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Title: Advances in Proton Radiography

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Proton Radiography Team

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Los Alamos NATIONAL LABORATORY EST. 1943

Advances in Proton Radiography

Los Alamos National Laboratory has used high energy protons as a probe in flash radiography for a decade. In this time the proton radiography project has used 800 MeV protons, provided by the LANSCE accelerator facility at LANL, to diagnose over three-hundred dynamic experiments in support of national and international weapons science and stockpile stewardship programs. In addition, 24 GeV protons, provided by the Alternating Gradient Synchrotron at Brookhaven National Laboratory, have been used to study the capability of proton radiography at higher beam energies. Through this effort significant experience has been gained in using charged particles as direct radiographic probes to diagnose transient systems. The results of this experience will be discussed through the presentation of data from experiments recently performed at the LANL pRad facility as well as results from previous electron radiography work performed at the Idaho Accelerator Center.

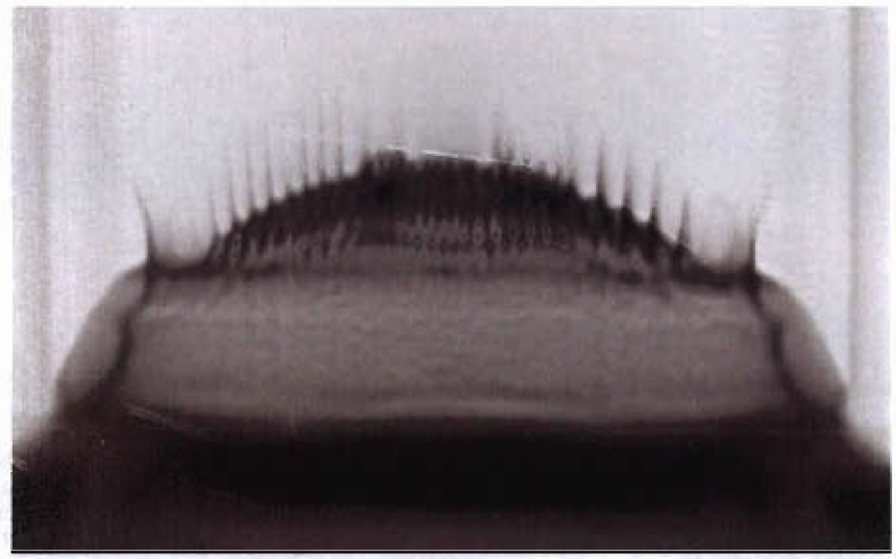
Advances in Proton Radiography

Khariton Readings

March 14, 2011

Frank Merrill for the proton radiography team
Los Alamos National Laboratory

800 MeV Proton Radiography



Proton Radiography Team

National Security Technologies

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DE-3

Joe Bainbridge, Robert Lopez, Mark Marr-Lyon, Paul Rightley

HX-3

Wendy Vogan McNeil

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P-25

Deborah Clark, Eduardo Compos, Camilo Espinoza, Gary Hogan, Brian Hollander, Julian Lopez, Fesseha Mariam, Frank Merrill, Christopher Morris, Matthew Murray, Alexander Saunders, Cynthia Schwartz, Dale Tupa

