be decoupled from optical either by measuring the optical train resolution alone

(and/or by using image plates at the image plane to acquire image due to the lens)

Hardware

Spatial resolution object

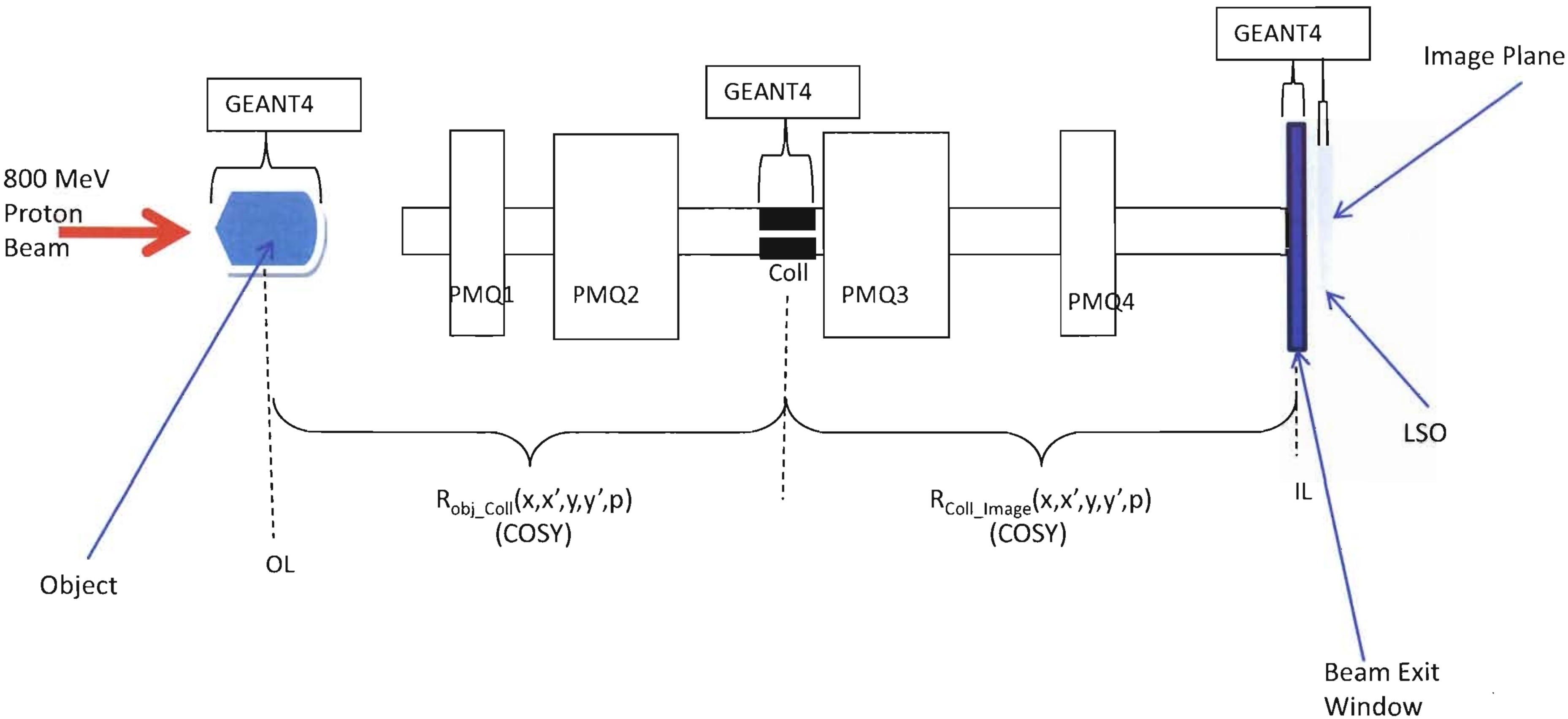


Density resolution objects
(Cu and Teflon)

Tungsten collimators

Collimator in beam pipe

GEANT4 Simulations: Scheme



Optical Train Resolution measurements using optical Mask over the LSO

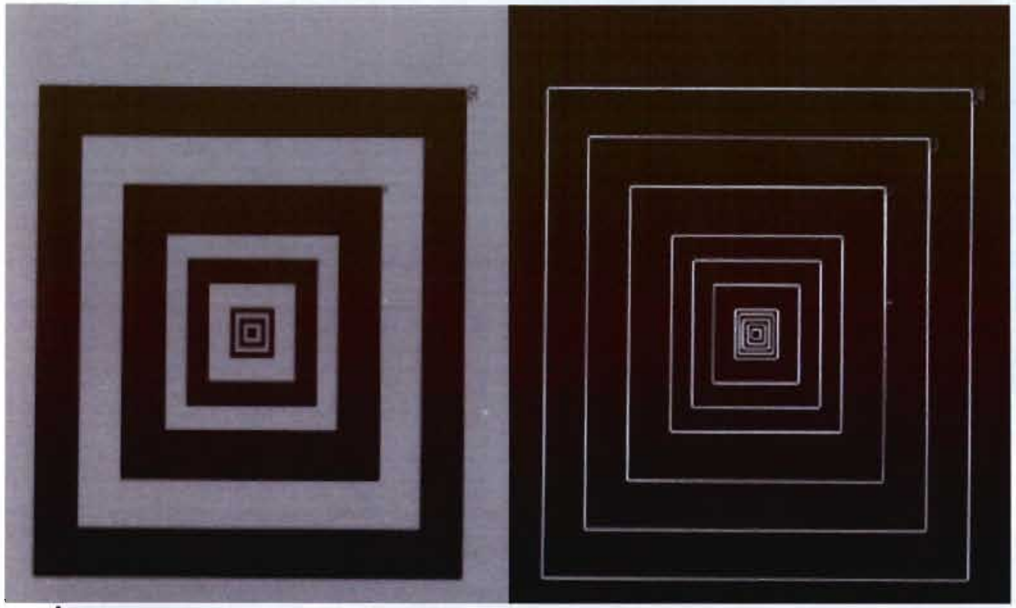
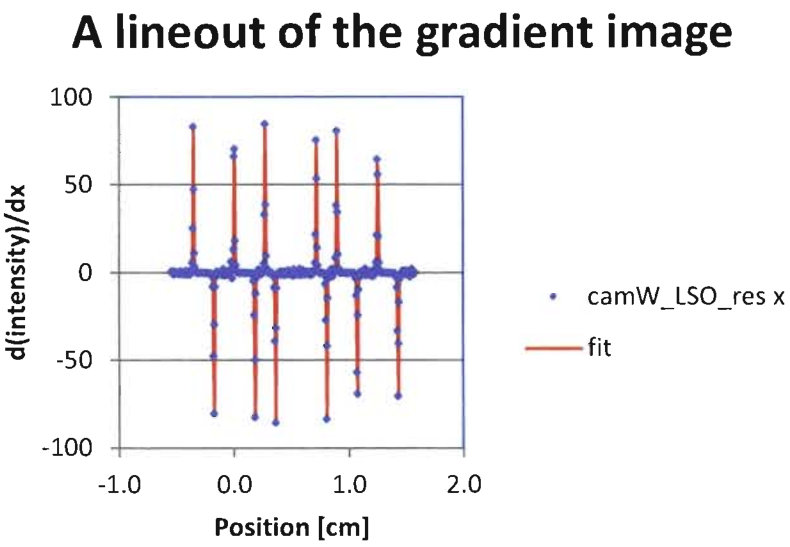


Image Gradient

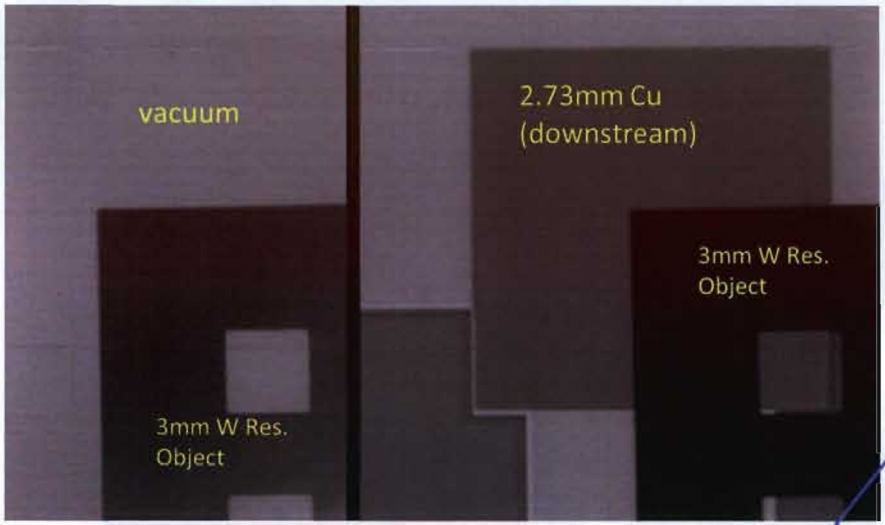


Average of the Gaussian fits to each peak = LSO & Optical resolution = σ_{opt} = 44 microns (~ 3 camera pixels)

