Proton Radiography at FAIR: density diagnostics for HEDgeHOB experiments

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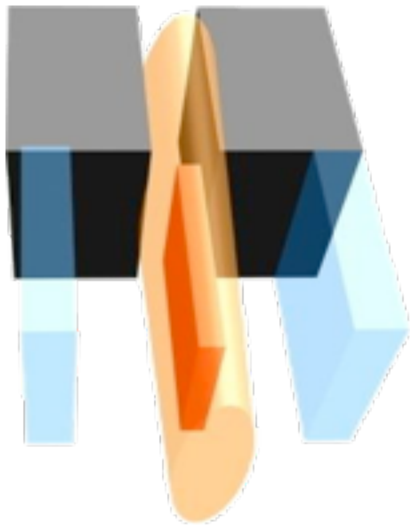
HEDgeHOB collaboration will construct and run at FAIR two main HEDP experiments: HIHEX and LAPLAS

HIHEX

Heavy Ion Heating and Expansion

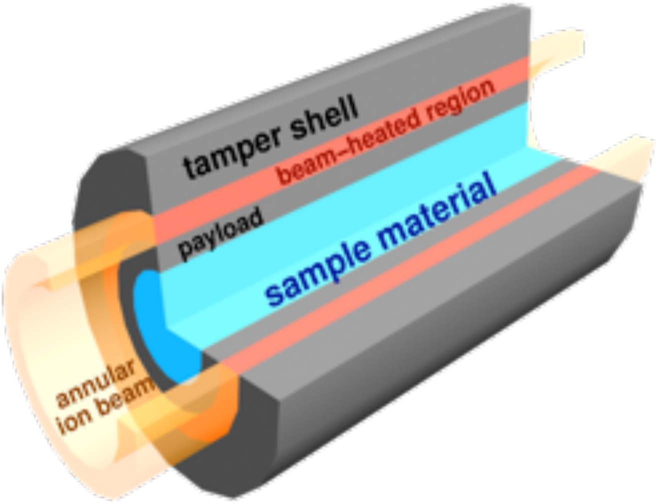


- uniform quasi-isochoric heating of a large-volume dense target
- isentropic expansion in 1D plane or cylindrical geometry

Numerous high-entropy HED states:
EOS and transport properties of e.g., non-ideal plasmas, WDM and critical point regions for various materials

LAPLAS

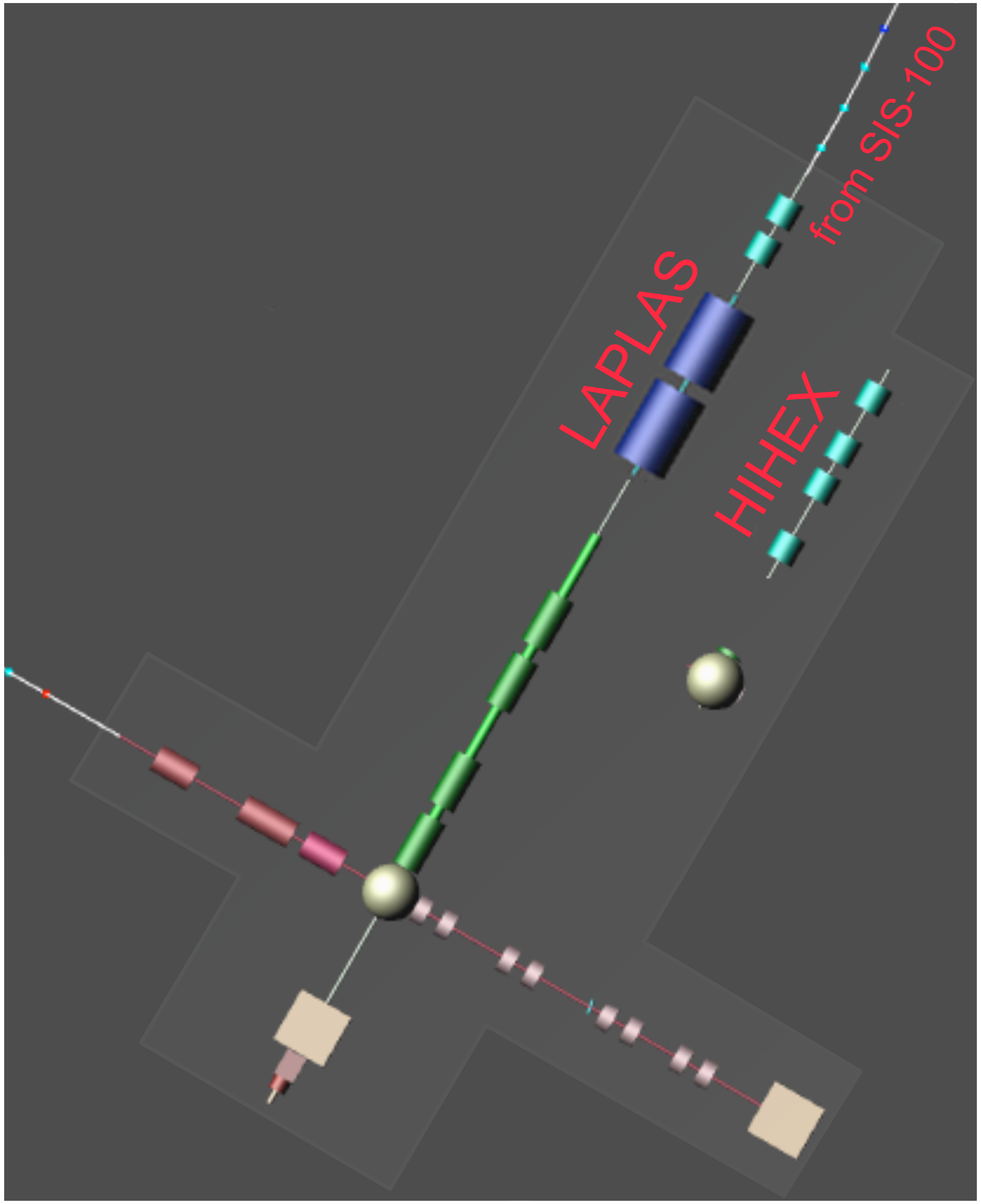
Laboratory Planetary Sciences



- hollow (ring-shaped) beam heats a heavy tamper shell
- cylindrical implosion and low-entropy compression

Mbar pressures @ moderate temperatures:
high-density HED states, e.g. hydrogen metallization problem, interior of Jupiter and Saturn

Plasma Physics beam lines and cave at FAIR

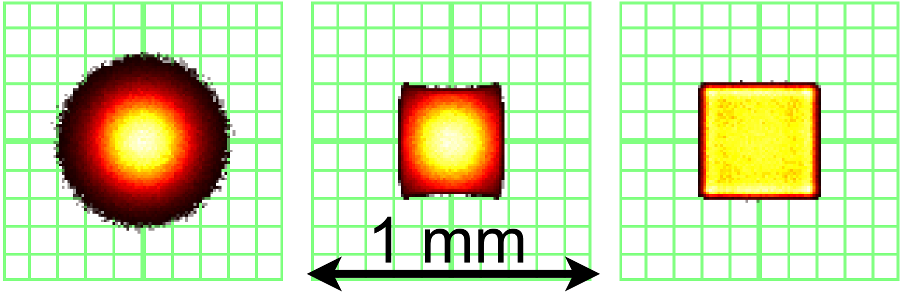


SIS-100:

One beam line
with replaceable elements:

- **HIHEX** experiments

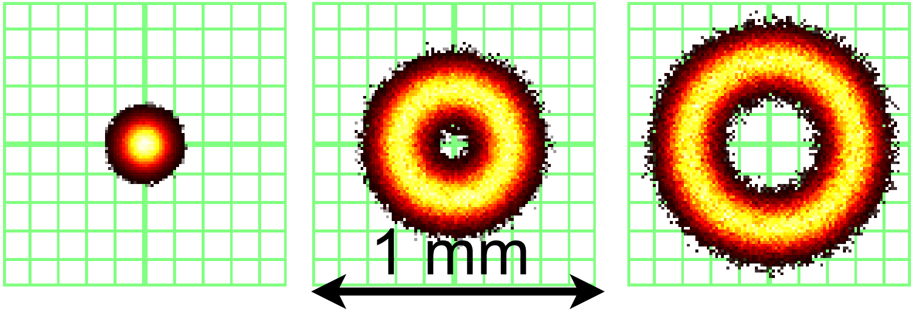
beam shaping system



Transverse distributions of beam intensity at focal plane for HIHEX experiments

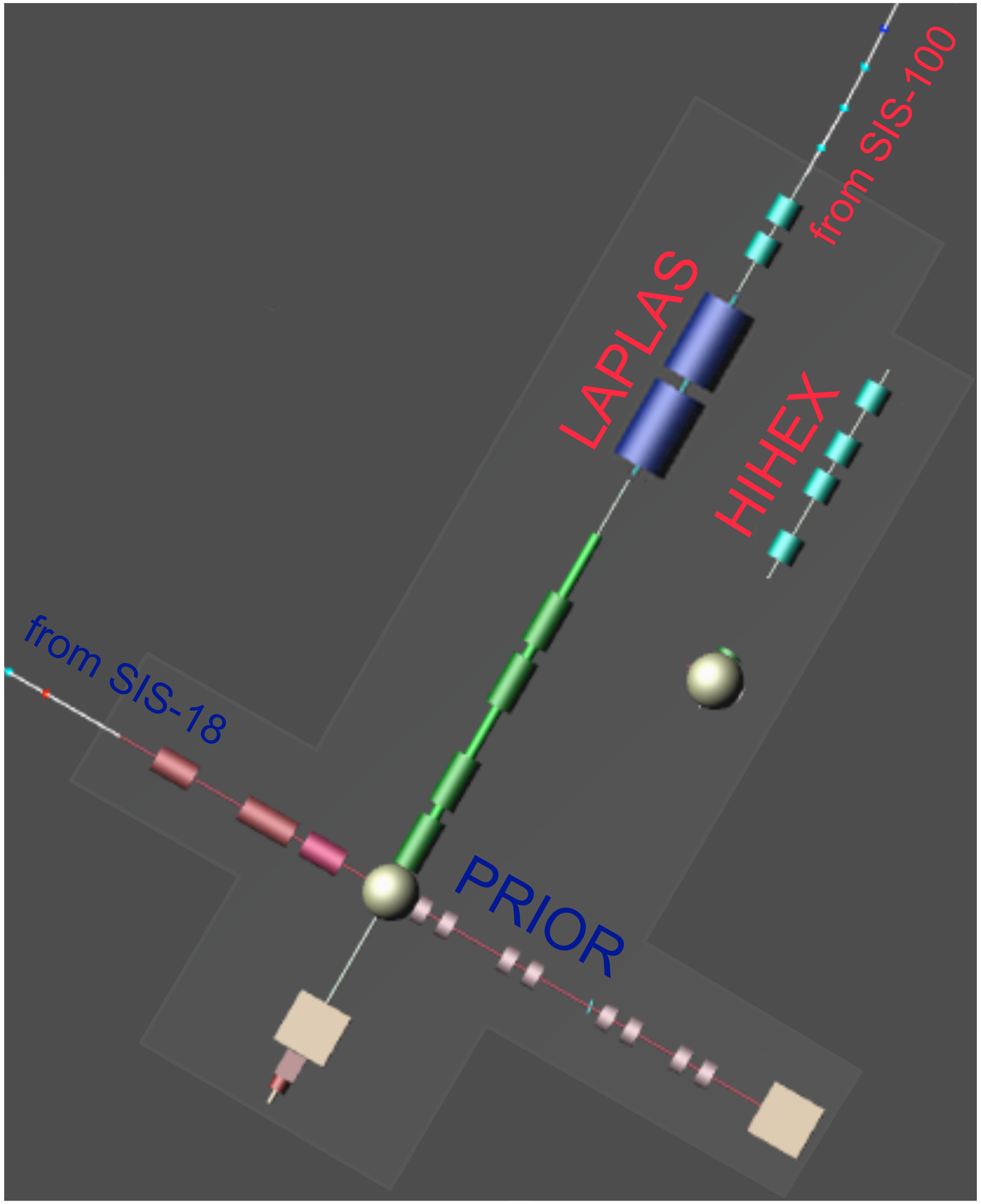
- **LAPLAS** experiments

RF beam deflector (“wobbler”)
to provide annular ion beam



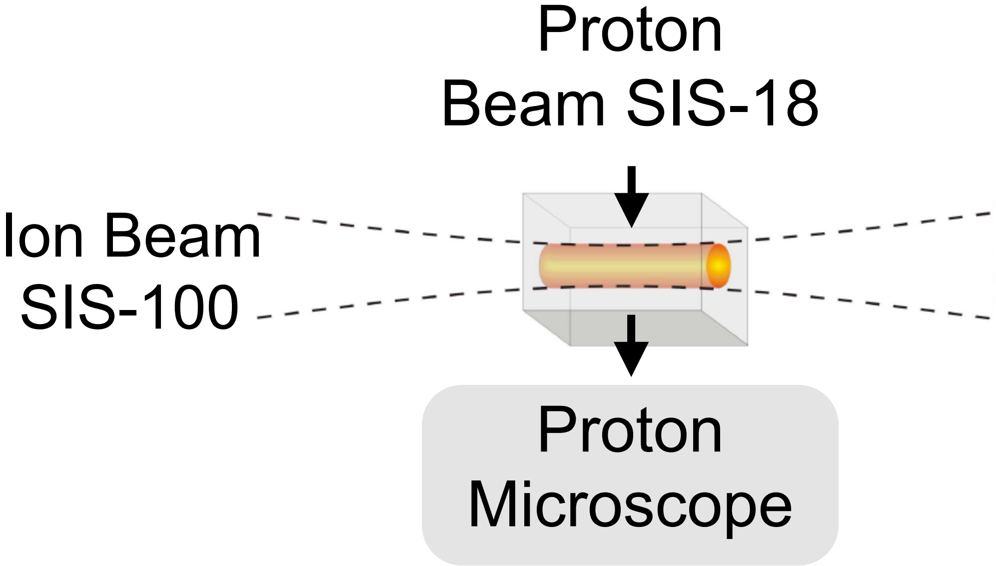
Transverse distributions of beam intensity at focal plane for LAPLAS experiments

Plasma Physics beam lines and cave at FAIR



SIS-18:

a dedicated radiography beam line - density diagnostics for **LAPLAS** and **HIHEX** experiments



Proton Beam SIS-18

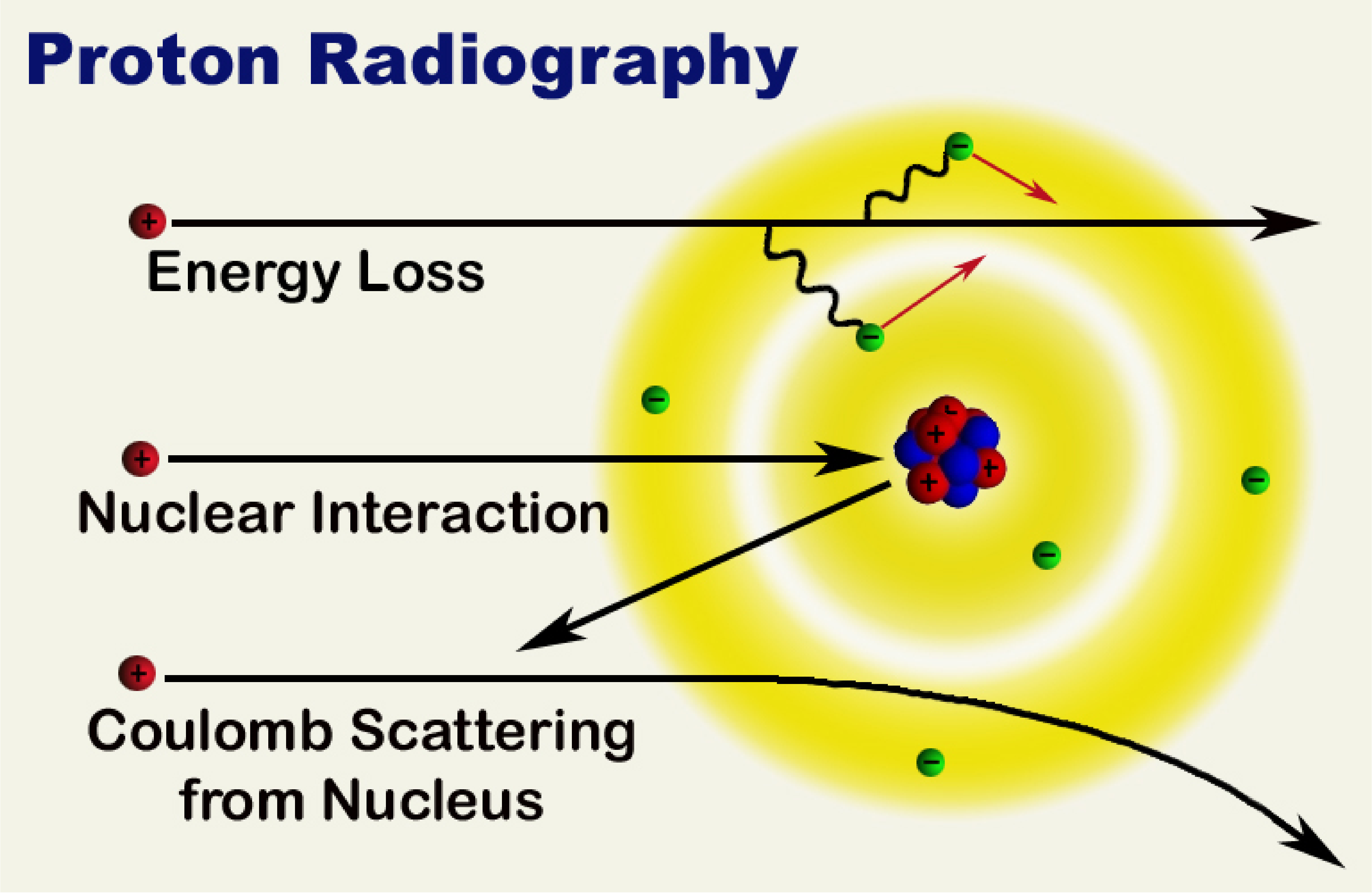
Ion Beam SIS-100

Proton Microscope

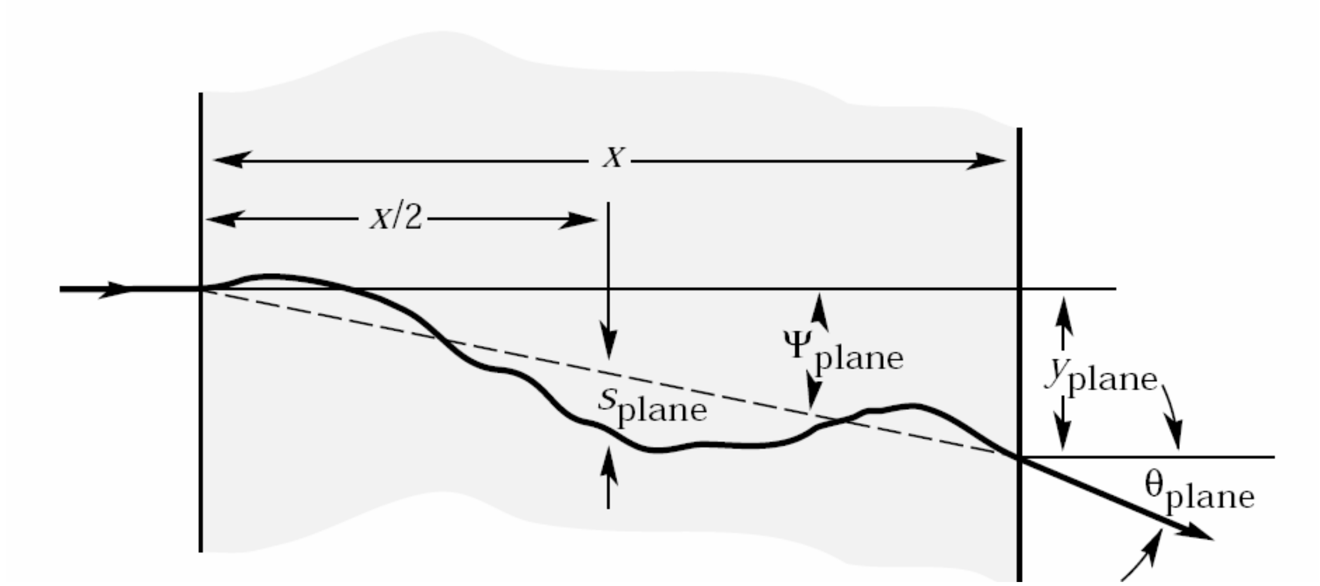
PRIOR - **Pr**oton M**i**crosc**o**pe for FAI**R**:

- proton energy **4.5 GeV**
- up to **~20 g/cm^2** (Fe, Pb, Au, etc.)
- **≤10 µm** spatial resolution
- **10 ns** time resolution (multi-frame)
- **sub-percent** density resolution
- proton illumination spot size: **3–15 mm**
- imaging, aberrations correction by magnets

Proton Interactions



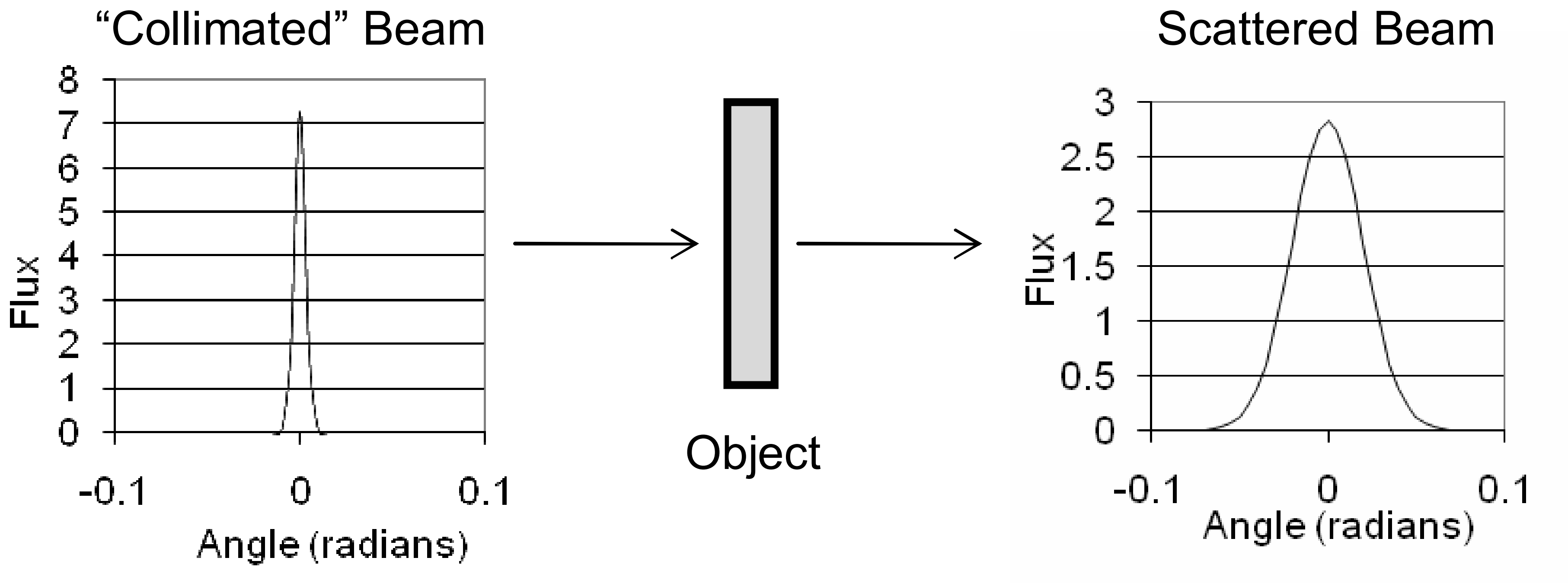
Multiple Coulomb Scattering



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

RMS Width

Full Width Half Maximum=2.35 θ_o


“Collimated” Beam

Scattered Beam

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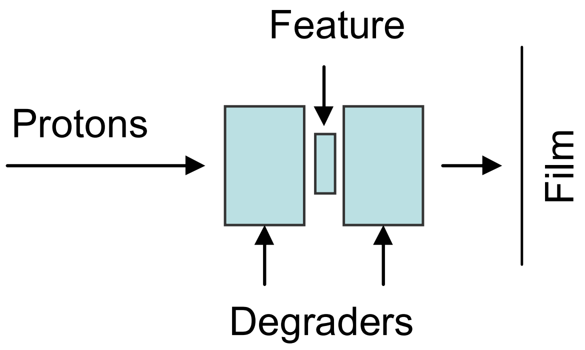
*C. Amsler et al., Physics Letters **B667**, 1 (2008)

Marginal Range Radiography



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

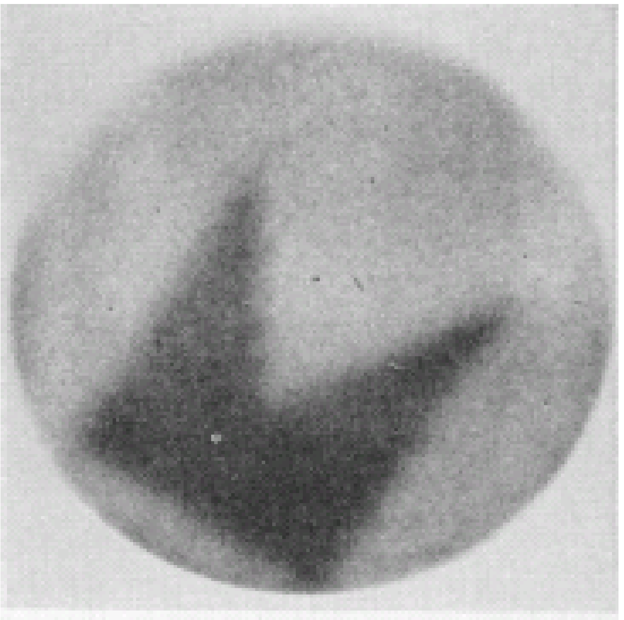


Fig. 1. Proton radiograph of aluminum absorber 7 cm in diameter and 18 g/cm^2 thick, with an additional thickness of 0.035-g/cm^2 aluminum foil, cut in the shape of a pennant, inserted at a depth of 9 g/cm^2. The addition of 0.2 percent to the total thickness produces a substantially darker area on the film.

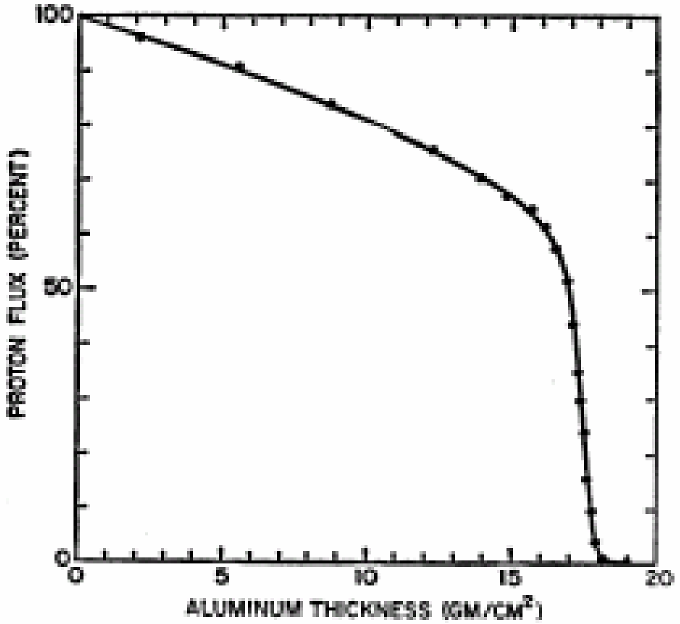
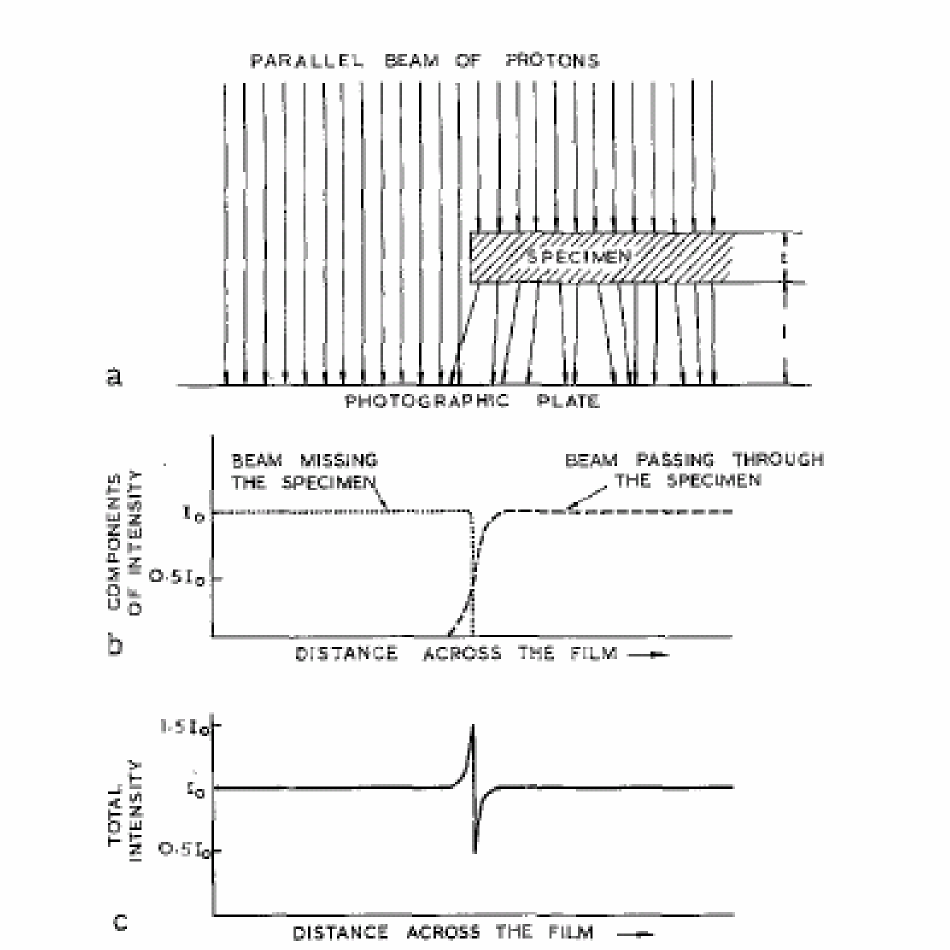


Fig. 2. Proton flux as a function of depth in aluminum. The steeply falling portion of the curve near 18 g/cm^2 is used to obtain the high contrast of Fig. 1.