SAFE-S7

Rodger Liljestrand

Los Alamos Neutron Science Center

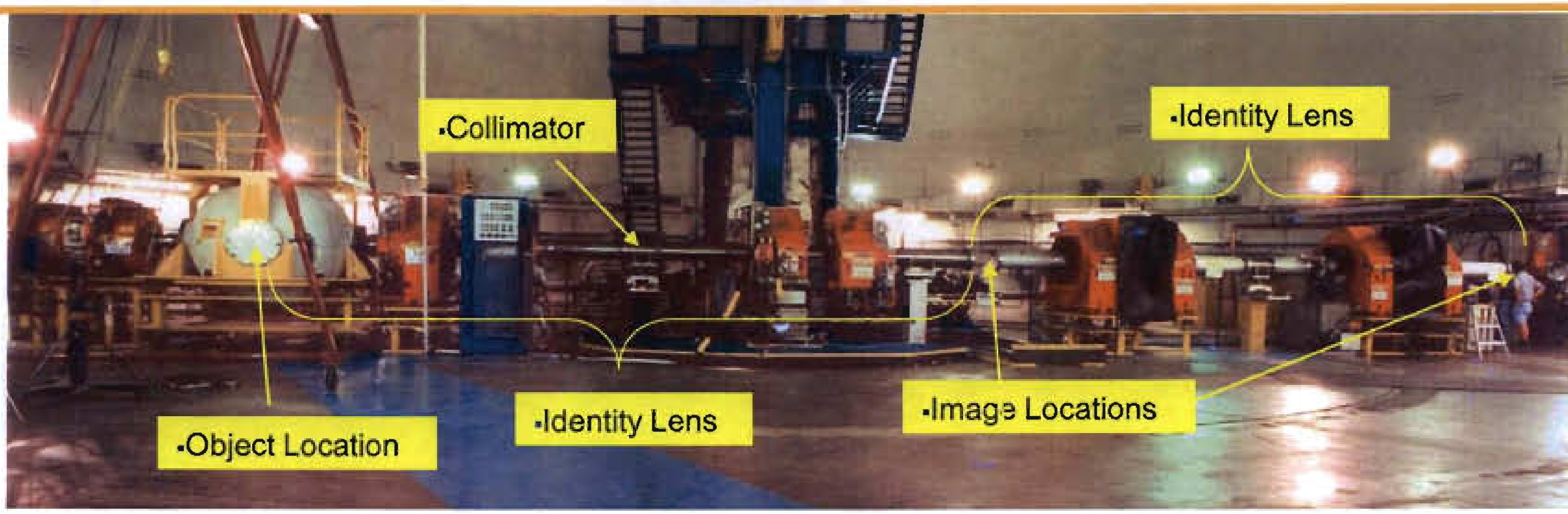
Area C Dome

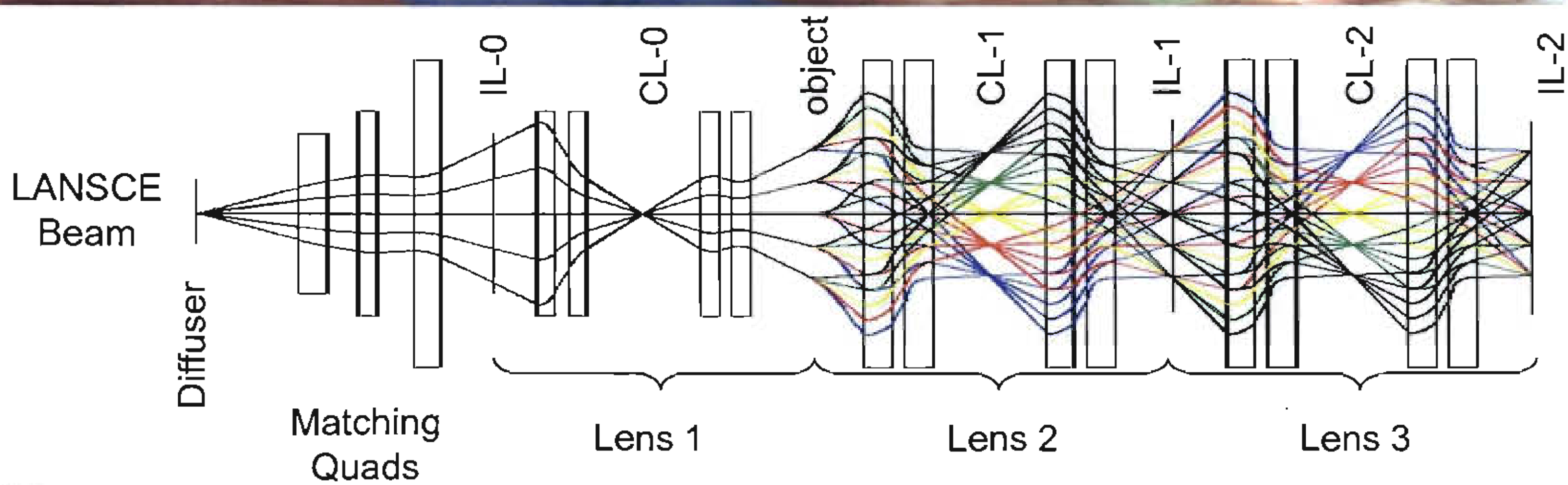
Contained Dynamic Experiments

- Fe Vessel
- 1 m radius
- 5 cm wall

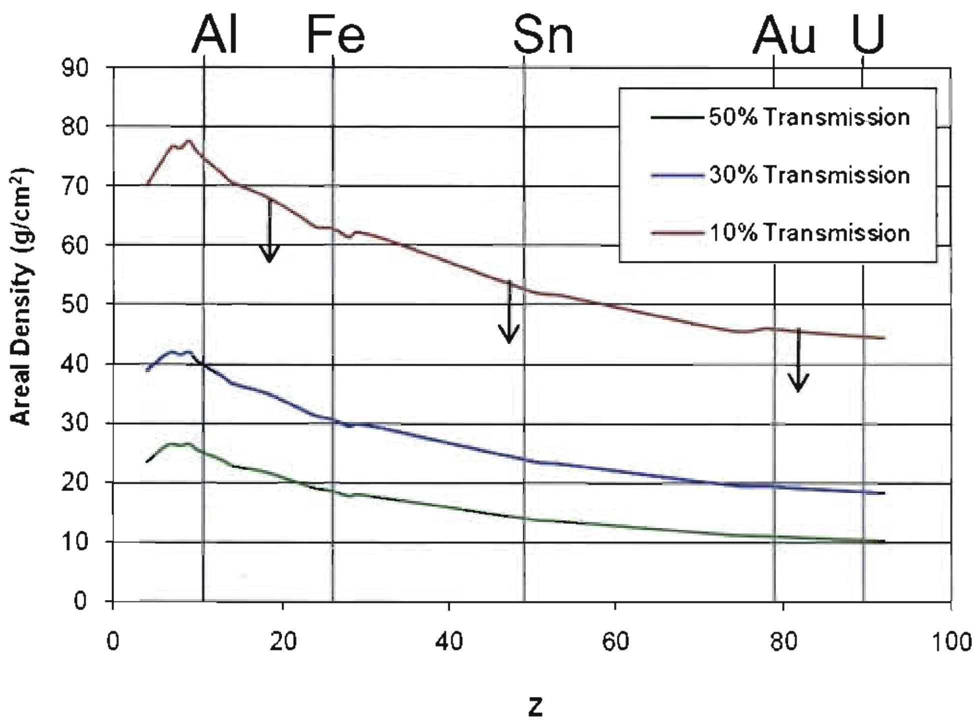
- <4.5 kg/shot
- 2 shots/week
- 3 weeks/month
- 6 months/year

pRad at LANSCE





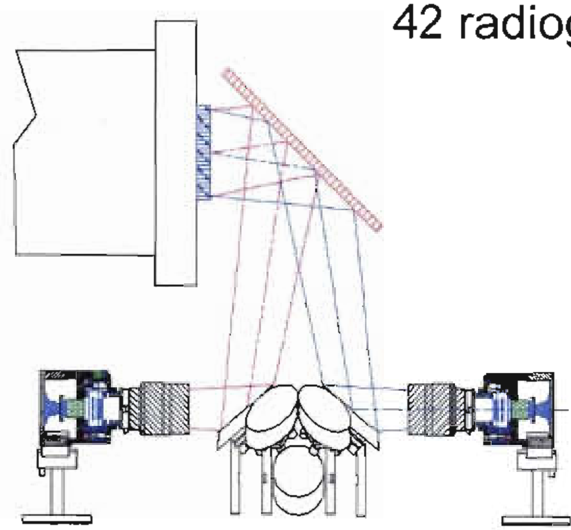
When is an object too thick?



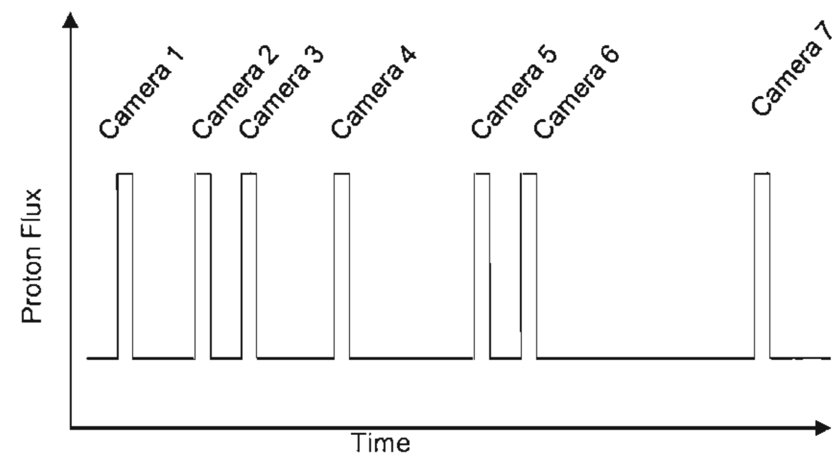
- Areal density contours of constant transmission as a function of atomic number.