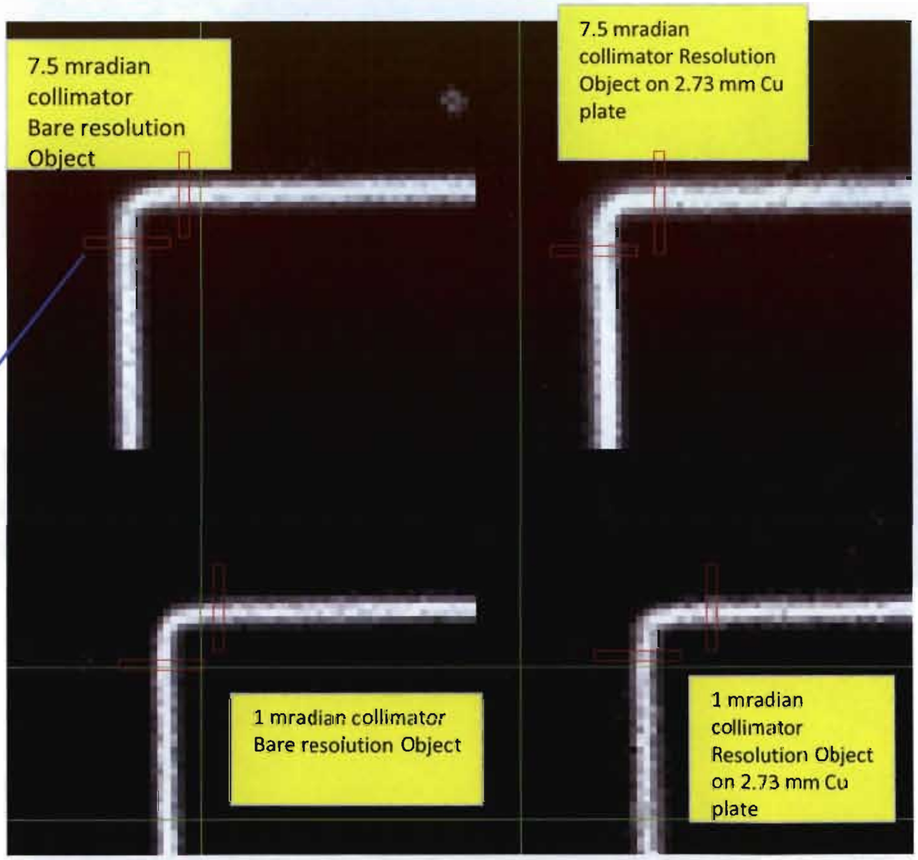
2000 by 2000 pixels, high DQE camera was used

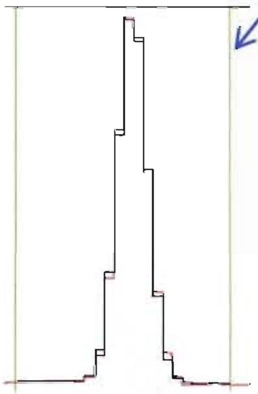
Edge Resolution Measurements at center of optic axis