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.

Proton Scattering Radiography



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

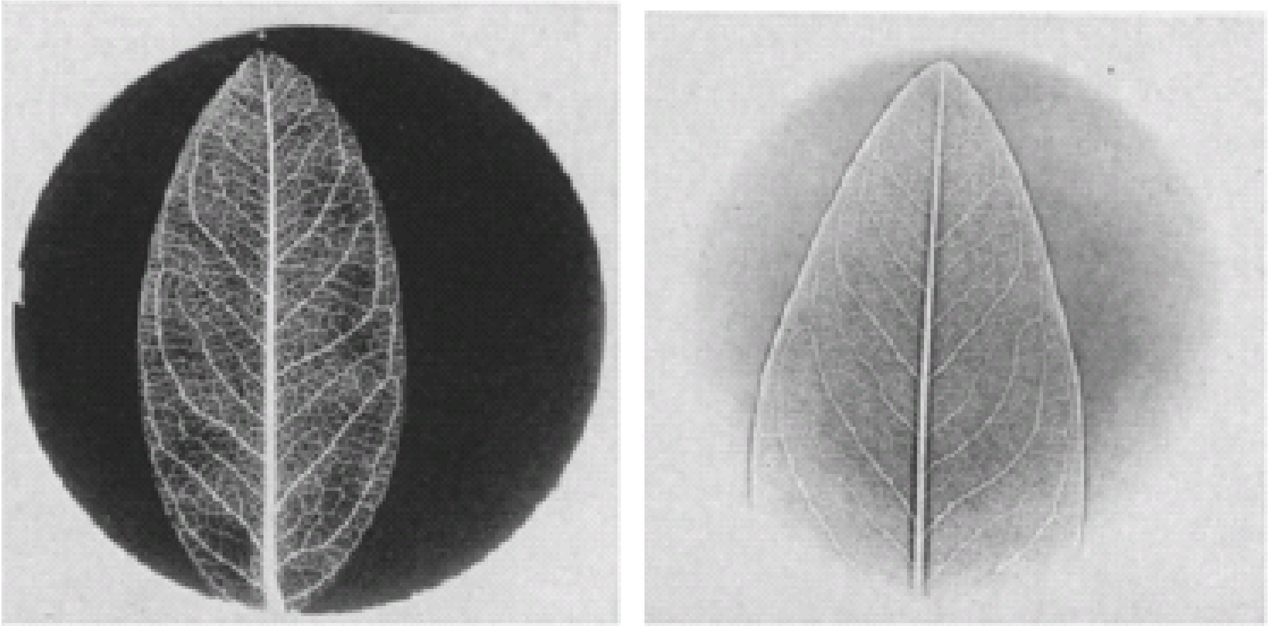


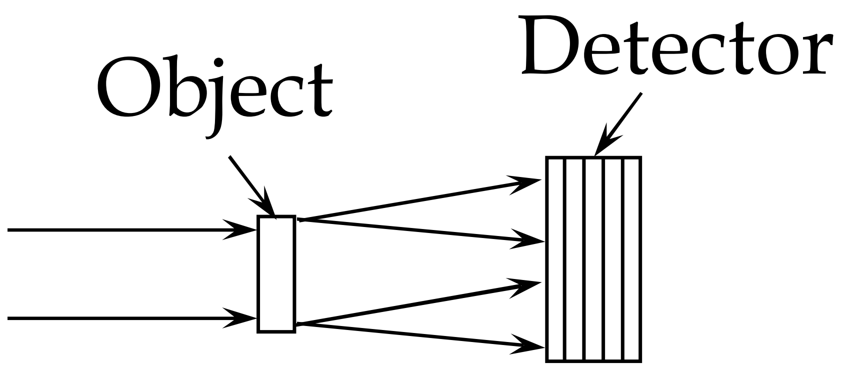
Fig. 6a and b. Radiographs of leaves by a) marginal range radiography with 196 mg/cm² of extra Al absorber, and b) scattering radiography with leaf sandwiched between two 6.9 mg/cm² Al layers and 14 mm from the film

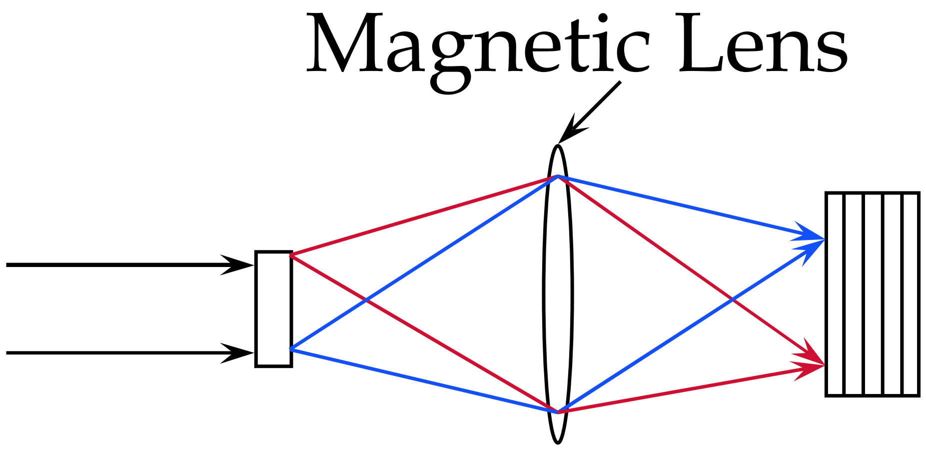
Scattering Radiography

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

LANL Transmission Radiography (1995)

188 MeV secondary proton beamline at LANSCE





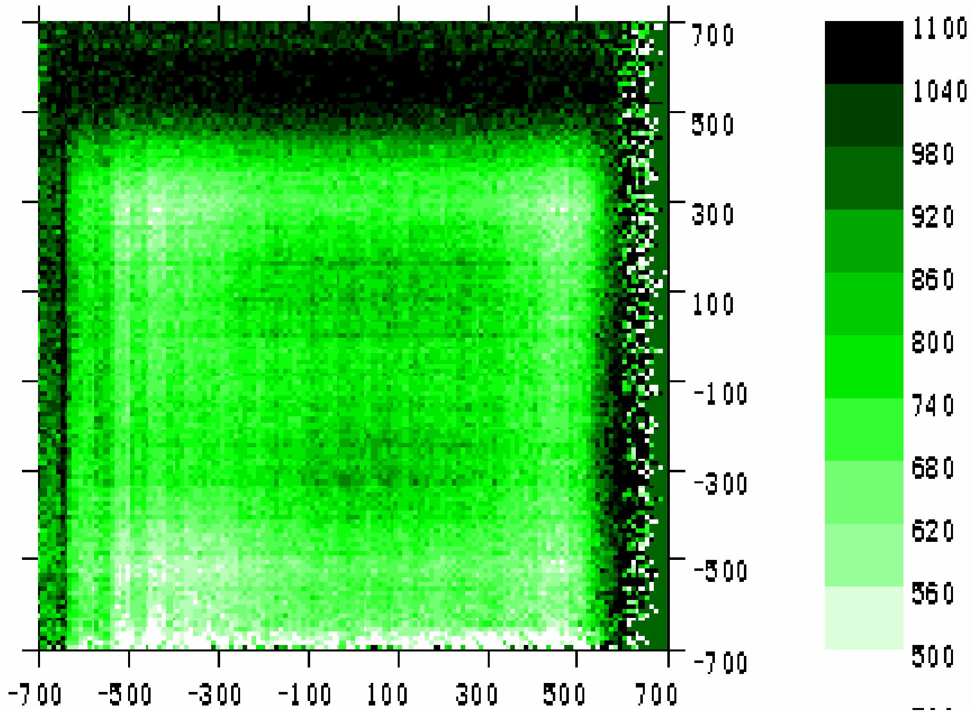
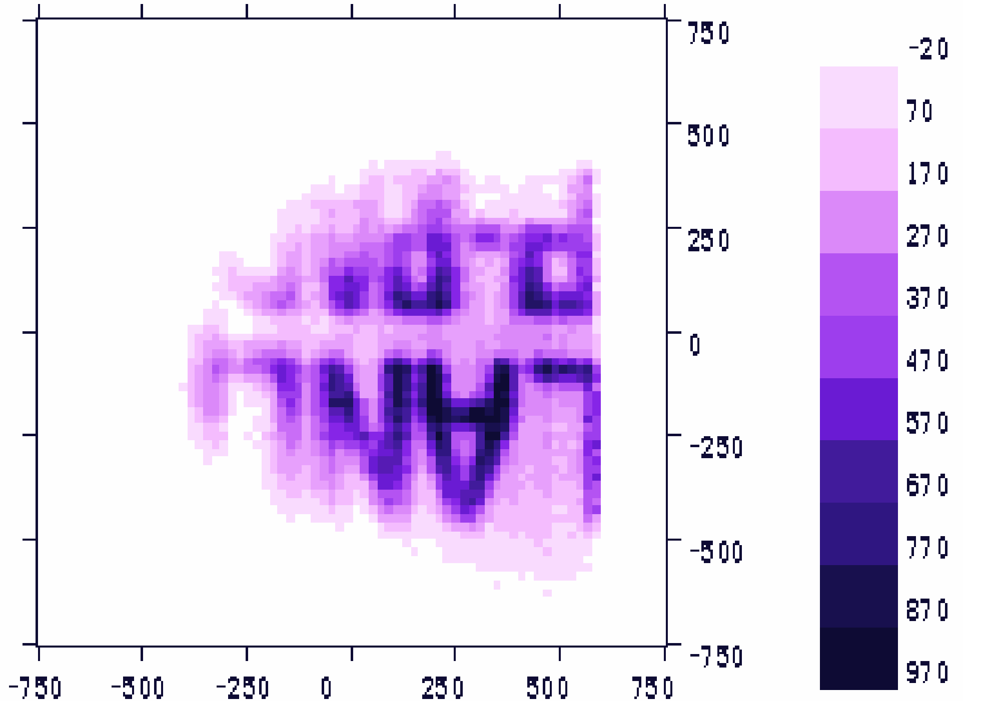
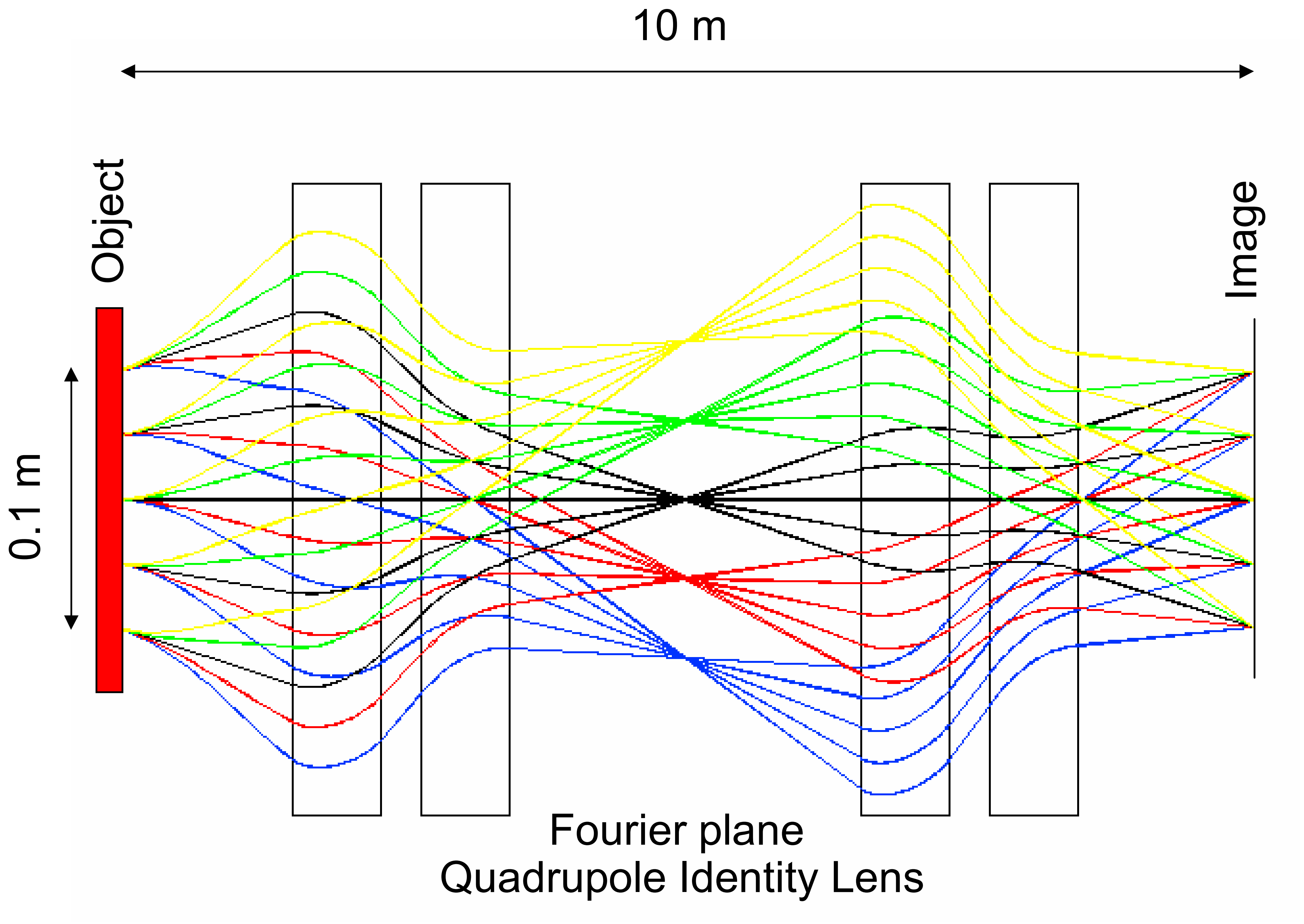