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

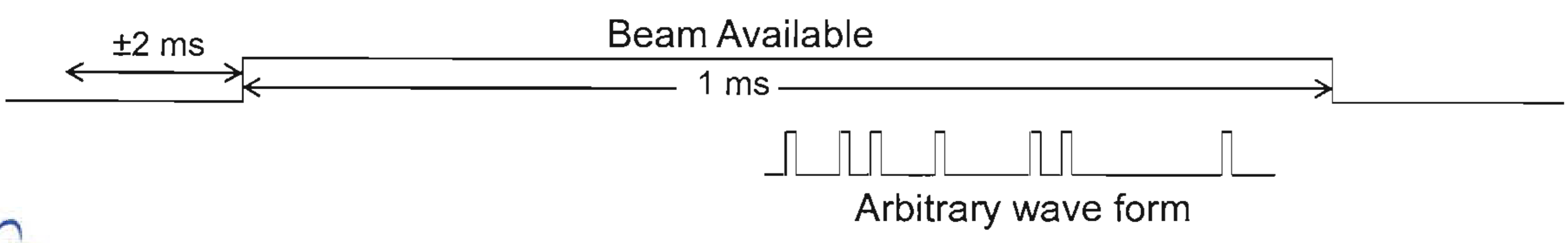
800 MeV Linac Timing Capabilities



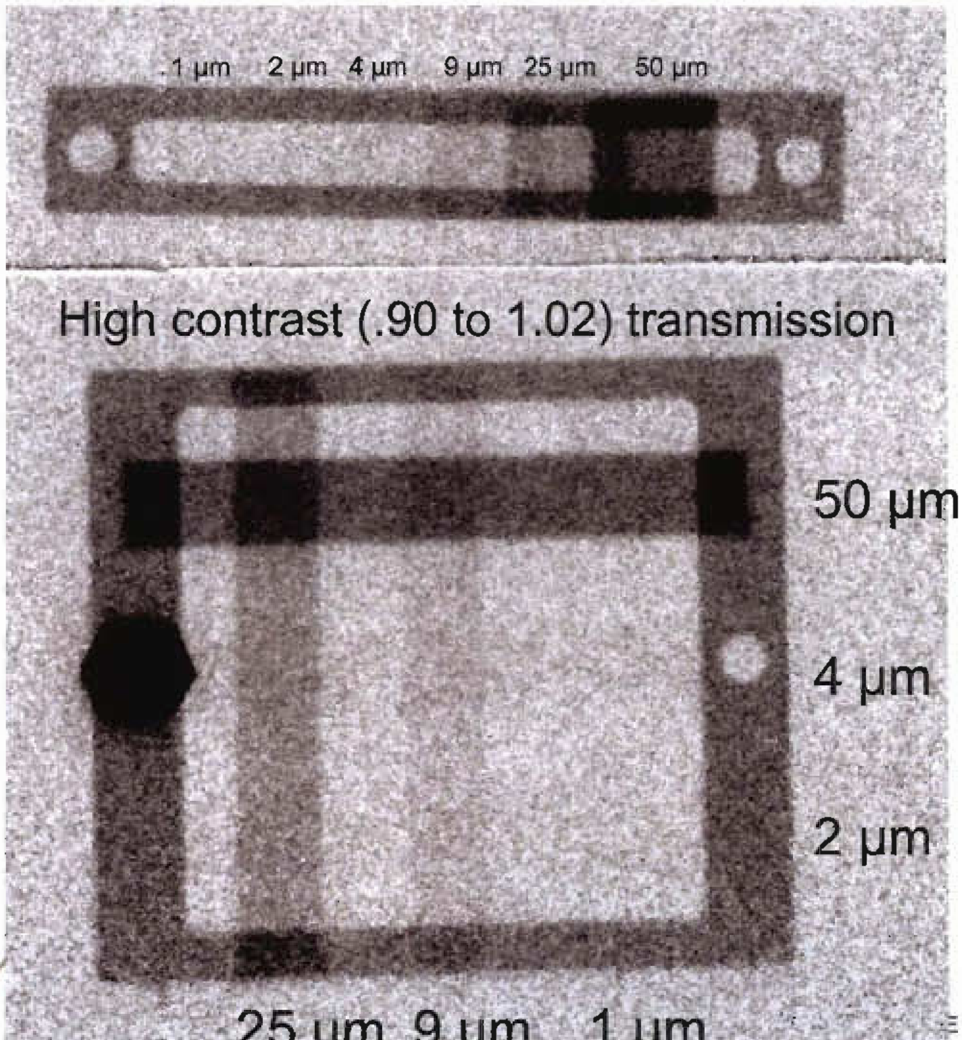
42 radiographs per dynamic



Developing flexibility for "asynchronous" dynamic events



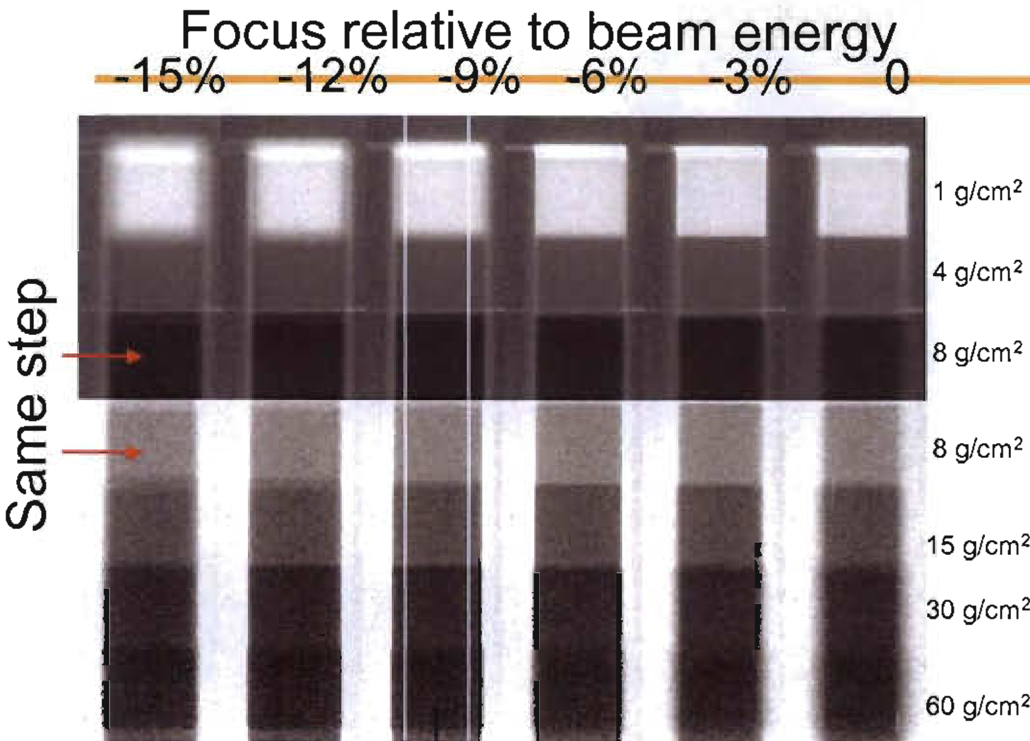
High Dynamic Range

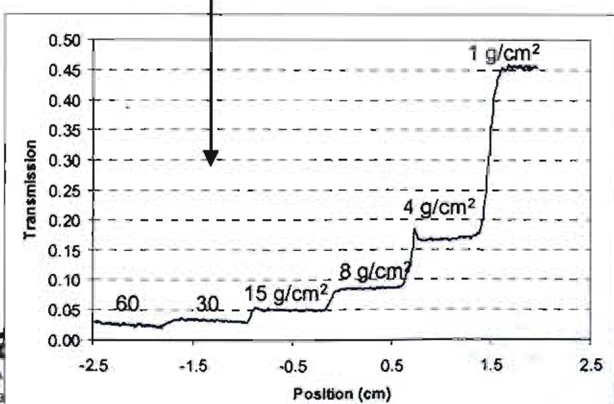


Tantalum Foils:

1 µm	1.66 mg/cm^2
2 µm	3.32 mg/cm^2
4 µm	6.64 mg/cm^2
9 µm	14.94 mg/cm^2
25 µm	41.50 mg/cm^2
50 µm	83.00 mg/cm^2

Thick Tantalum Step Wedge (Dynamic Range)





Scanned focus of radiography system.

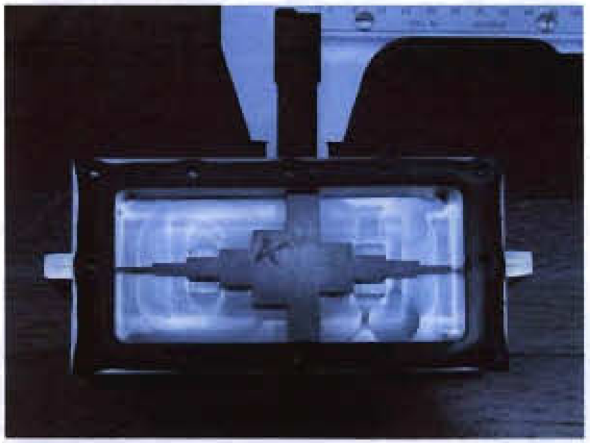
Radiography system was optimized for thin region (5 mrad collimator).

~2% Transmission through thickest step. Could be increased to ~15%.

50% transmission through thinnest step. Would increase to 99% (with 5mRad collimator).

Dynamic range (both Transmission and focus) is a stretching 800 MeV radiography capabilities.

Half the dynamic range fits well.



High Energy Protons are Ideal for Thick Objects

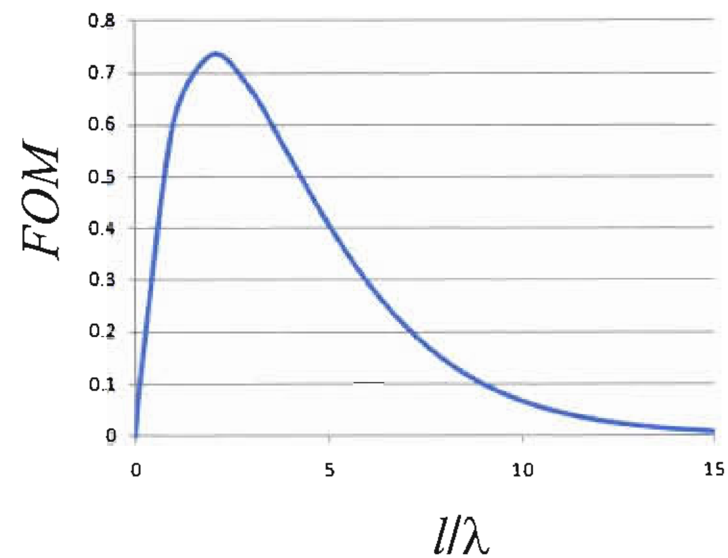
FOM=Figure of Merit

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

$$N = N_0 e^{-l/\lambda}$$

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

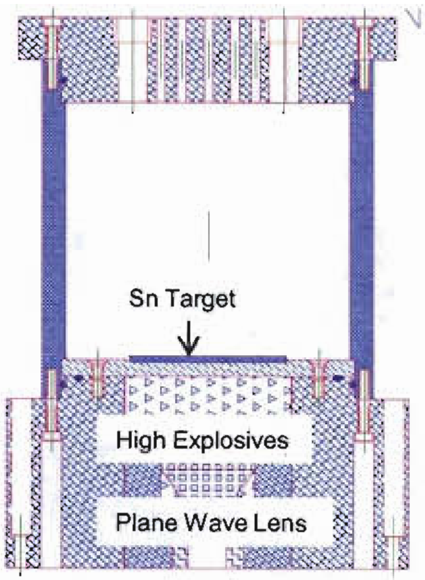
FOM is maximized when $l=2\lambda$



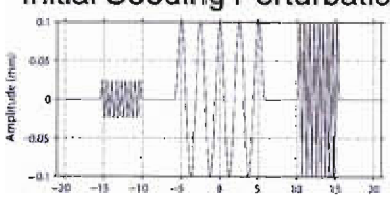
X-rays, λ=25 g/cm^2, l_{opt}=50 g/cm^2 (4 MeV)

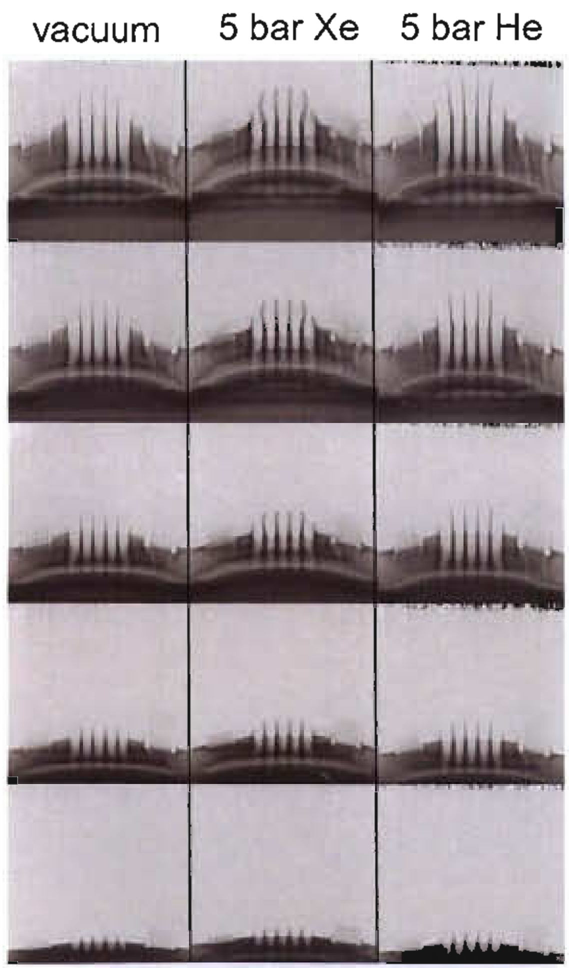
Protons, λ=185 g/cm^2, l_{opt}=370 g/cm^2 (>5 GeV)