Gradient of image



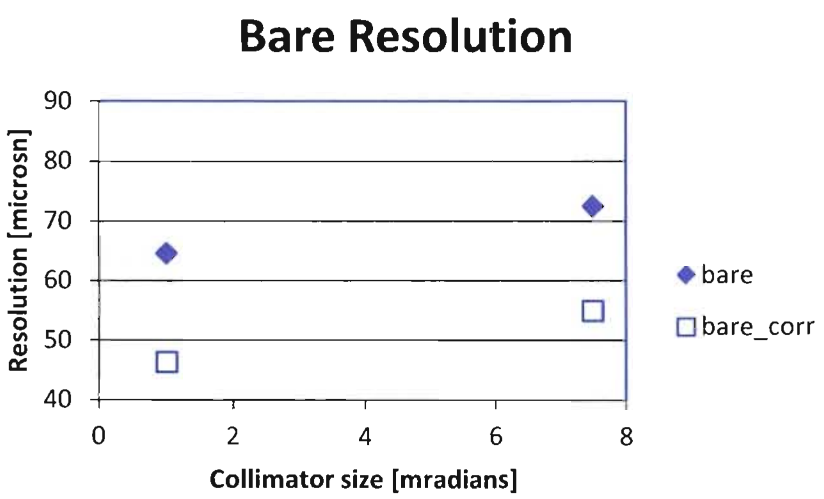
Resolution Plate Images

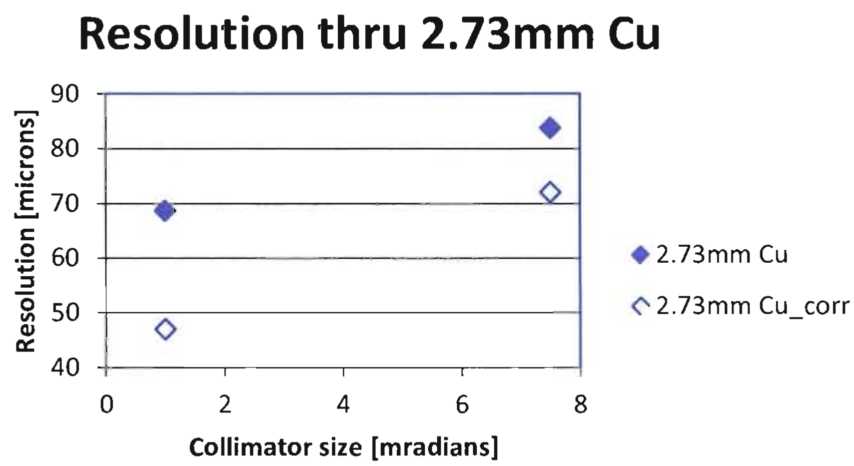




Gaussian Fit

Resolution Measurements at two Collimator sizes

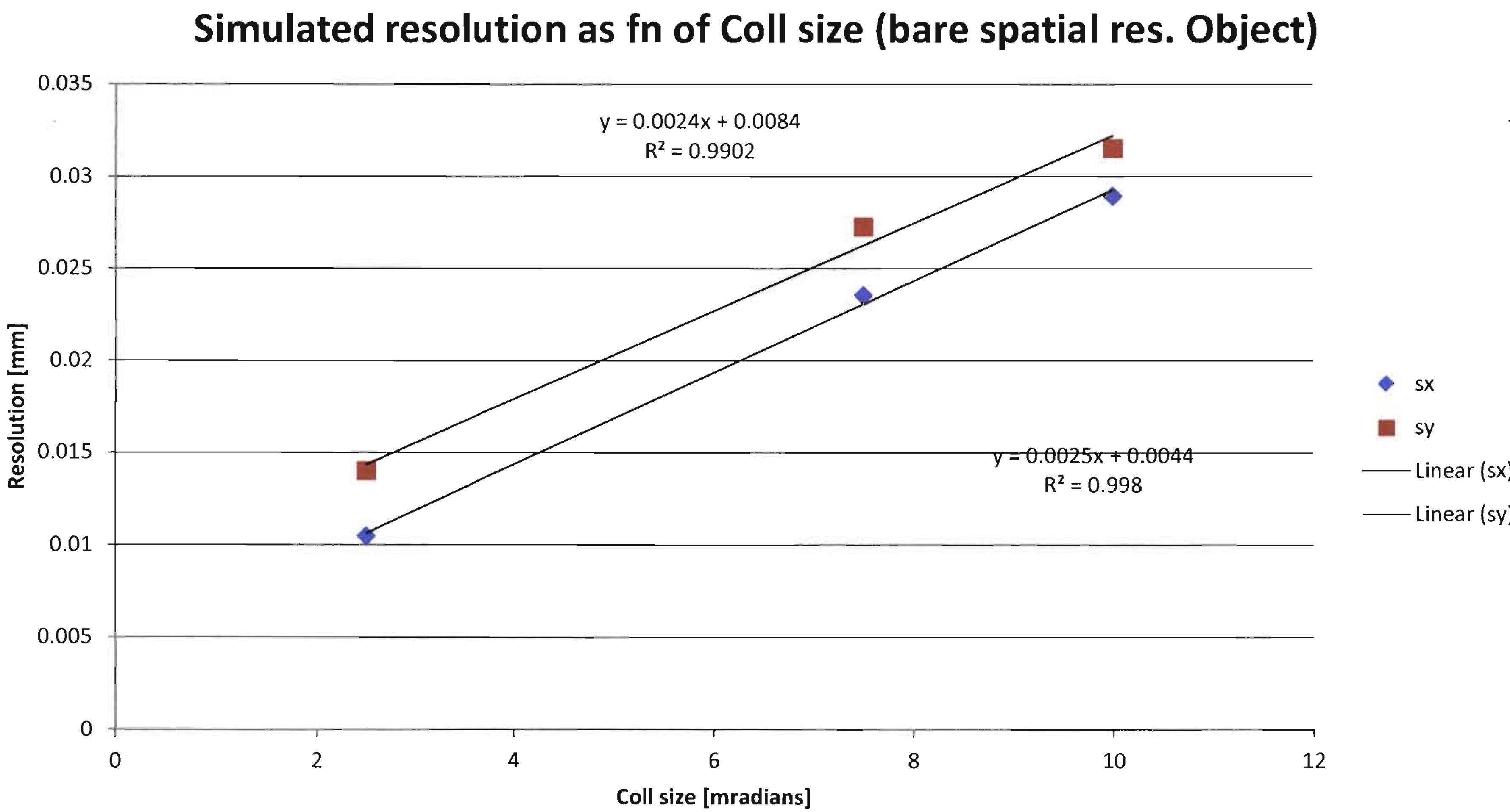




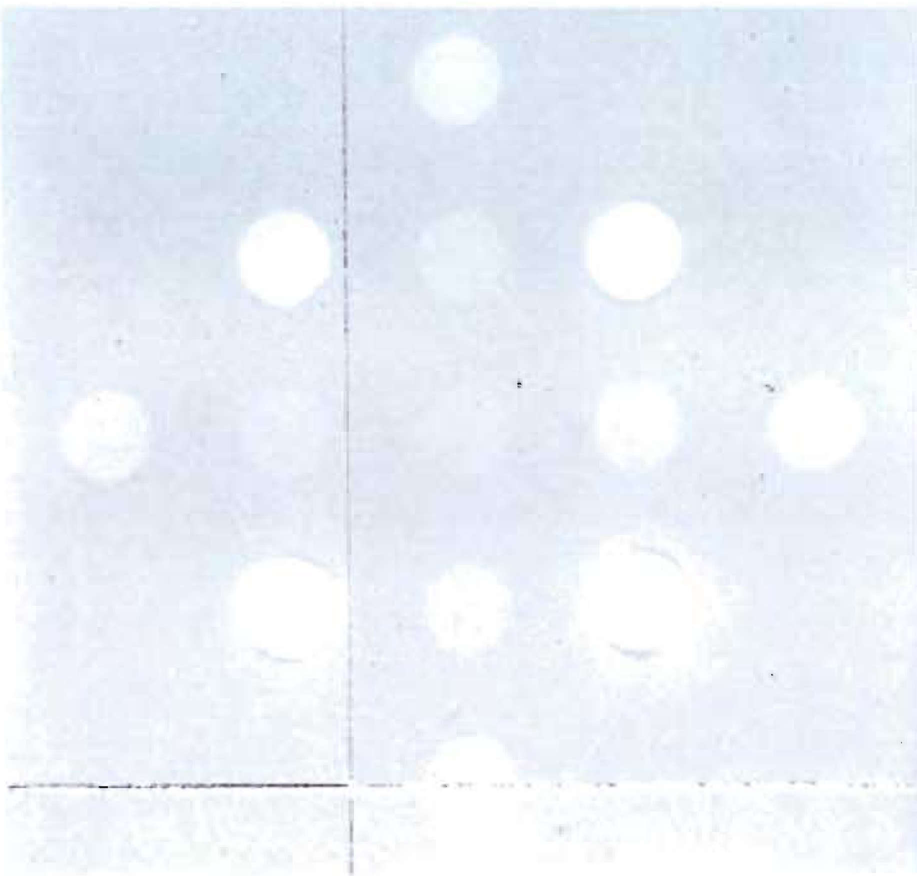
These and all radiographic measurements done with a severely malfunctioning magnifier lens. Some of the magnets had lost field strengths by as much as 5%. This is a serious degradation for imaging lenses.

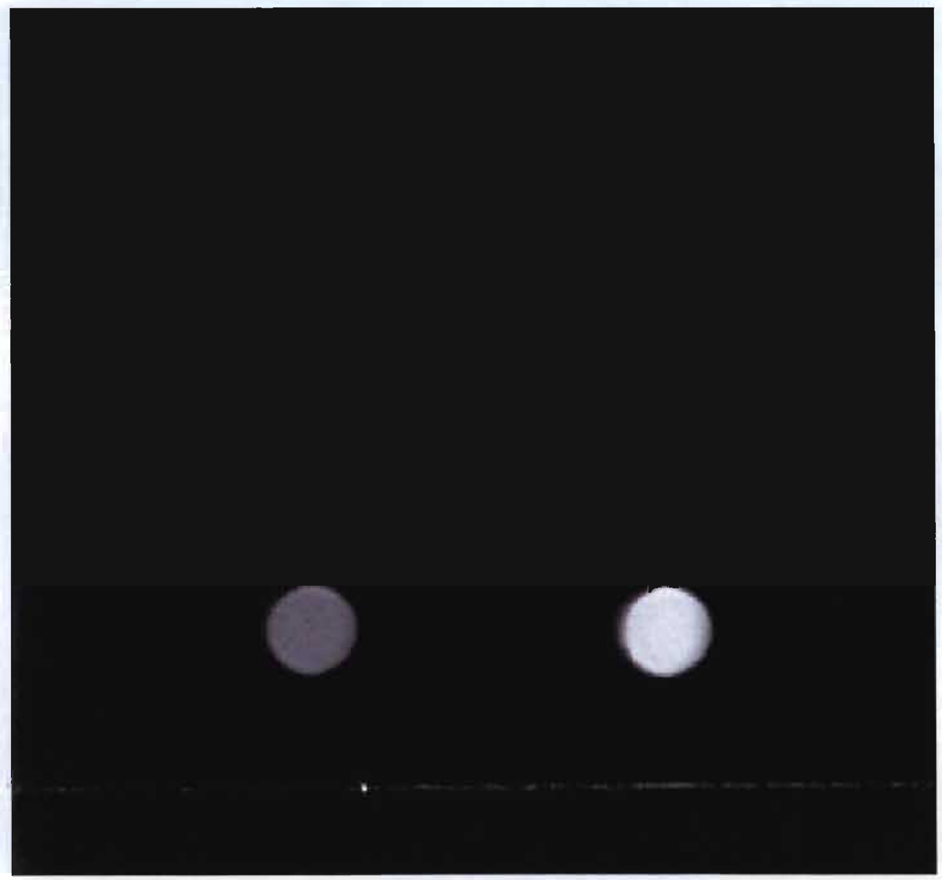
Despite this it is seen that with Optical corrections the resolution at 1 mradian collimator is comparable to the bare resolution