Image at the detector is substantially blurred.

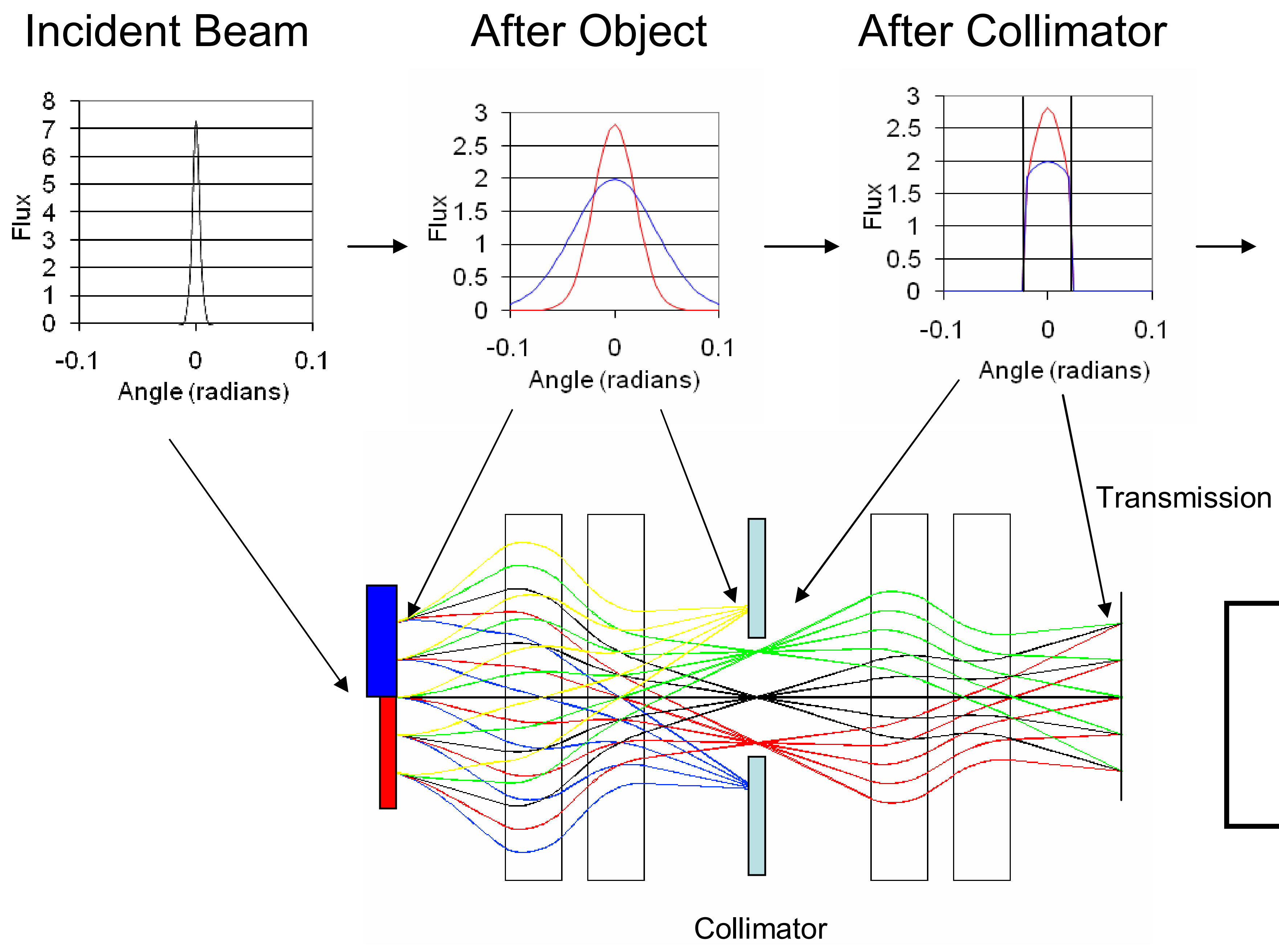


Magnetic imaging lens preserves image with high resolution.

Magnetic Imaging Lens



Contrast from Multiple Coulomb Scattering



Measured transmission provides information of object thickness

Transmission

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

Transmission Calculation

$$T_{\square\,\square\,\square} = {}^{-x}\!/_{\lambda}$$

Nuclear removal processes:

λ_c - scattering angle (radians)

x - areal density

$$T_{MCS} = 1 - {}^{-\theta^2}\!/_{2\theta_\square^2}$$

$$\theta_\square = \frac{14.1M}{\square\beta}\sqrt{\frac{x}{x_\square}}$$

Multiple Coulomb Scattering with collimation:

θ_o - scattering angle (radians)

x - areal density

x_o - radiation length

p - momentum (MeV)