Richtmyer-Meshkov Instability Studies

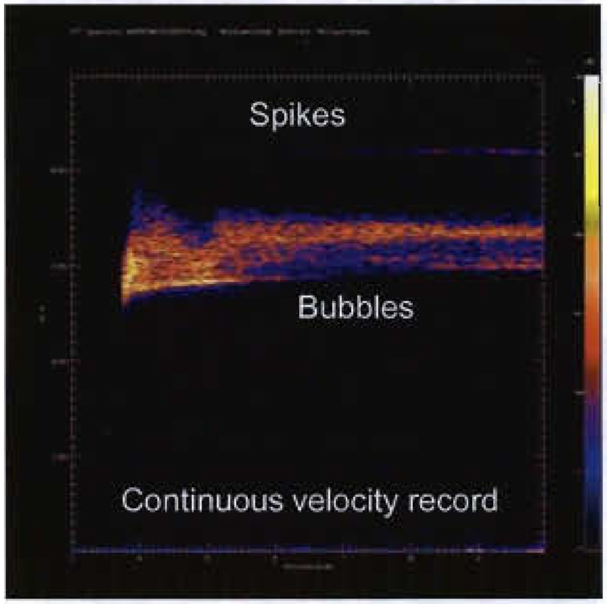


Initial Seeding Perturbation

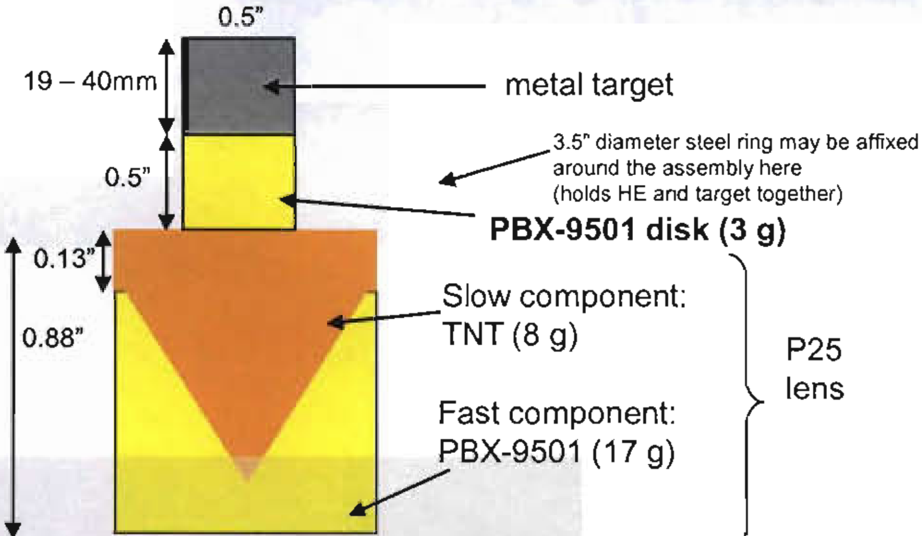


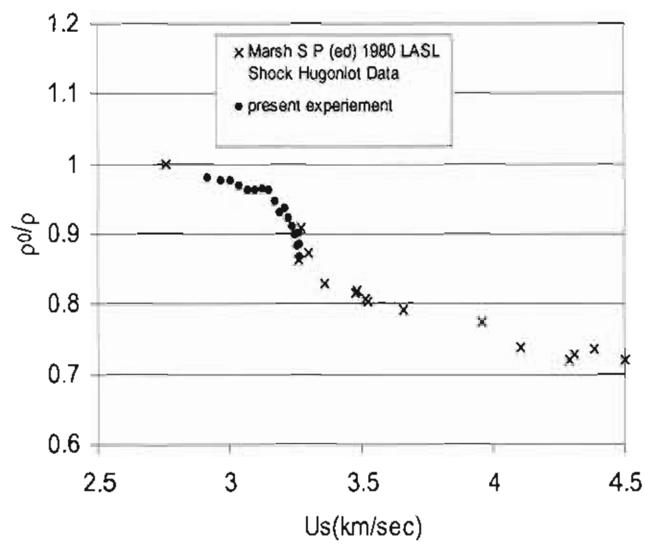


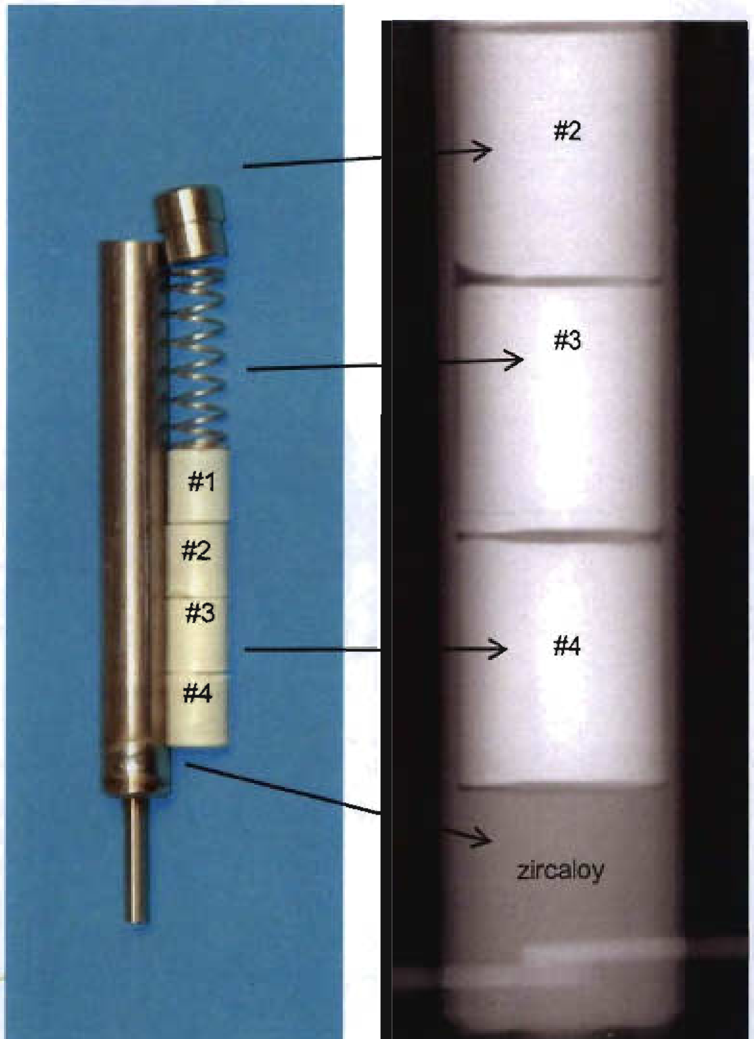
Photon Doppler Velocimetry



Equation-of-state measurements



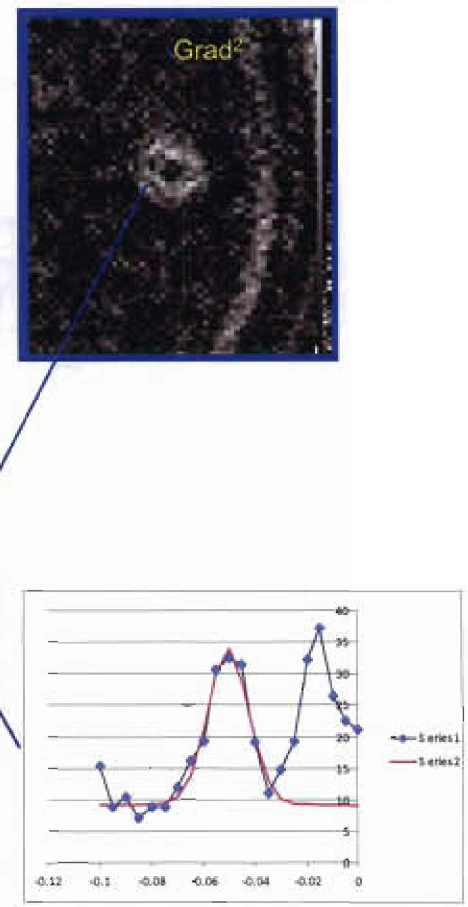




UNCLASSIFIED

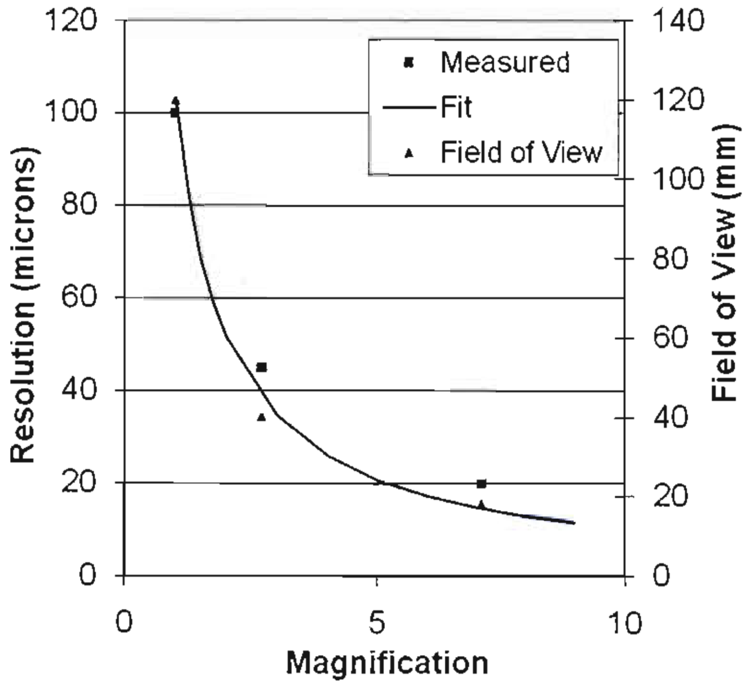
Filtered Back Projection:

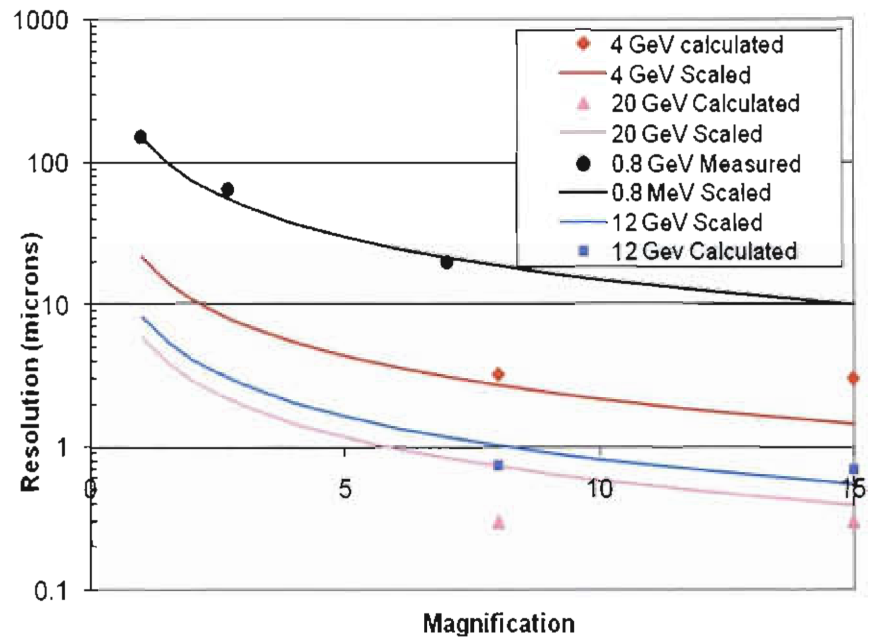
Fainter 250 μm long by ~150 to 200 μm diameter inclusions are shown in the circles



Resolution	~ 80 μm
$Diameter_{Inclusion}$	~ 350 μm
$Length_{Inclusion}$	~ 550 μm

Combining Higher Energy with Magnifiers

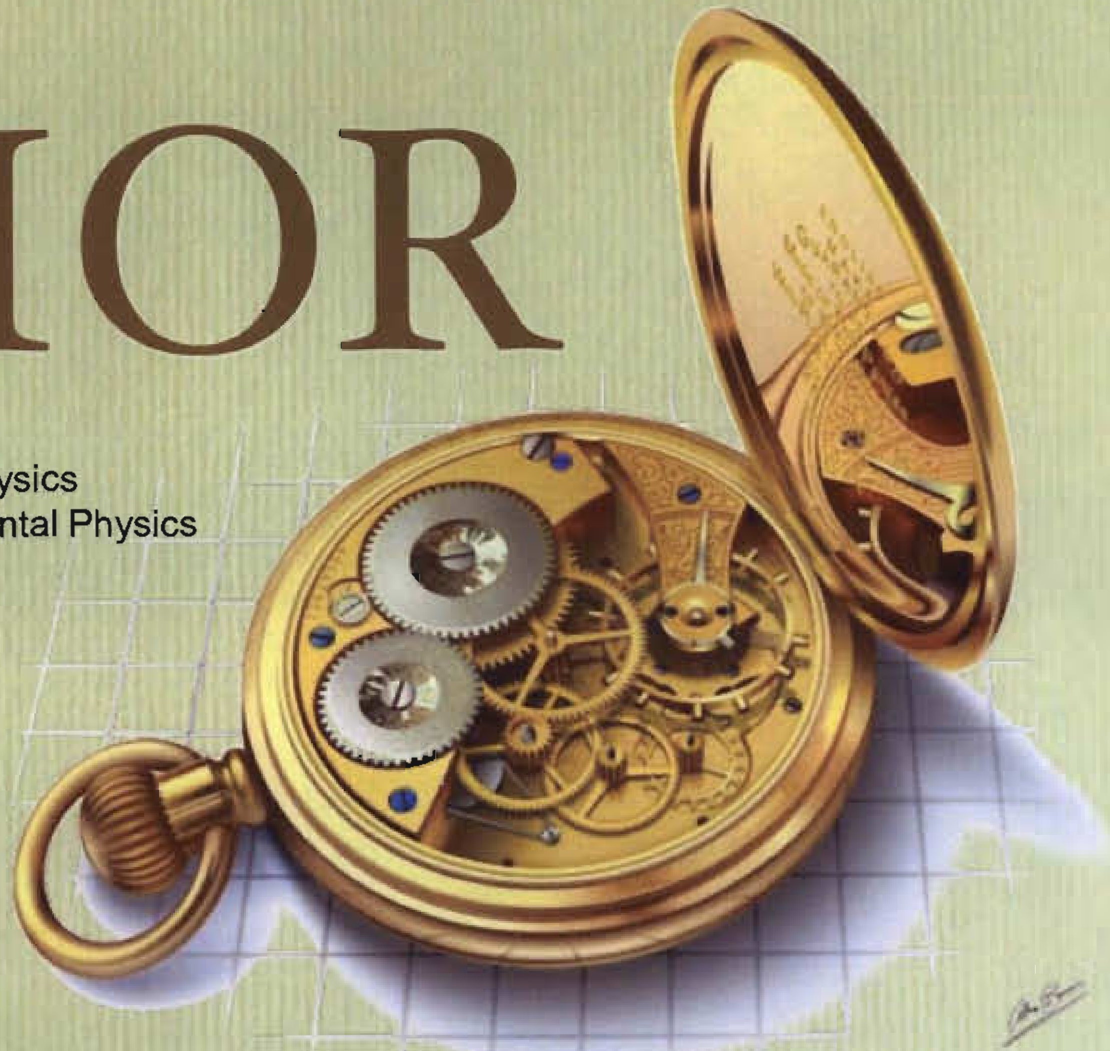




Magnification at high energy could result in high resolution (<1 micron?) with a 20 mm field of view

PRIOR

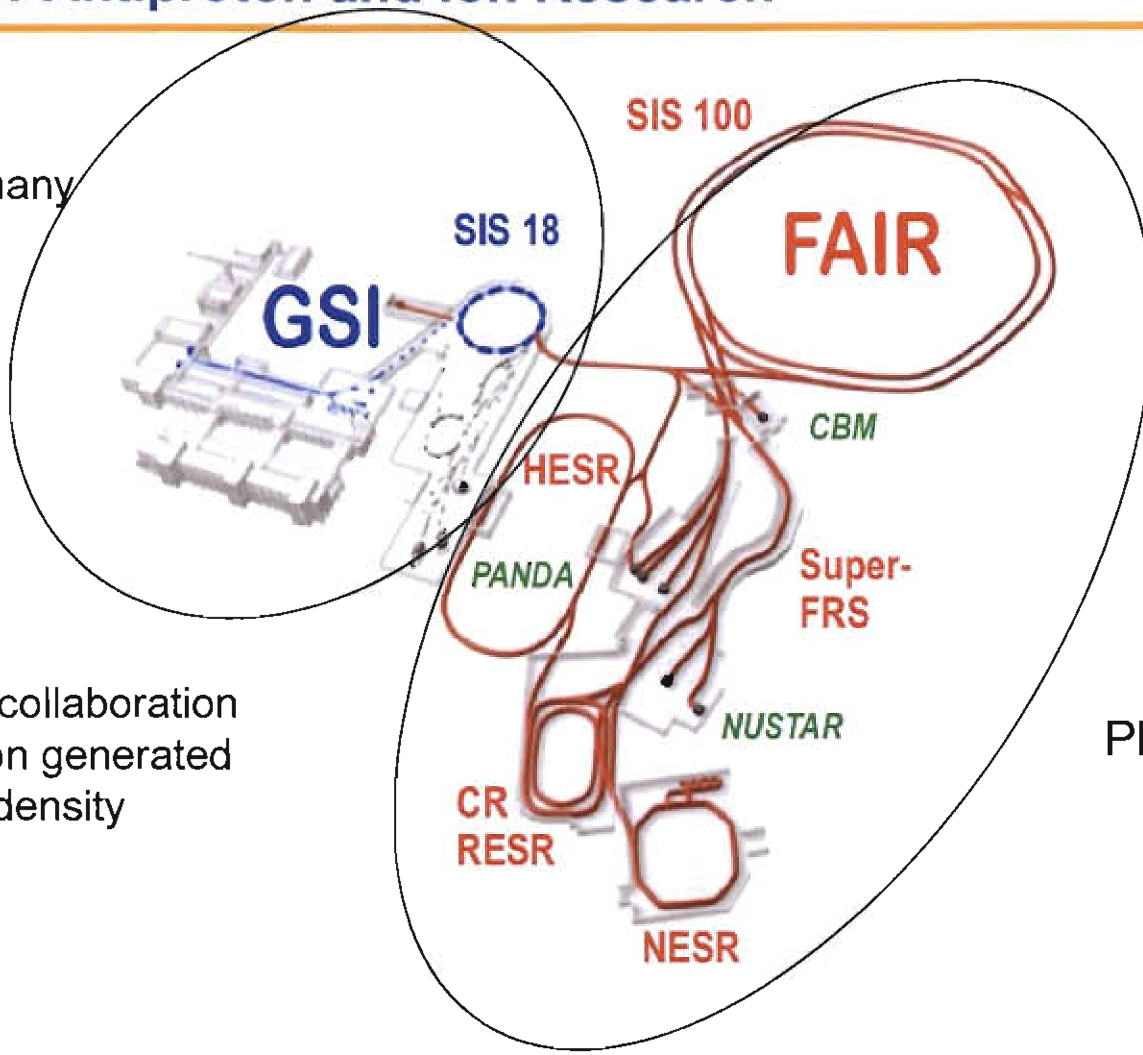
GSI
Institute of Problems for Chemical Physics
Institute for Theoretical and Experimental Physics
Los Alamos National Laboratory
Technische Universitat Darmstadt