Simulations: Spatial Resolution for three collimators

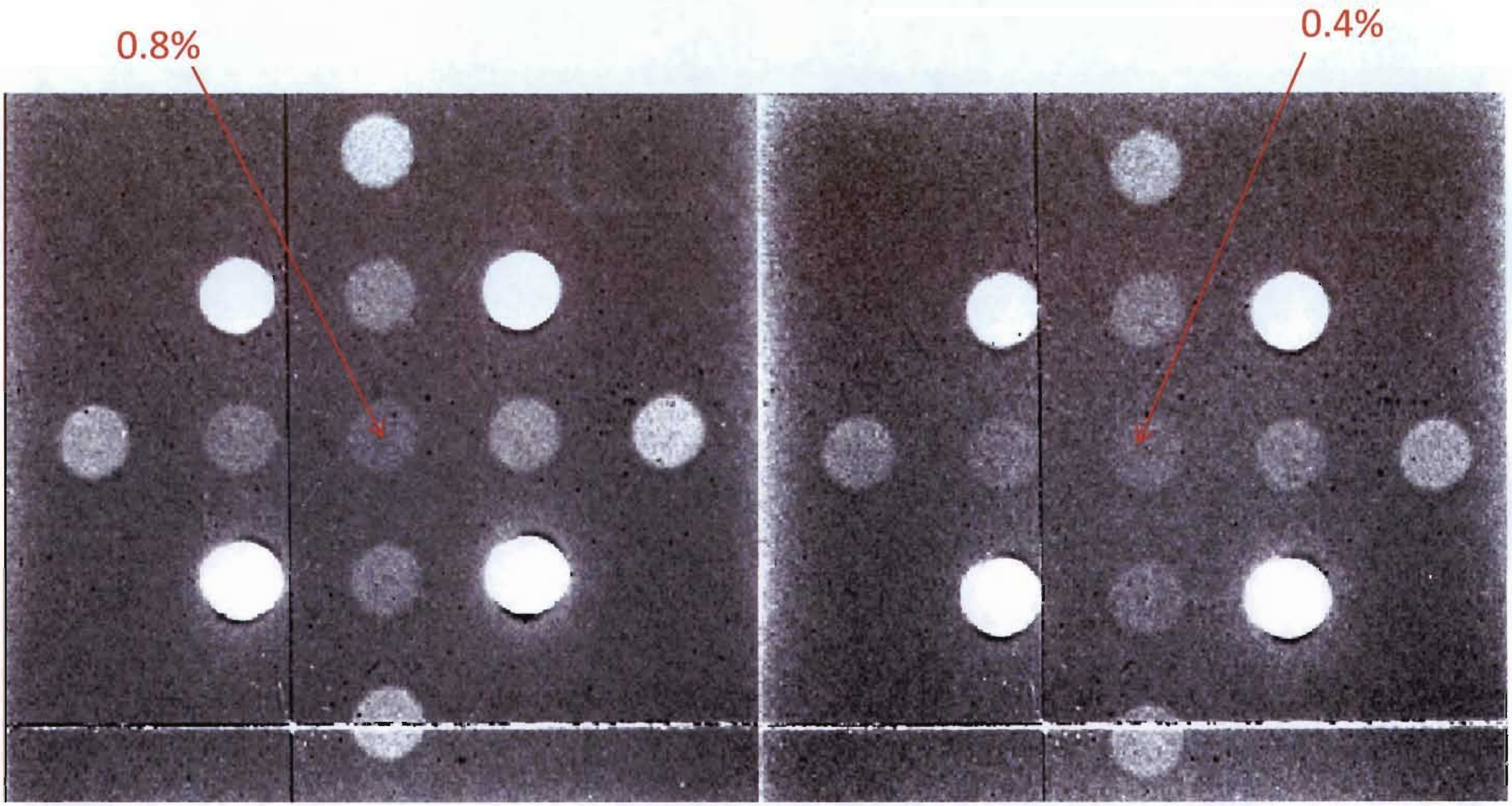


7.5 mradian Collimator: Transmission normalized to beam and flattened


3.04 mm Cu Substrate


3.04 mm Cu Substrate on 2.73mm Cu plate

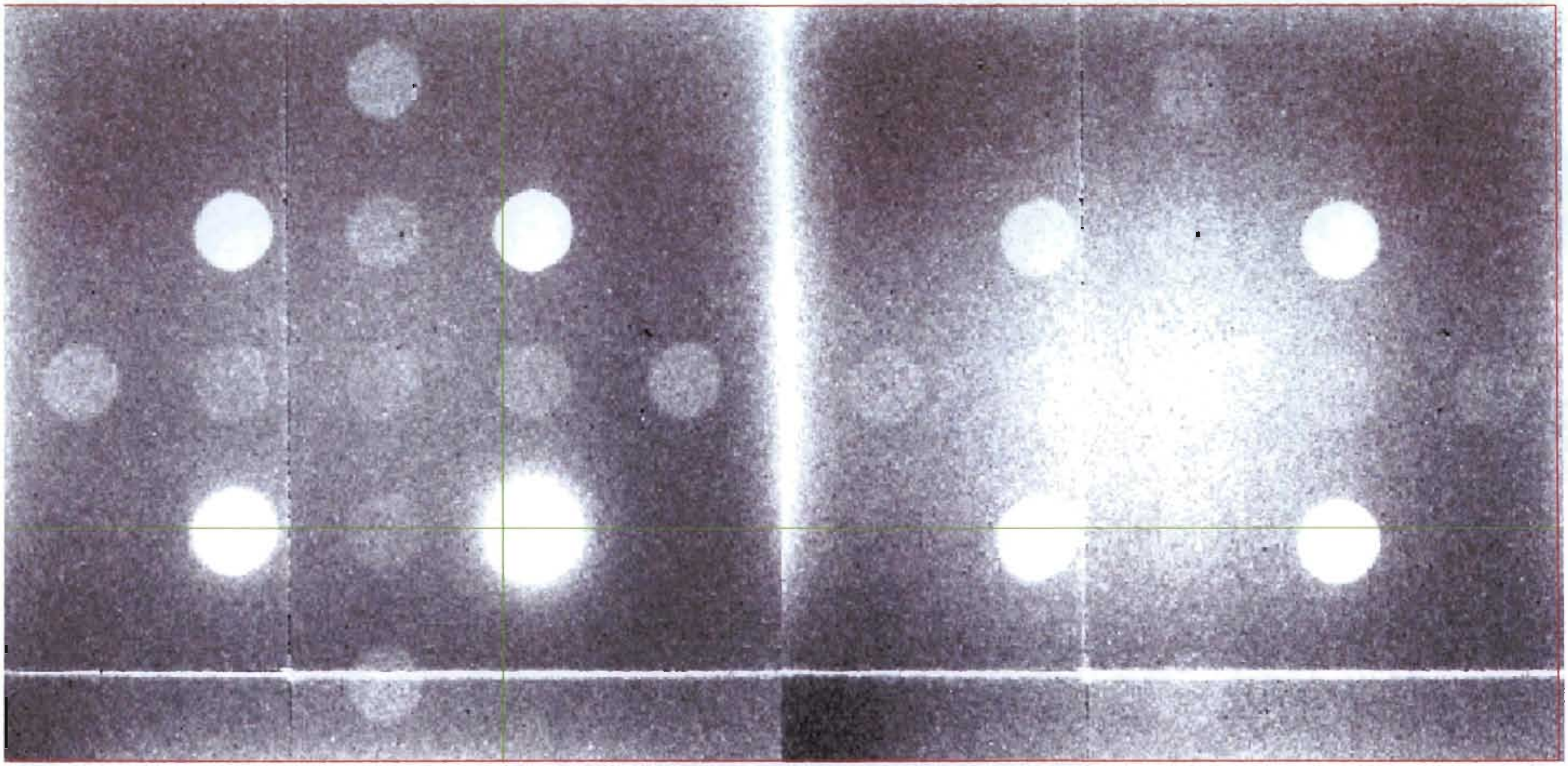
7.5 mradian Collimator: Transmission normalized to flat parts



3.04 mm Cu Substrate

3.04 mm Cu Substrate on 2.73mm Cu plate

1.0 mradian Collimator: Transmission normalized to flat parts

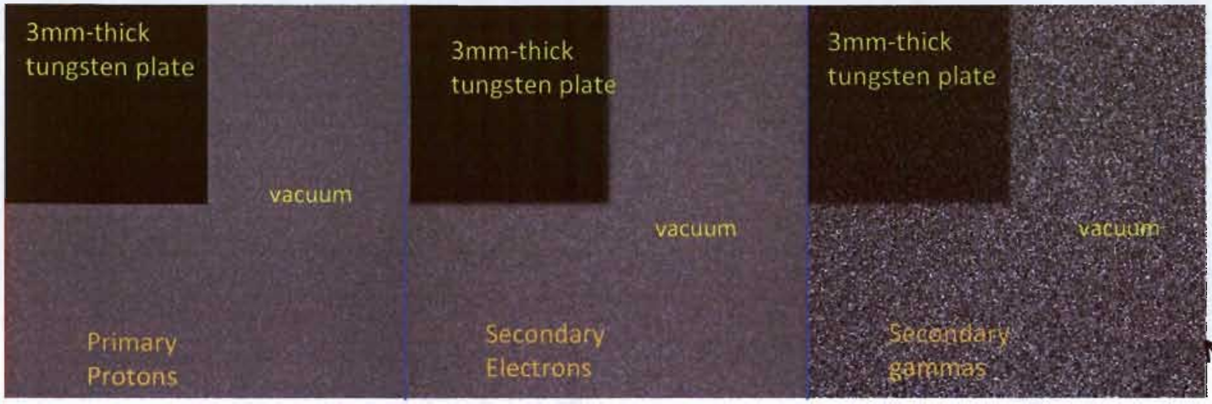


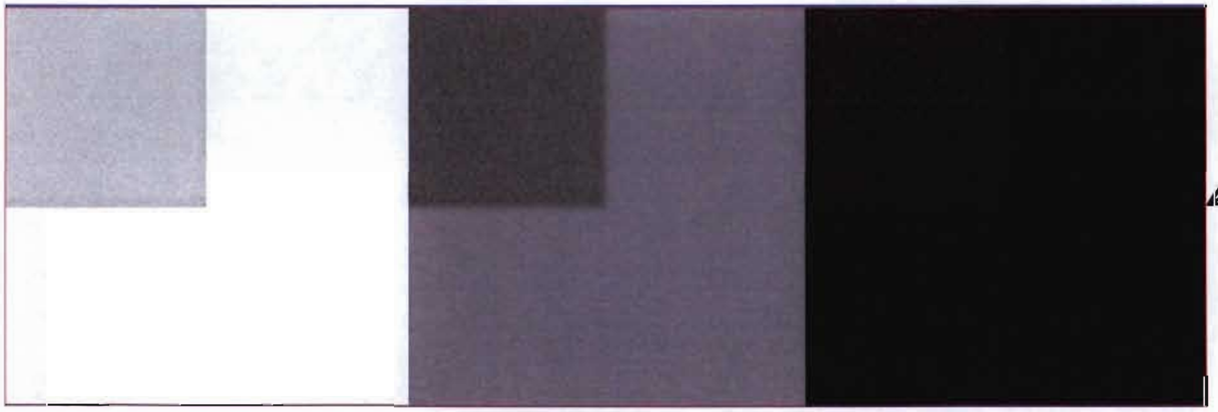
3.04 mm Cu Substrate

3.04 mm Cu Substrate on 2.73mm Cu plate

Simulation: Secondary Particle Contributions to Image on LSO Scintillator

Image of Energy deposited on LSO by three species of particles.





Secondary particles produced by the interaction of the primary protons with a 20mil-Kapton window at a standoff distance of about 1 cm from the LSO scintillator

Each image is gray scaled independently for visual display purposes

Log scale: All images on same gray scale

	Primary Protons	Secondary Electrons	Secondary gammas
Flux @ LSO	1	1.30%	0.09%
Deposited Energy @LSO	1	3.70%	0.07%

CONCLUSION: The most significant contributions are from secondary electrons and gammas. But, relative to the primary protons their fluxes are still too small to affect the resolution perceptively.

Conclusion

- General trend of better spatial resolution with smaller collimator is verified qualitatively
- Simulations and measurement do no agree

  a) Simulation may not be realistic: Improvements should include

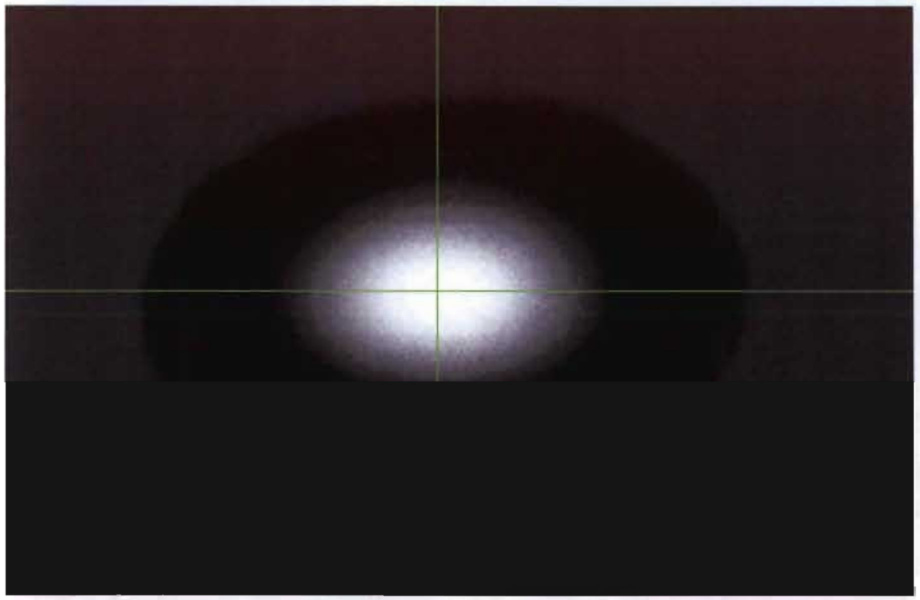
  - Recent beam emmittance measurements + diffuser and window effects
  - Transport matrices with measured fringe fields, and geometric terms

  b) Measurements were compromised by demagnetized quads in the lens.