β - relativistic velocity

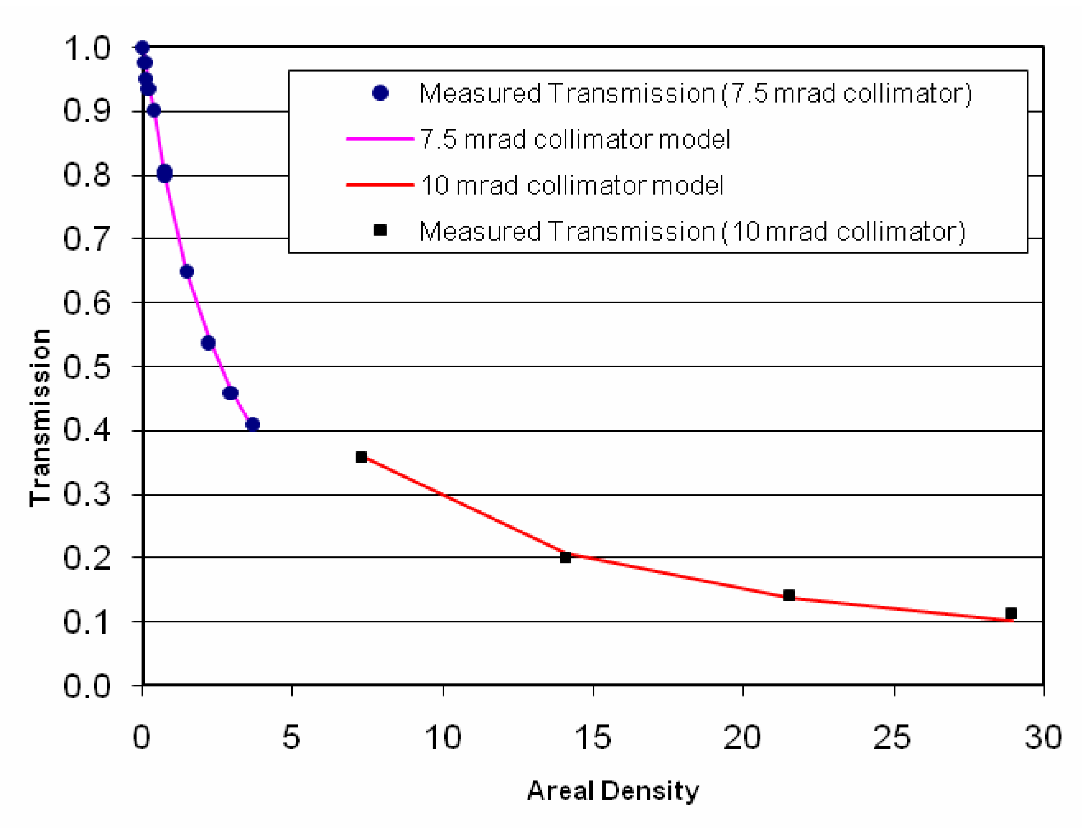
$$T = {}^{-x}\!/_{\lambda}\left(1 - {}^{-\left(\frac{\theta\,\square\beta}{14.1M}\right)^2 \frac{x_\square}{2x}}\right)$$

Total EstimatedTransmission:

Good to 5-10%

Principles of Proton Radiography

Accurate Areal Density Reconstructions

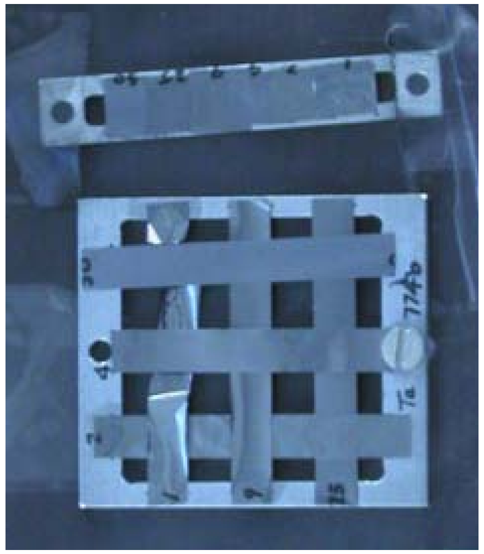


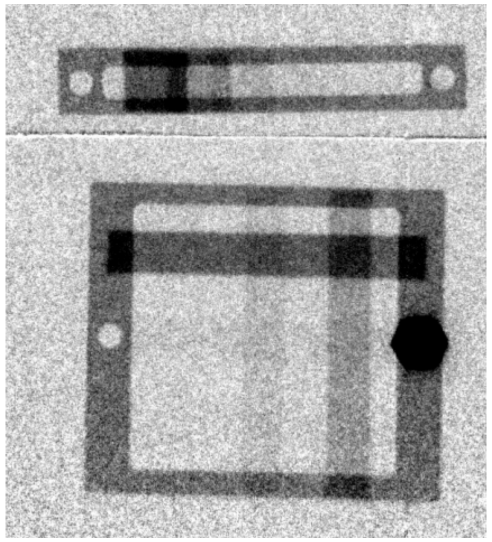
$$T = e^{-\left(x/\lambda_c + \left(\frac{\theta_c p\beta}{14.1MeV}\right)^2 \frac{x_o}{2\left(x+x_f\right)}\right)}$$

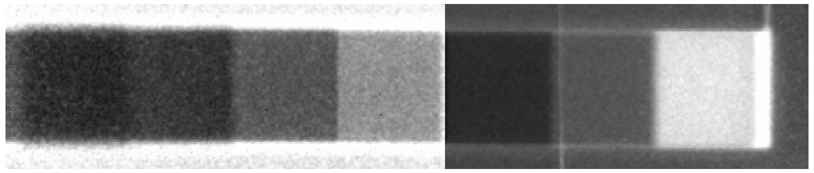
Adjust parameters to fit transmission data:

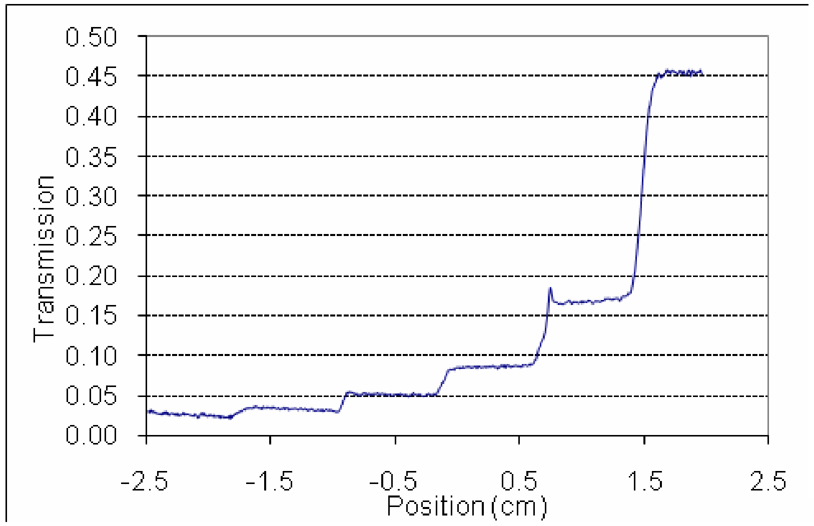
- λ_c - nuclear collision length
- X_f – fixed radiation length (windows, beam angular spread)

Build a step wedge and adjust parameters to fit measured data



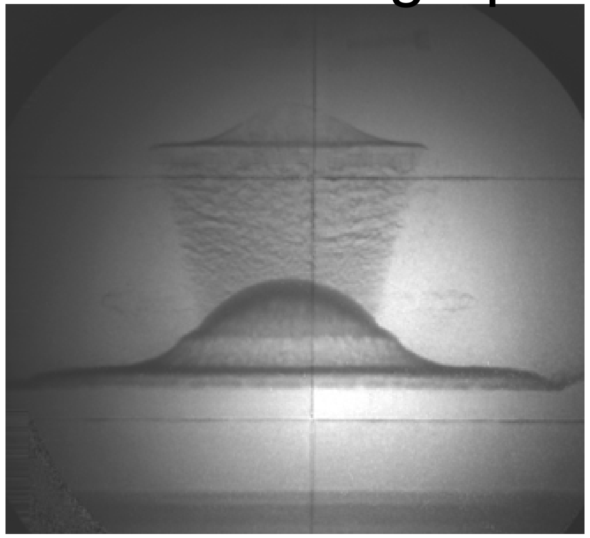






Radiographic Analysis

“Raw” Radiograph



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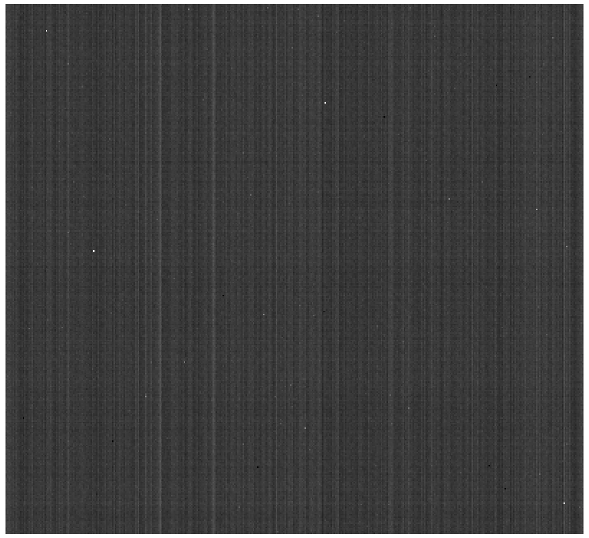
Dark Field



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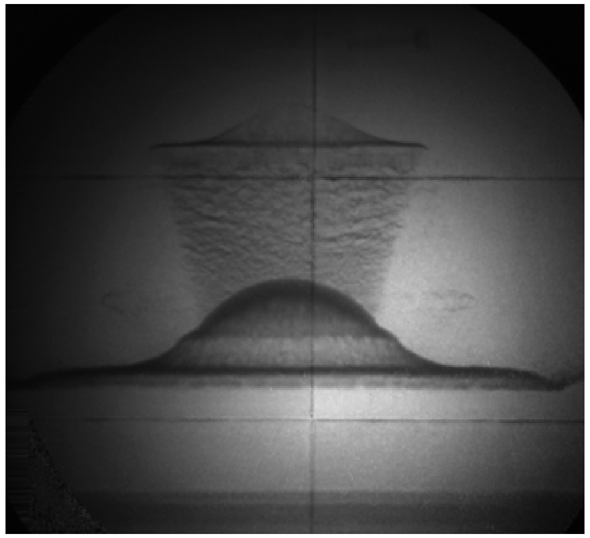