Proton Microscope for FAIR

Facility for Antiproton and Ion Research

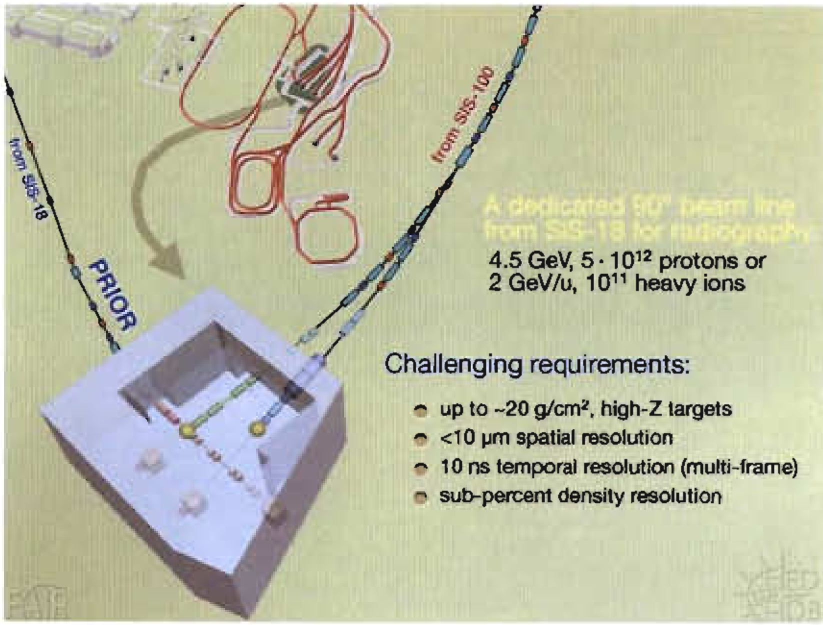
Existing facility
Darmstadt, Germany

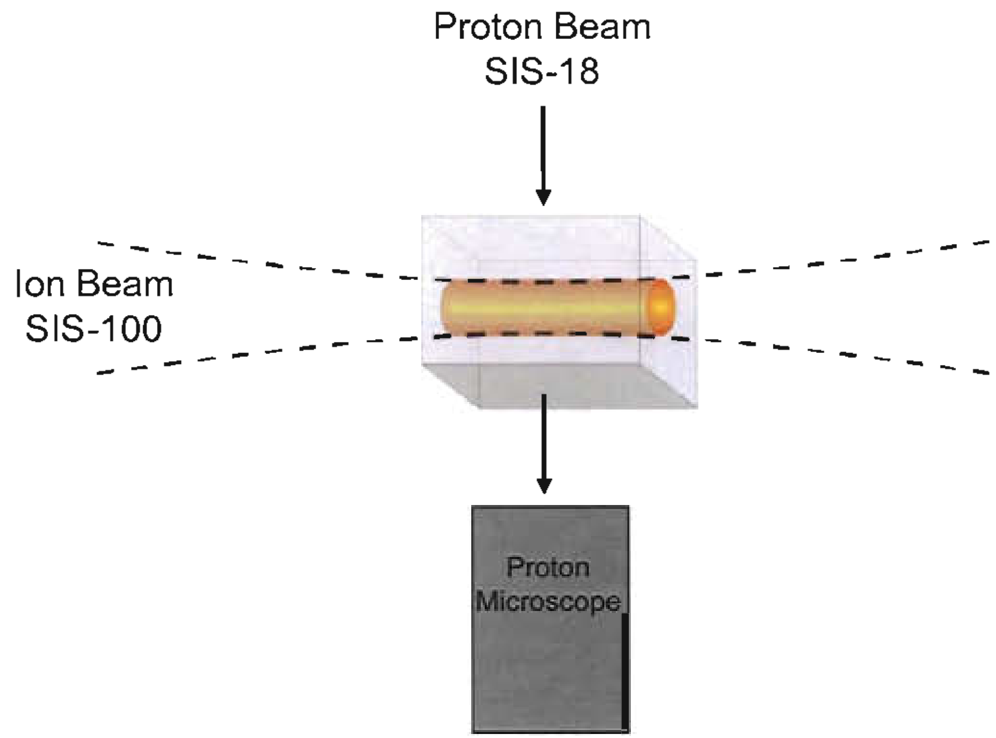


HEDgeHOB collaboration performing ion generated high energy density

Planned Upgrade

Proton Microscope and Ion Heating at FAIR

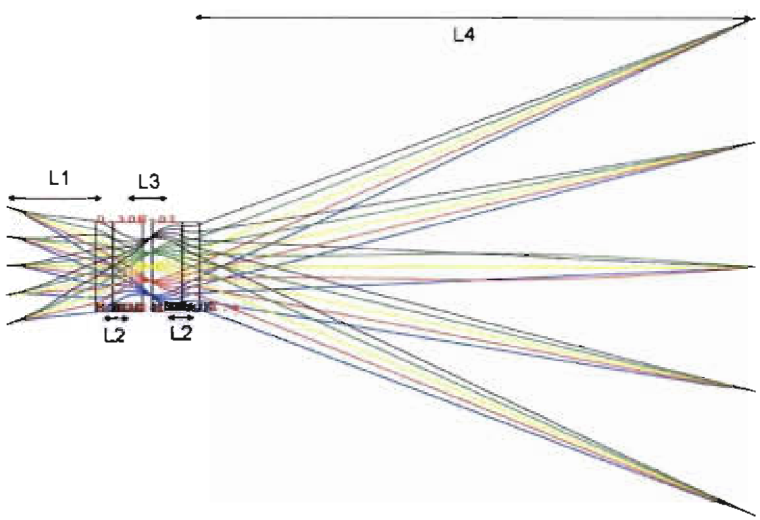




PRIOR Goals

4.5 GeV Proton Microscopy

Proton trajectories through the baseline PRIOR lens design.



Lens and detector design goals (in accordance with FAIR pRad specifications):

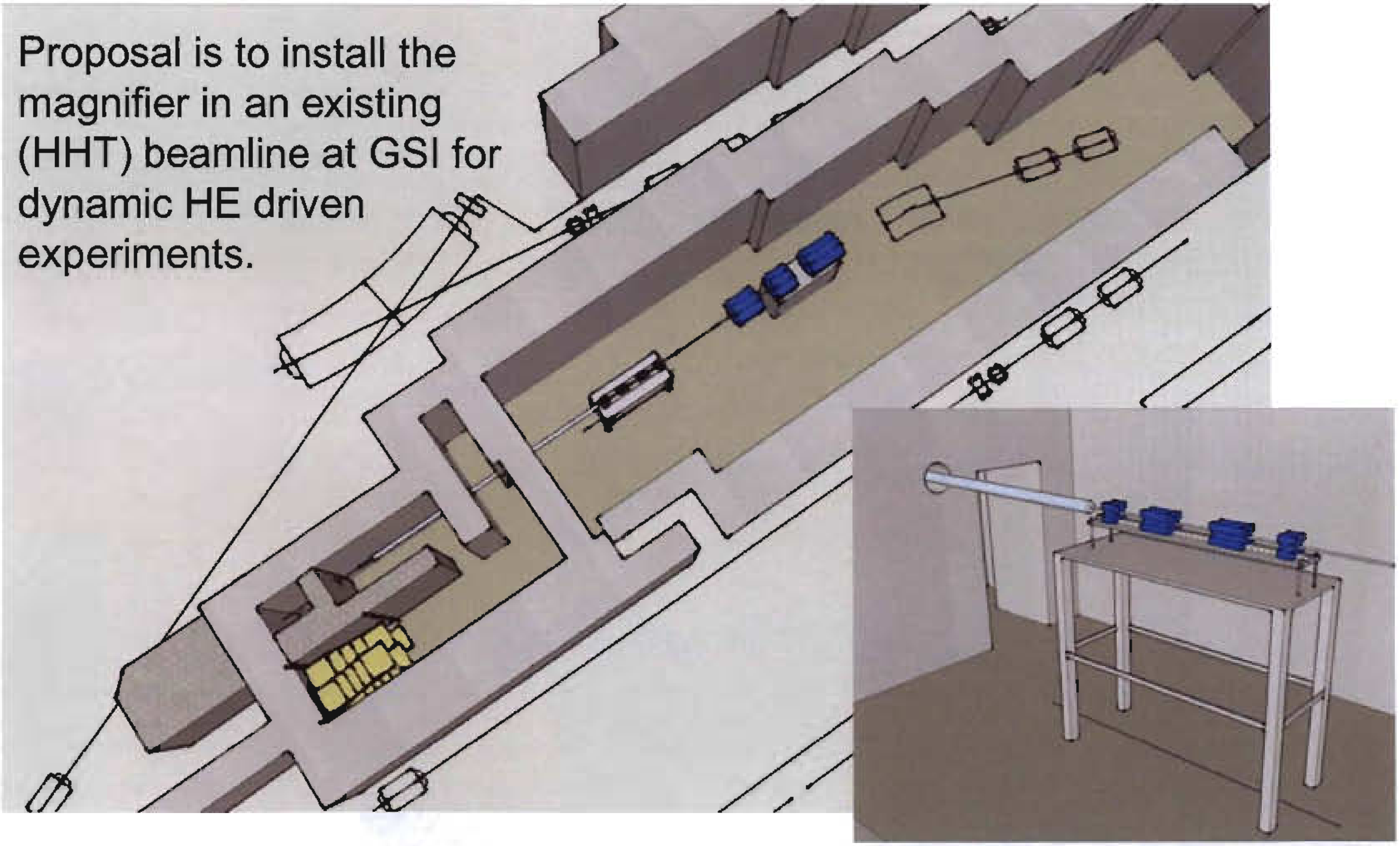
- less than 10 µm spatial resolution;
- sub-percent density resolution;
- target areal density up to 5 – 50 g/cm^2, high-Z targets;
- temporal resolution <10 ns (for FAIR), <100 ns (for GSI);
- field of view: 20 mm;