  - Make sure we have fully magnetized lens or carry out the experiments using the –I electromagnetic lens
- Use Image plates at the image plane to cleanly separate magnetic and optical resolution

Support Slides

Beam at the 7.5-mradian Collimator



The beam is aligned on the collimator to within:

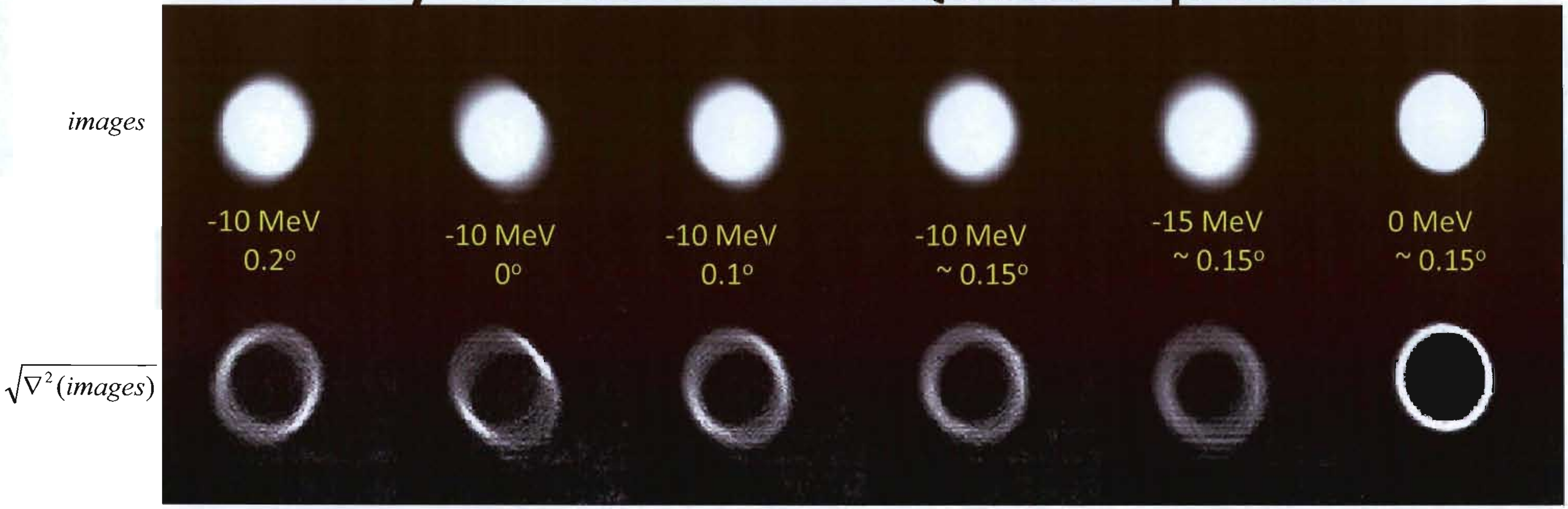
- dx~0.7mm, and dy ~0.4mm

$\sigma_x = 6.9mm,\ \sigma_y = 4.8mm$

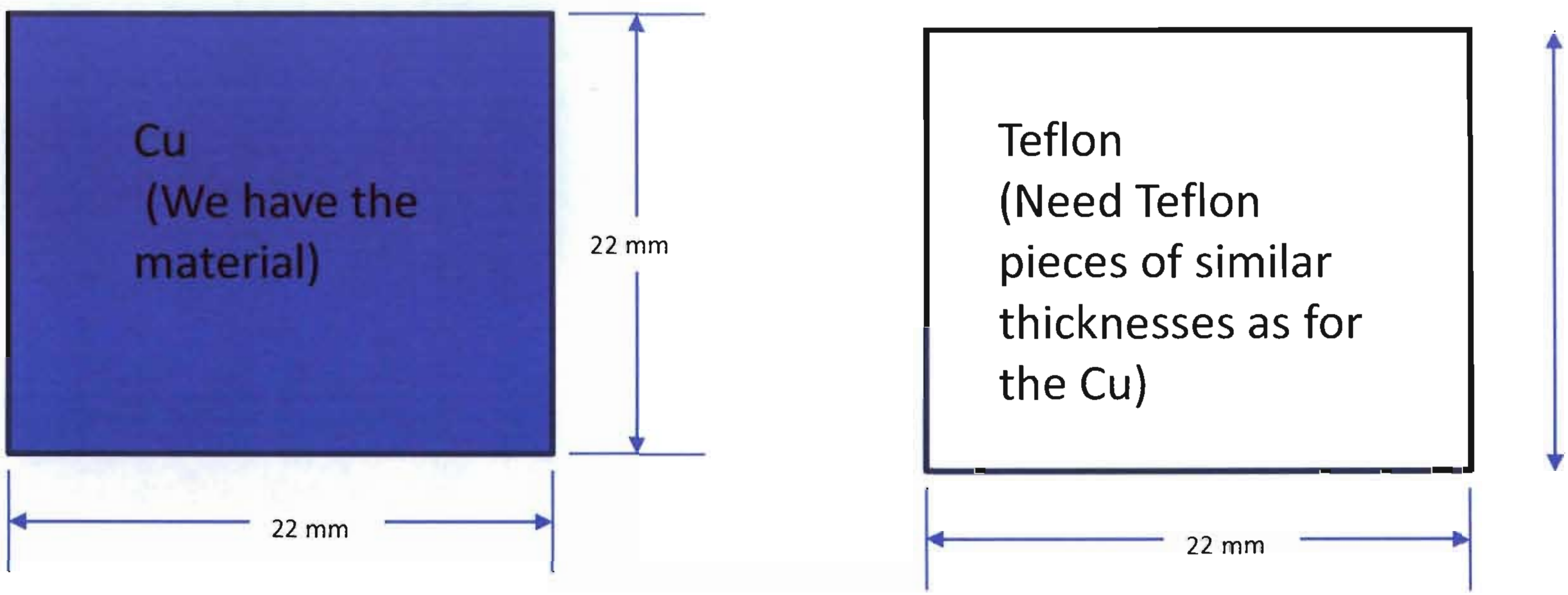
Applying the theoretical object-to-collimator transport matrix ➔

$\theta_x = 1.3\ mrad,\ \theta_y = 1.2\ mrad$

Blur due to Rotational Misalignment of any of the four Quadrupoles



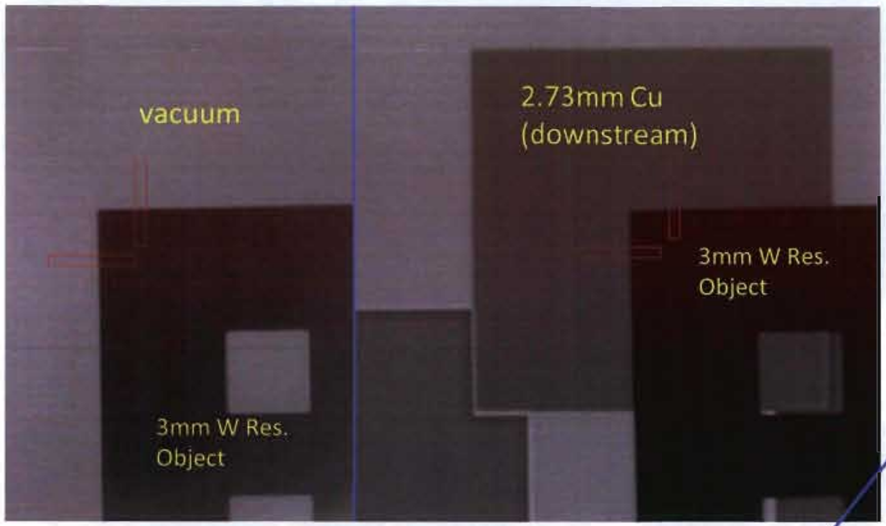
Flat Objects for measuring resolution as fn of object thickness and collimator size