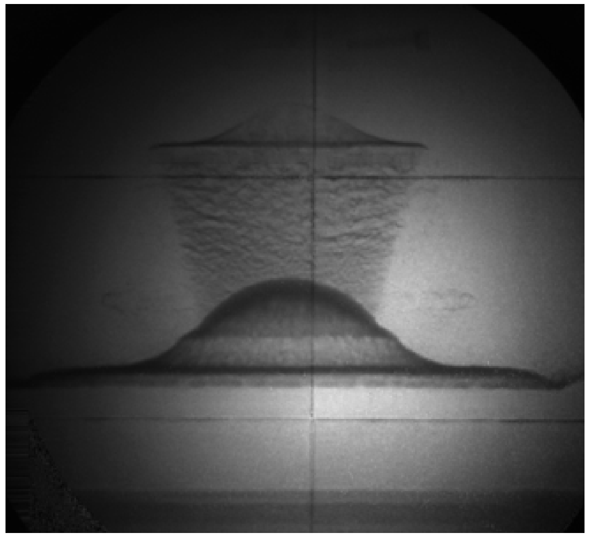

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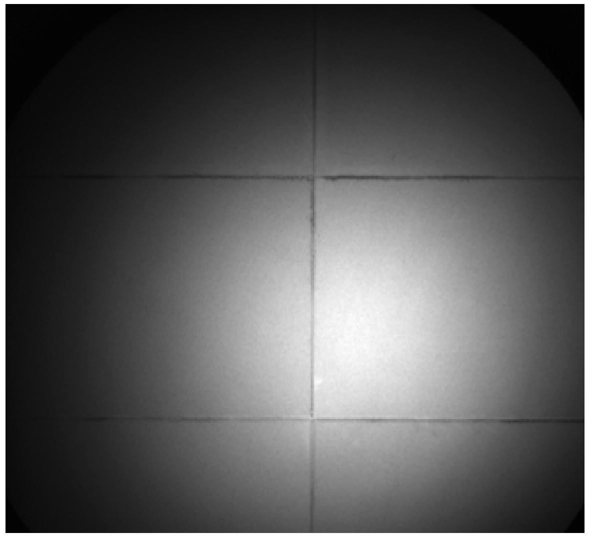
Beam Picture



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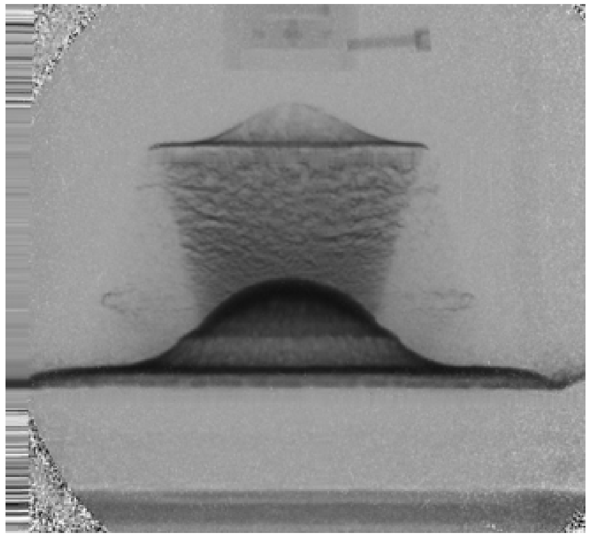
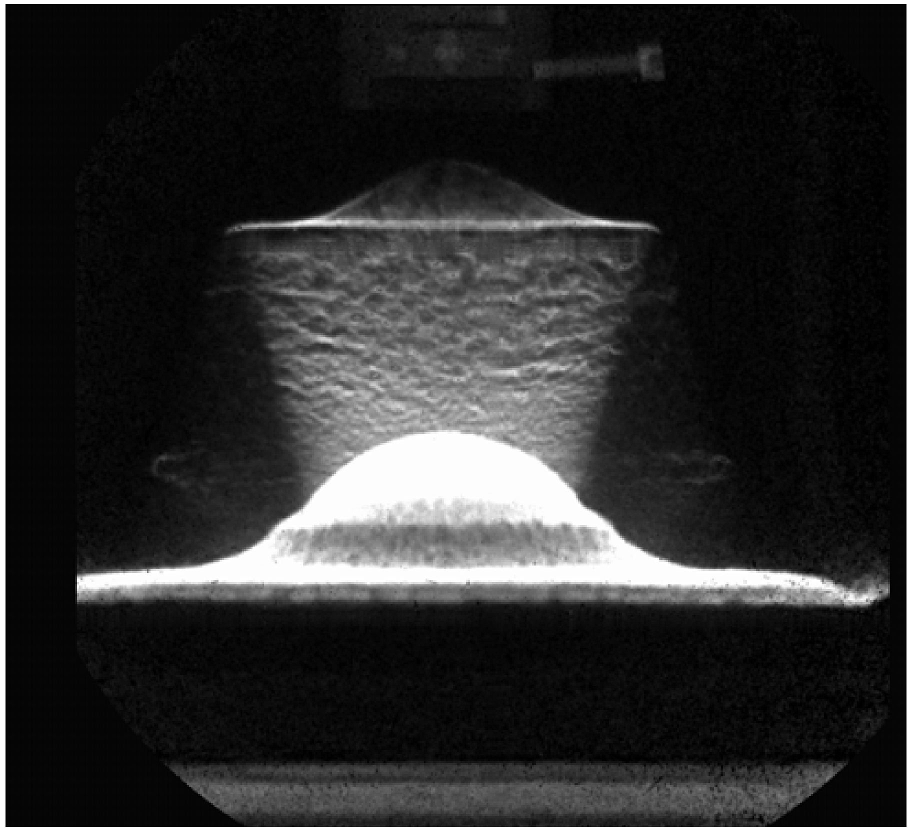
Transmission



Density Reconstruction

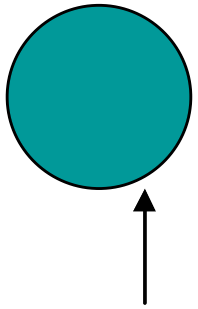
Invert to calculate Areal Density

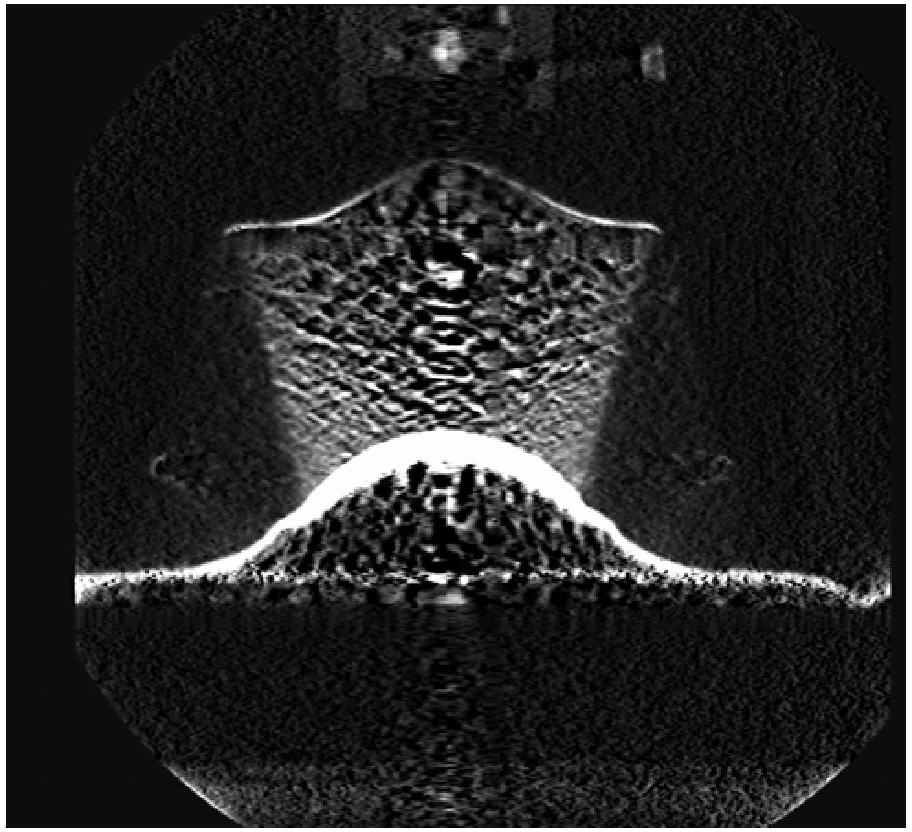
$$T = e^{-x/\lambda}\left(1 - e^{-\left(\frac{\theta_c p\beta}{14.1\,MeV}\right)^2 \frac{x_o}{2x}}\right)$$



Areal Density (g/cm^2)

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





Volume Density (g/cm^3)

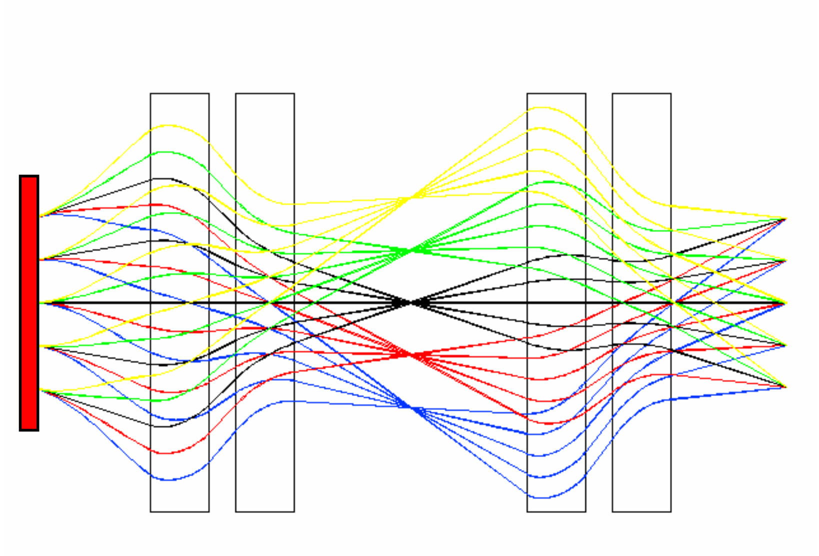
Beam Optics

First Order Beam Optics

$$\begin{bmatrix} x_i \\ x'_i \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} x_o \\ x'_o \end{bmatrix}$$

Requirement for an imaging lens

$$\begin{bmatrix} x_i \\ x'_i \end{bmatrix} = \begin{bmatrix} m & \overset{\downarrow}{0} \\ M_{21} & 1/m \end{bmatrix} \begin{bmatrix} x_o \\ x'_o \end{bmatrix}$$



Second Order Beam Optics

$$x_i = mx_o + T_{116}x_o\delta + T_{126}x'_o\delta$$

$$x'_o = \underbrace{m_x}_{\text{Matching condition}} x_o + \overbrace{\phi}^{\text{Scattering in object}}$$