Dynamic experiment design goals:

- HE experiments: GSI is certified for up to 100 g TNT loads;
- HE containment: already available at GSI “red Russian” vessel Beam pipe downstream of the vessel will be a part of the containment system;
- vacuum system capable of achieving < 1 mbar vacuum in containment system.

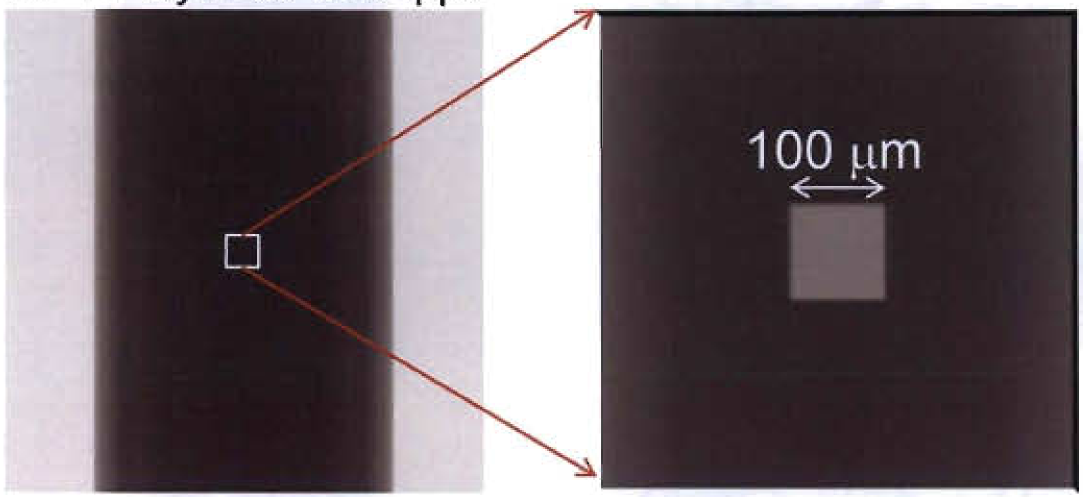
Intermediate Installation at GSI

Proposal is to install the magnifier in an existing (HHT) beamline at GSI for dynamic HE driven experiments.

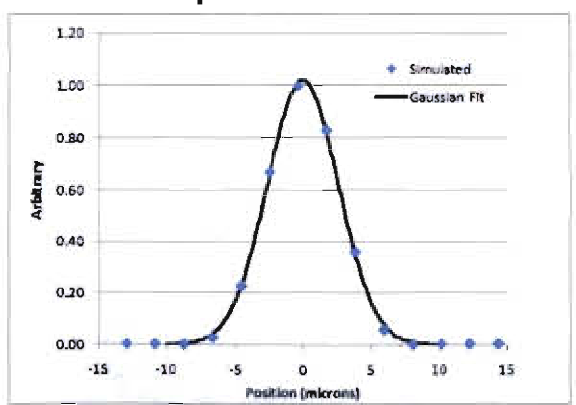


Forward Model Simulations of PRIOR Microscope

0.5 mm Cylinder of Copper

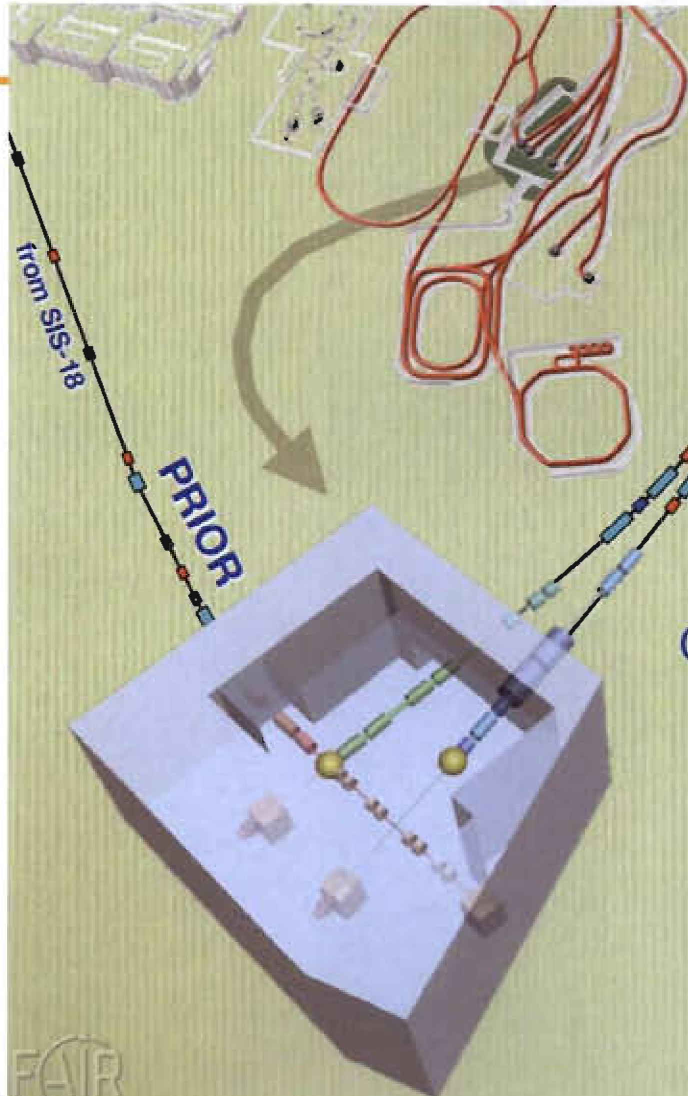


Line Spread Function



- Gaussian Line Spread Function
- ~8 µm FWHM resolution
- Prediction with no noise

4.5 GeV Protons Available at FAIR



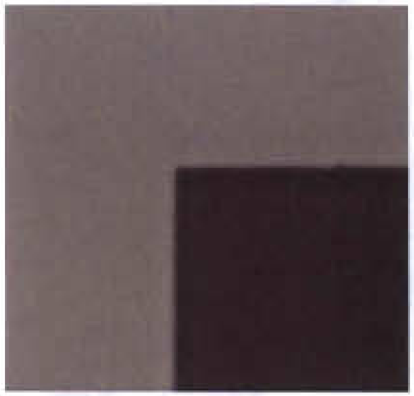
A dedicated 90° beam line from SIS-18 for radiography:
4.5 GeV, $5 \cdot 10^{12}$ protons or
2 GeV/u, 10^{11} heavy ions

Challenging requirements:

- up to ~20 g/cm^2, high-Z targets
- <10 μm spatial resolution
- 10 ns temporal resolution (multi-frame)
- sub-percent density resolution

Resolution limits

CCD (1 frame)



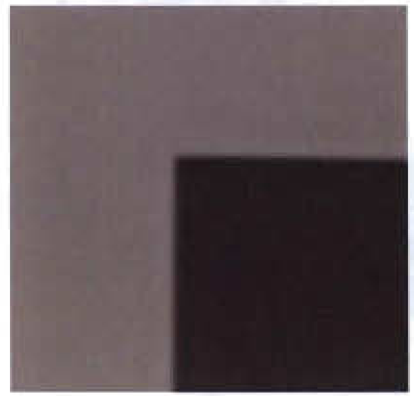
Total Resolution 47 µm
Camera Resolution 41 µm

2000 x 2000 Pixels

Limit: Fast Gated Diode

DQE: 15%

Hybrid Si-CMOS (18 frames)



Total Resolution 70 µm
Camera Resolution 65 µm

700 x 700 Pixels

Limit: Pixel Count

DQE: 80%

Image Plate

Total Resolution 41 µm
Detector Resolution ~41 µm

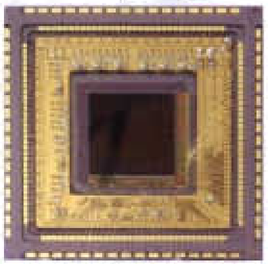
Limit: Exposure time

DQE: ~100%

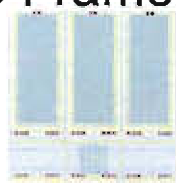
Hard to increase DQE of fast gated CCD cameras (limited by photo cathode on diodes), increasing pixel count to 1400x1400 and frames/camera>6 appears straight forward (~$2M).