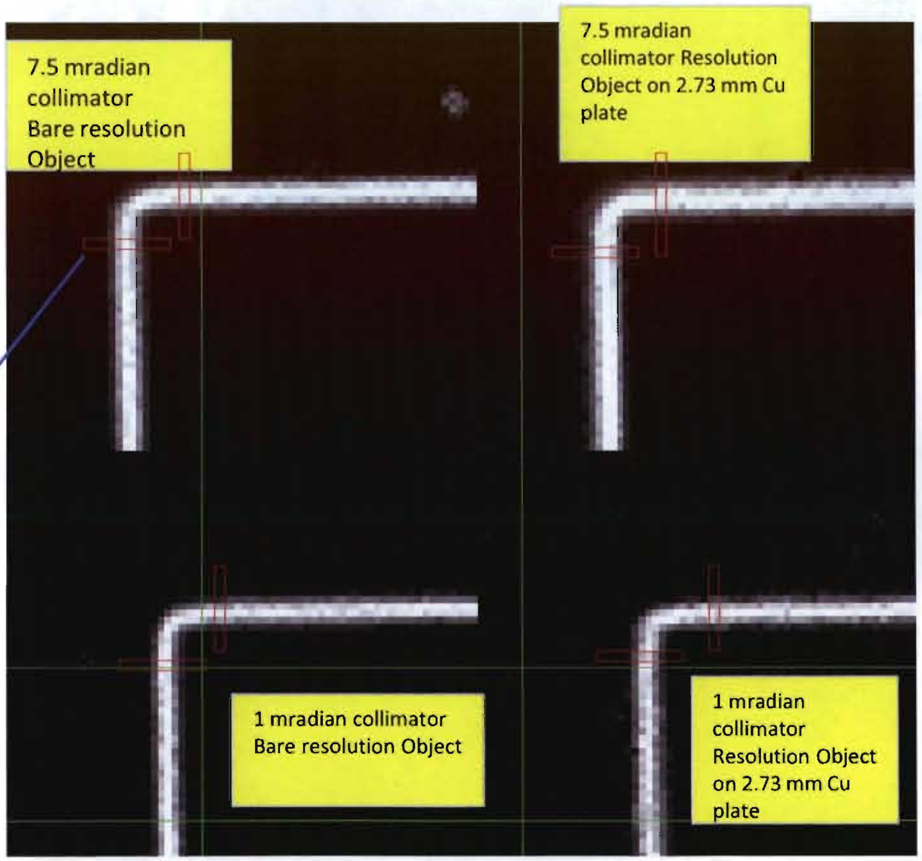
Cu/teflon Thickness [mm]
2.73
5.94
12.62
25.04
38.2

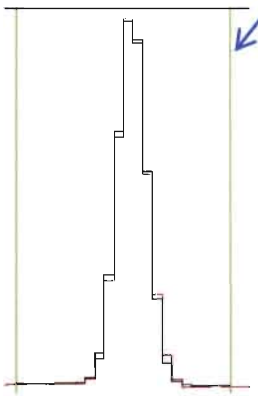
Edge Resolution Measurements

Resolution Plate Images



Sqrt(grad^2)

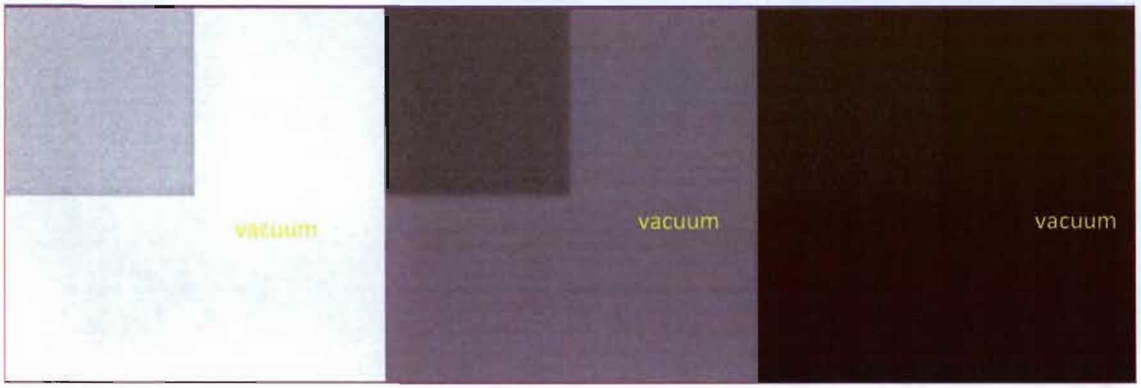




Gaussian Fit

Simulations:

Secondary Particle Contributions to Energy Deposited on LSO Scintillator



Energy deposited on LSO by three species of particles in logarithmic scale.

Secondary particles produced by the interaction of the primary protons with a 20mil-Kapton window at a standoff distance of about 1 cm from the LSO scintillator

	Primary Protons	Secondary Electrons	Secondary gammas
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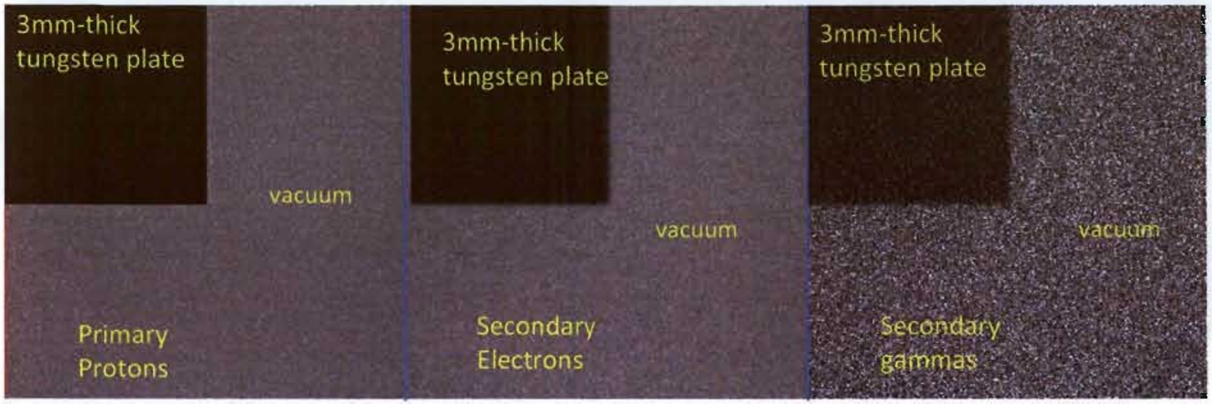

Energy deposited on LSO by three species of particles. Each image is gray scaled independently for visual display purposes

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John Perry
ISR-1

Forward Models of Proton Radiography with Geant4

P-25

Los Alamos
NATIONAL LABORATORY
EST. 1943

International, Space & Response
ISR

UNCLASSIFIED DC: Jeremy Danielson

Outline

- Introduction
  - Why should we simulate PRad?
  - Codes utilized
  - Computational resources
- The "Pipeline"
  - How do we use ROOT, Geant4, and the glue that binds the pipeline together?
  - Modularity and easy, n-scalable serial implementation
- Parameters studied
- Output Examples
  - Single hole tungsten plate
  - Resolution plate
  - Limning object
- Conclusions
- Questions?

Introduction

- GRA at LANL from 03/10 onwards
- Graduate of Purdue University in Nuclear Engineering
- Current research involvements
  - PRad simulation framework
  - Active interrogation (ISIS)
  - Passive muon interrogation (PhD work)
  - Software development for data visualization and data acquisition (CLYC, ISIS, etc.)
  - GBM (GLAST Burst Monitor) simulations
- LANL provides an incredible, agile setting for collaboration across many scientific fields. This is an extremely useful resource for engineers and scientists.

Why should we simulate PRad?

- Proton radiography involves many fine working components that must all be in tune for a successful image(s)
- An accurate simulation framework of PRad facilitates parameterized studies of the process for a fraction of cost, time, and effort
  - Lens settings
  - Blur effects
  - Collimator sizes
  - Secondary particle production
  - Beam settings
- The computational cost for answering these questions is both low and also continues to decrease as the simulation world marches onward

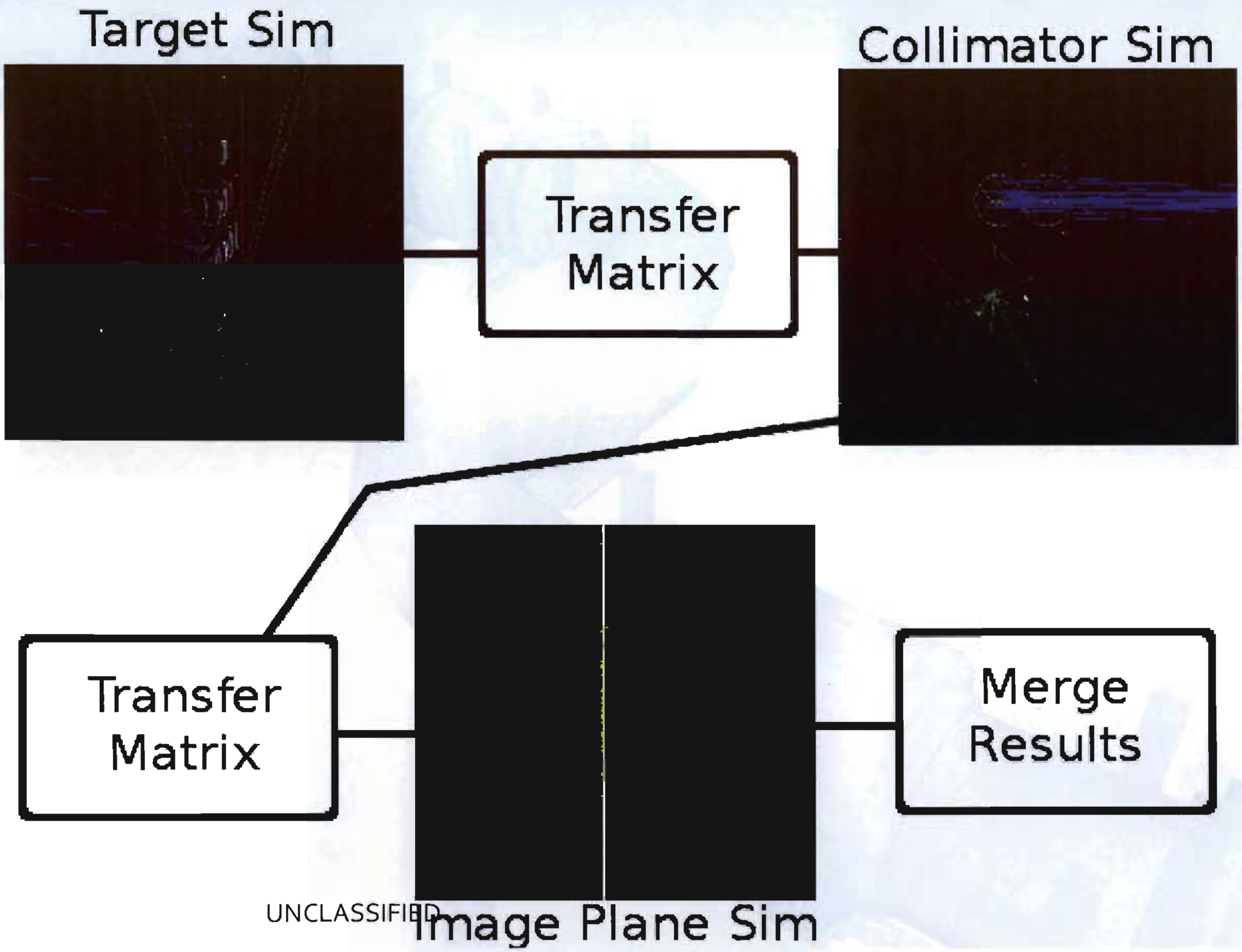
Codes Utilized

- Geant4
  - Provides a comprehensive set of physics and transport processes to simulate targets, collimation, and image plane processes
- ROOT
  - Gives a structure for storing data during all points of the pipeline
- COSY
  - Generates beam-optic transfer matrices
- C++ "Glue"
  - Transfer matrices
  - Adds the final output for a particular run
- Bash shell scripting
  - Controls servers for handling the different jobs of the pipeline automatically

Computational Resources

- PRad simulations were done with either 100 million or 1 billion particle sets
- There are also 6 steps in the pipeline, thus the computational time benefits greatly from parallelization
- Performed simulations on ISR-1 servers
  - Each server: 64 cpu, Intel Xeon x7560 @ 2.27 Ghz
  - Each server: 132 Gb memory
  - Large disk arrays accessible through NFS

The "Pipeline"



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ROOT, Geant4, and Glue?

- Geant4 is used to simulate the scattering and other physics for transporting protons through the target, collimator, and image plane
  - Secondary particles are killed for the target and collimator simulations to speed up the simulation
- Each section of the pipeline contains n-number ROOT files
- The ROOT file stores each resulting particles information per event
  - Particle species
  - Energy
  - Position (x, y)
  - Direction (x', y')
  - Particle life flag
- The C++ module computes a transfer array for each particle based upon its momentum and solves for the final particles position
  - This module glues the pipeline together
- Outputs are in ROOT and pixilated formats

Modularity and Massive Serialization

- The pipeline was designed with modularity in mind
  - Any number of transfer matrices can be implemented
  - New targets are easy to implement and controlled by an argument
  - Collimator dimensions are controllable (length and opening size)
  - Several windows can be selected for the image plane simulation
- The pipeline design and supporting scripts allow for n-number parallelization via serial job submission
  - Typical run times for 1 billion particles on 100 cpu were 6-12 hours
  - The collimator was the source of most of the computational cost
- Limiting factors of mass serialization
  - Not cluster friendly -> Go to MPI implementation
  - File write bandwidth -> Better data writing than 1Gbps NFS

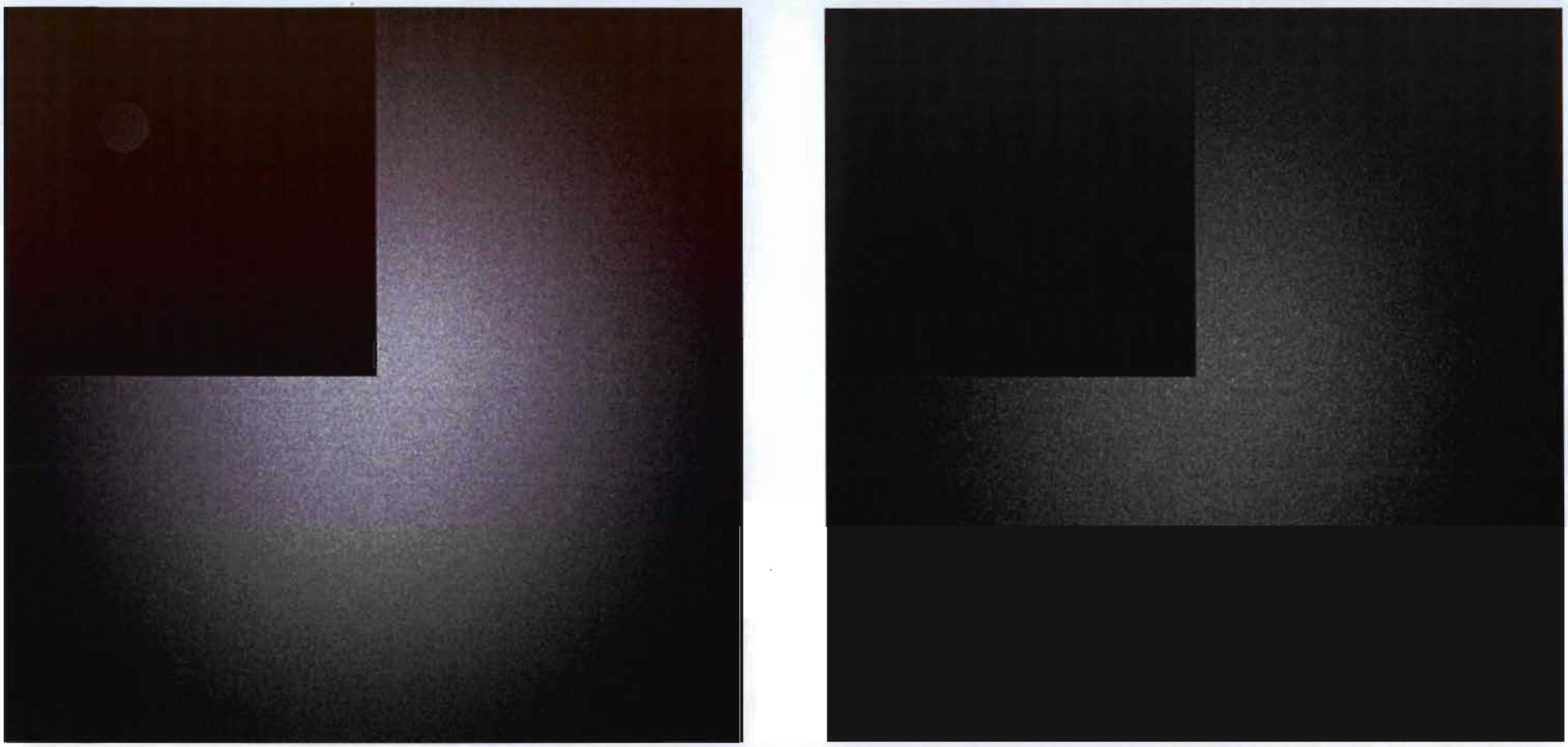
Parameters Studied

- Beam
  - Monochromatic vs. Polychromatic
  - Pencil beam vs. Gaussian beam (realistic)
- Target
  - Tungsten plate (spatial resolution object) with corner hole
  - Above with several thicknesses of preceding copper, 2.73 mm to >20 mm cu
  - Cu resolution plate (density resolution object)
- Transfer matrices
  - Lens energy setting
- Collimator
  - Length
  - Opening size
  - Center offset
- Image Plane
  - Energy deposition in LSO
  - Flux of particles before LSO
  - Windows
  - Covers