Next Generation Imagers Improving Resolution and Frame Count

pRad-1 Imager



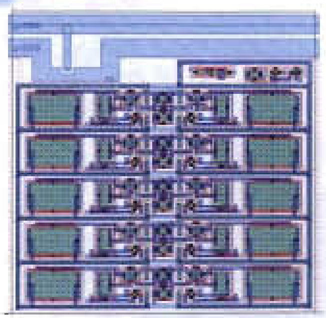
3 Frames



Single Pixel

pRad-2 Imager

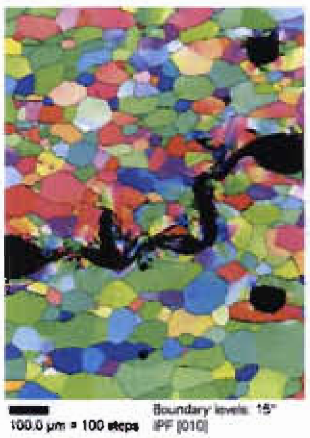
10 Frames



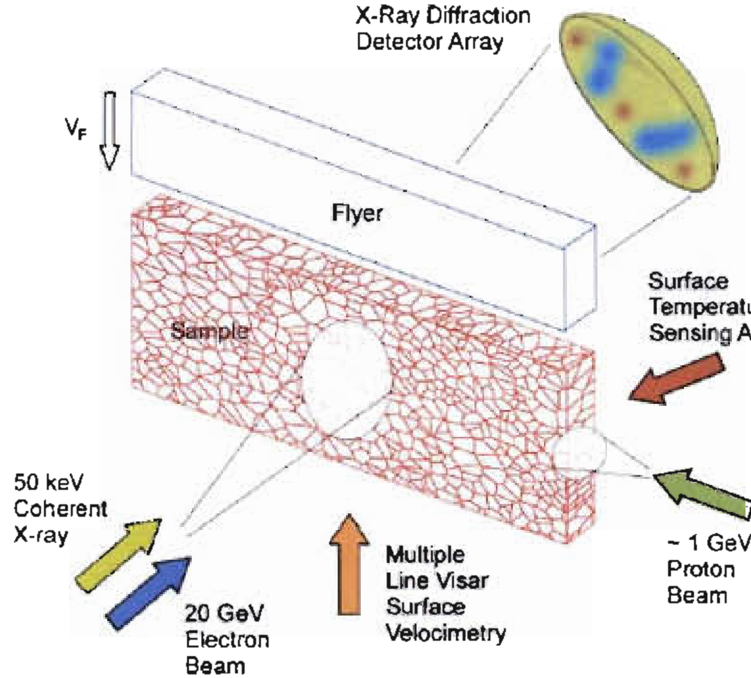
Single Pixel

Design Parameter	pRAD-1 Imager	New 2nd Generation pRAD Imager
Minimum integration time (Global shutter)	150 ns	50ns
Nominal min. inter-frame time	358 ns	150 ns
Effective Dynamic Range	11.4 bits	12 bits
Read noise	100 e-	~ 35 e-
Imaging array size	720×720 px	1100×1100 pixels
Number of frames	3	10
Pixel pitch	26 μm	40 μm
Sensor QE @ 415 nm	>80%	>90%
Chip size	21×22 mm^2	~44×45 mm^2
Optical Fill Factor	~100 %	~100 %
Saturation level/ Well depth	180 ke-	~ 150 ke-

MaRIE: Matter and Radiation In Extremes
MPDH: Multi-Probe Diagnostic Hall



The goal :- Predict dynamic microstructure and damage evolution



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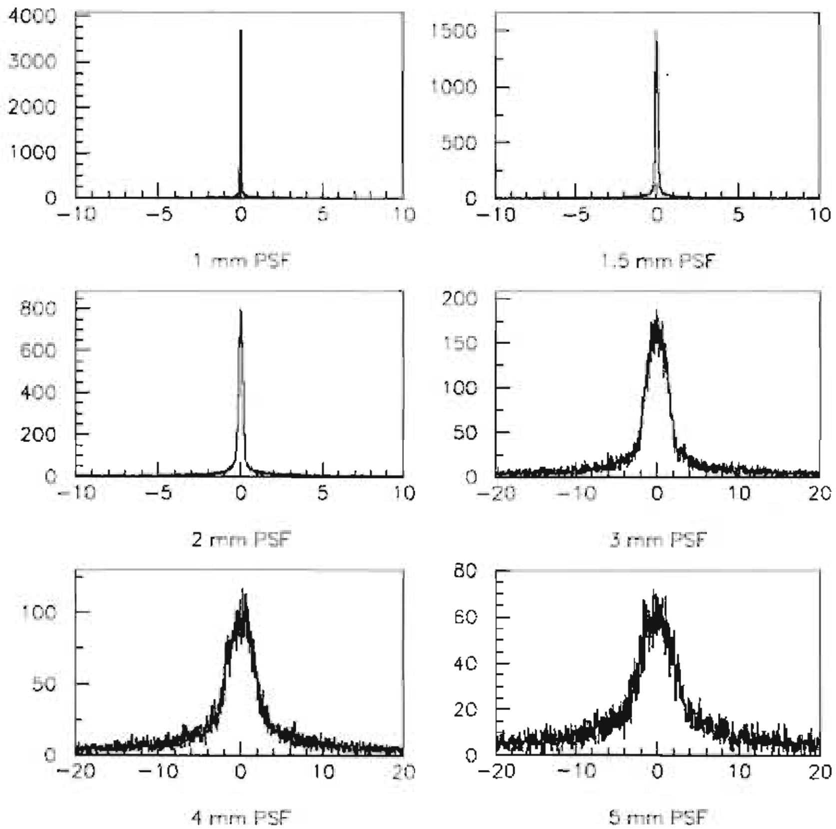
Meso-Scale Theory and Simulation

The first experiment :- Multiple, simultaneous dynamic in situ diagnostics with resolution at the scale of nucleation sites (< 1 µm; ps – ns)

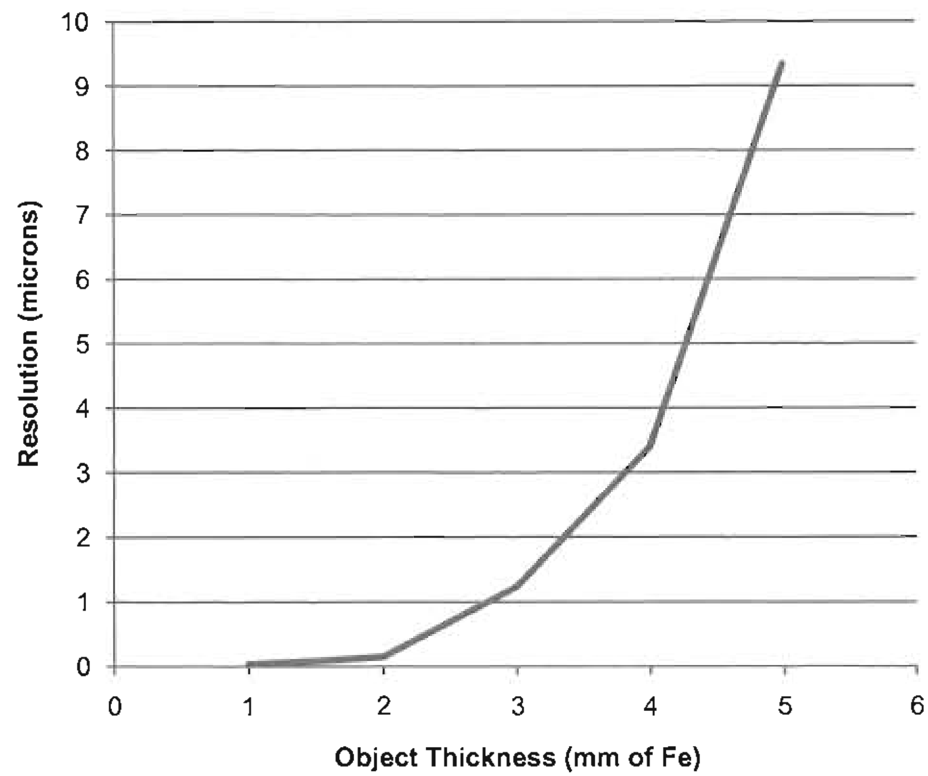
The model :- Accurate sub-grain models of microstructure evolution coupled to molecular dynamics

Transmission High Energy Electron Microscopy

Iron Object of Various Thicknesses



~RMS width of "core" through Iron



Layout of Marie