Output Examples

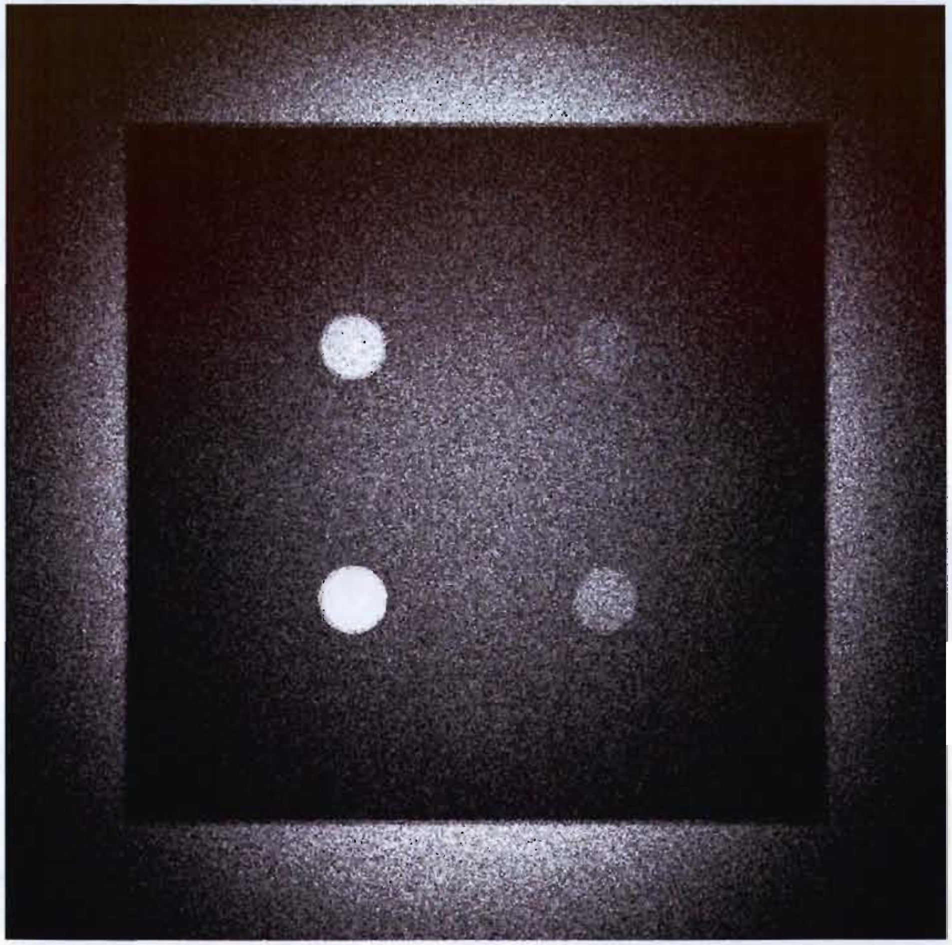
- Single hole tungsten plate (spatial res. object)
  - This plate was used to study edge resolution at the beam-optic axis, and served as a simple baseline for understanding the simulations
  - Clear and easy to understand
- Density resolution plate
  - A piece of copper that has several depths of holes placed strategically throughout the plate
  - Provides a more challenging simulation with many edge features
- Limning object
  - Counter-bored cylinders are useful to look at effects of chromatic blur based upon varying thicknesses of target material

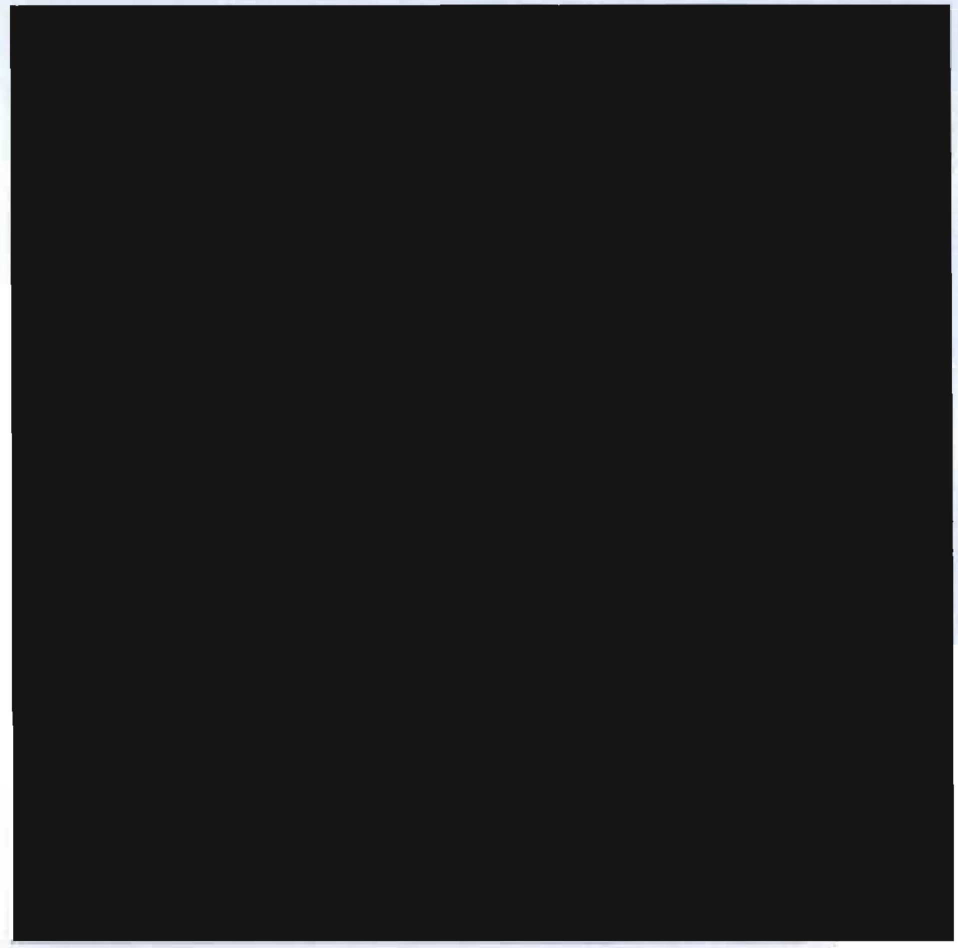
Spatial Resolution Tungsten Plate



Single hole tungsten plate | 7.5 mRad 2 inch collimator | kapton window | 799 MeV MT
(left) proton flux before LSO | (right) proton energy deposition in LSO

Density Resolution Plate





Resolution plate | 5.0 mRad 2 inch collimator | kapton window | 794 MeV MT
(left) proton flux before LSO | (right) proton energy deposition in LSO

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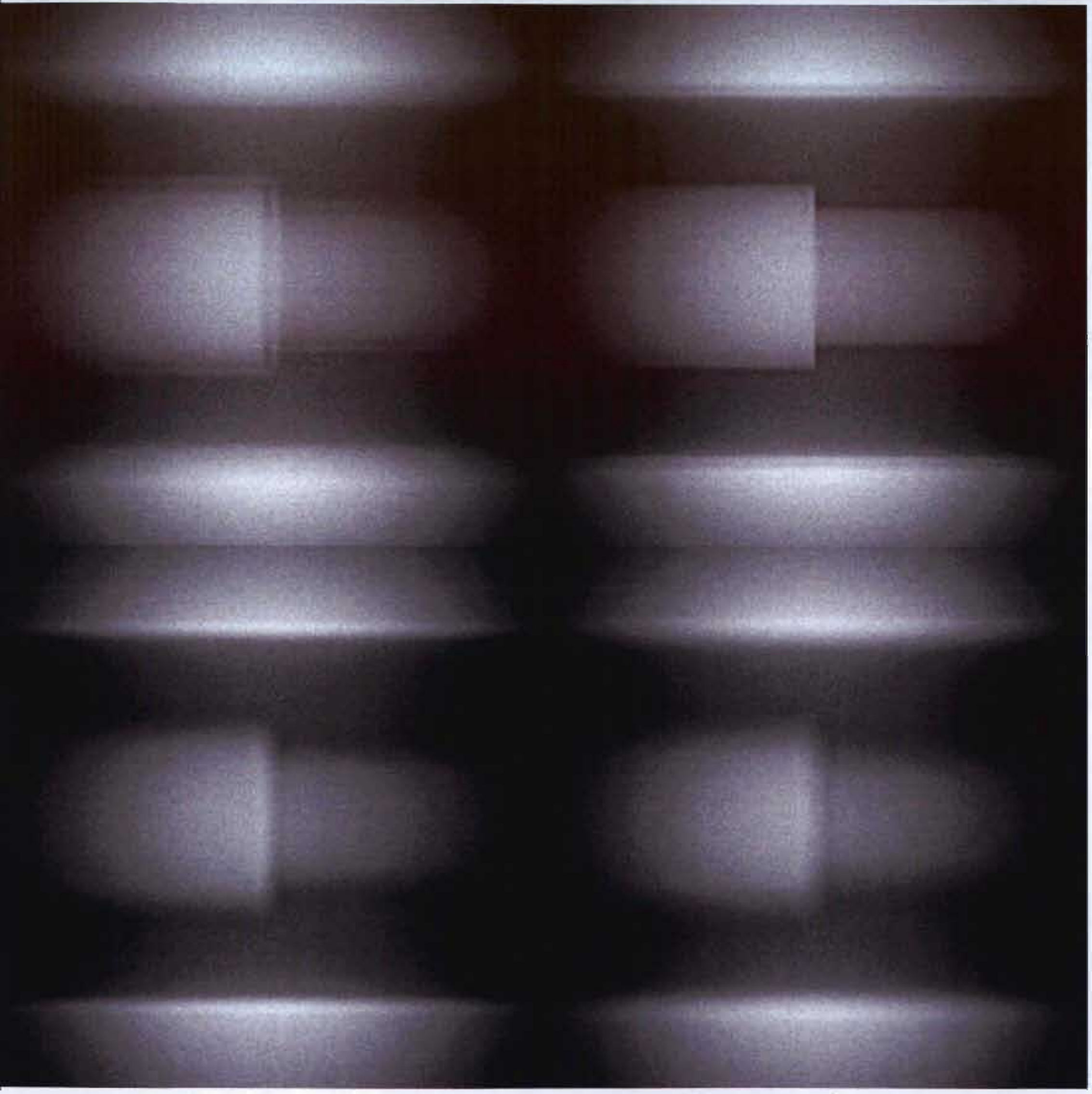
Limning Object



Limning Object

2inch 10 mRad collimator

Lens Settings:
(upper left) 750 MeV
(upper right) 766 MeV
(lower left) 790 MeV
(lower right) 800 MeV

Conclusions

- Simulations of PRad offer a cost effective tool for parameter analysis
- Computing capabilities and accuracy of simulation codes continue to improve which increases the attractiveness of simulations
- Through simulation we have obtained good insight on the effect of collimator size, openings, and chromatic blur

Questions?