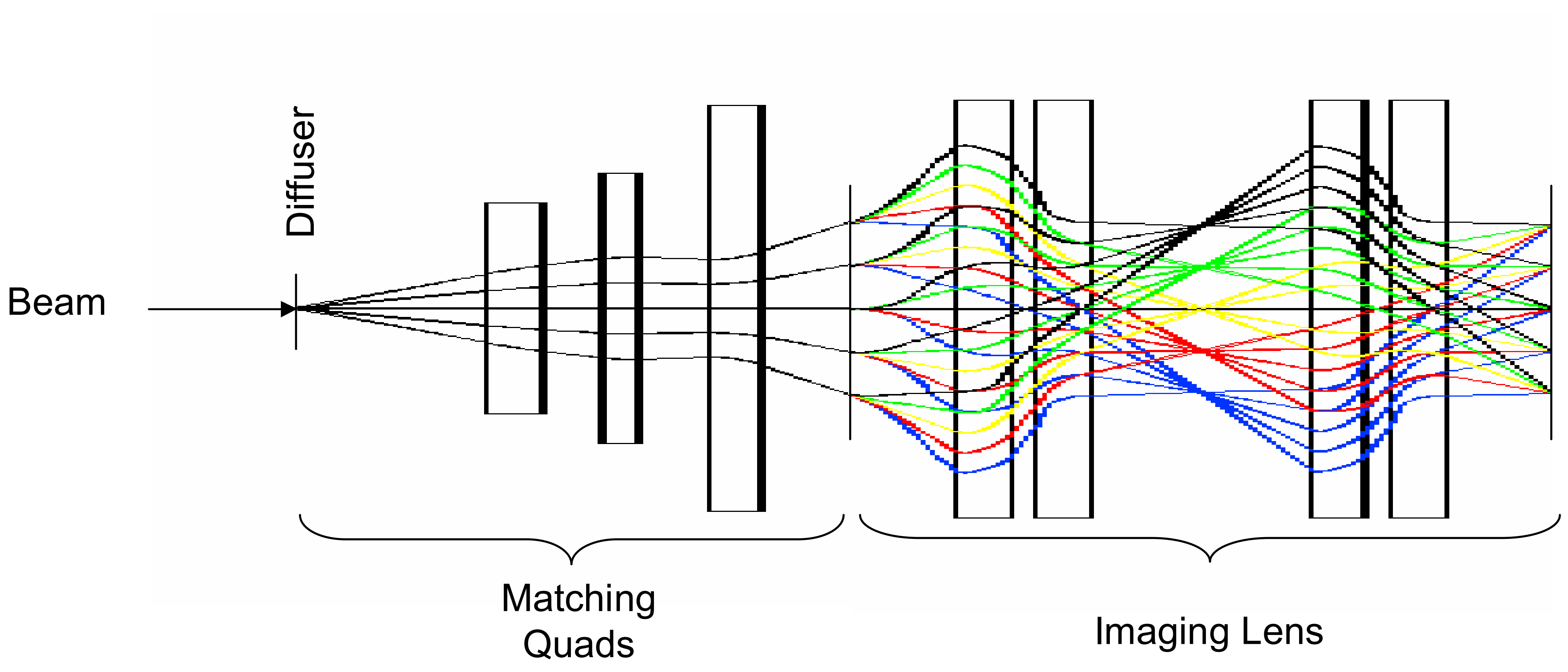
$$x_i = mx_o + T_{116}x_o\delta + T_{126}(m_x x_o + \phi)\delta$$

$$x_i = mx_o + (T_{116} + m_x T_{126})x_o\delta + T_{126}\phi\delta$$

$$m_x = \frac{-T_{116}}{T_{126}}$$

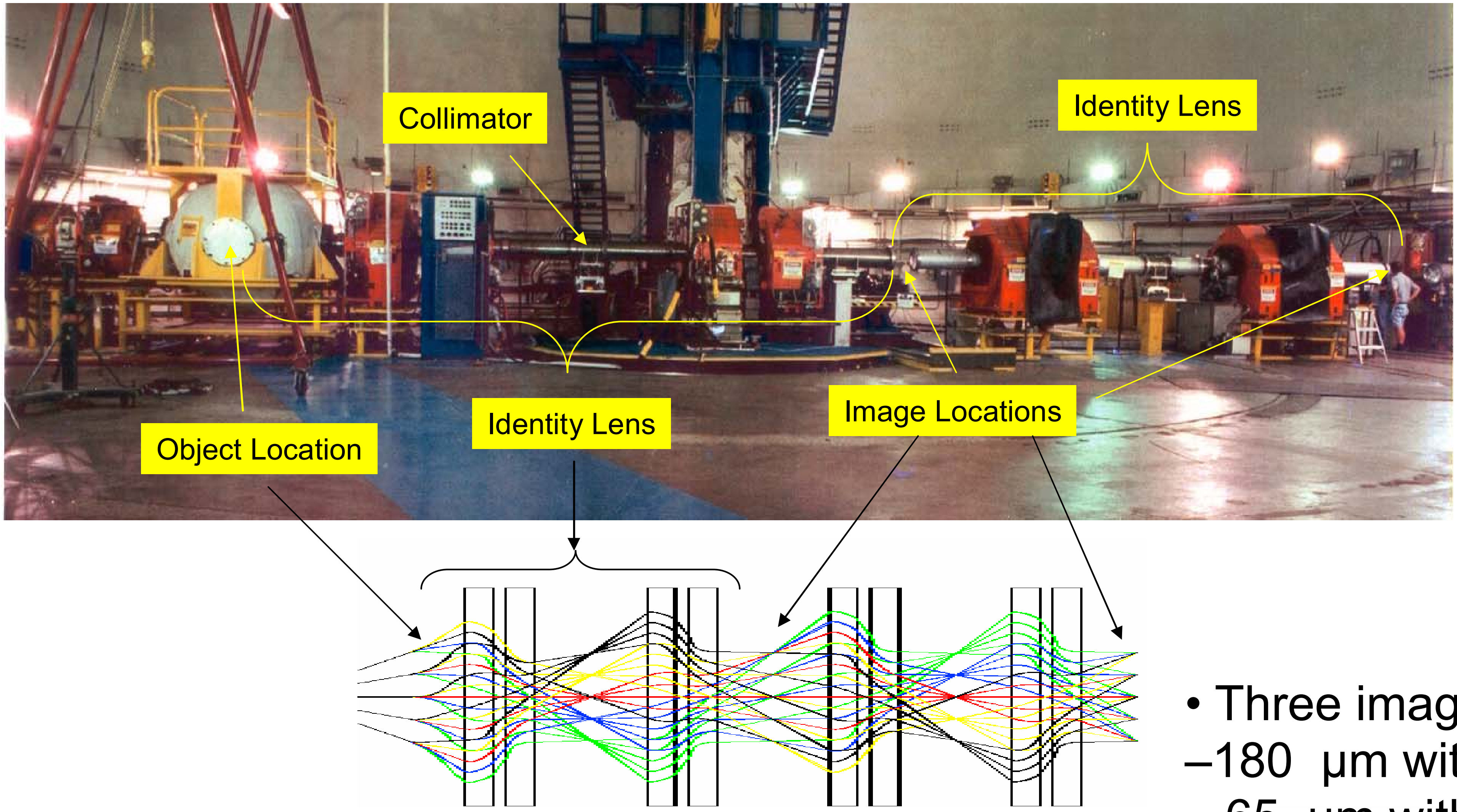
$$\boxed{x_i - x_o = \underbrace{\frac{T_{126}}{m}}_{\text{Chromatic length}}\phi\delta \qquad \text{Chromatic Blur}}$$

Proton Radiography System



- Beam is injected into diffuser at a waist in the beam transport
- Diffuser introduces angular spread to beeam.
- Matching quadrupoles transform angular spread to spot size with appropriate matching condition.
- Imaging forms image and Fourier plane near center of magnet center.

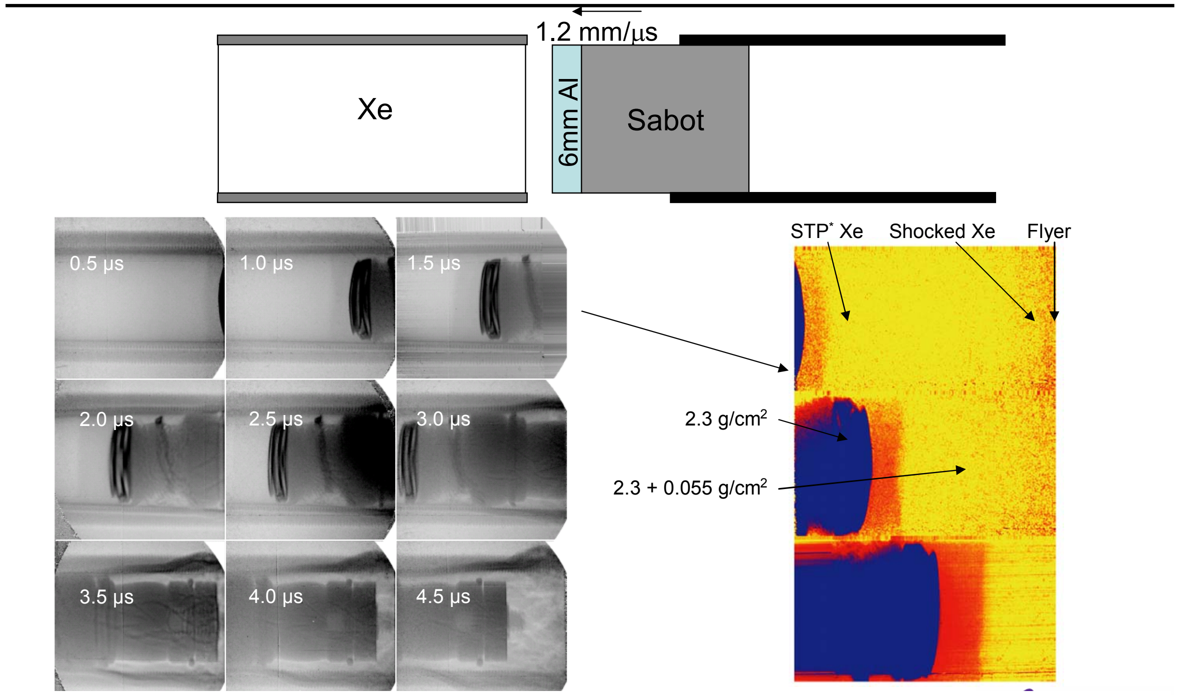
800 MeV pRad Facility at LANSCE



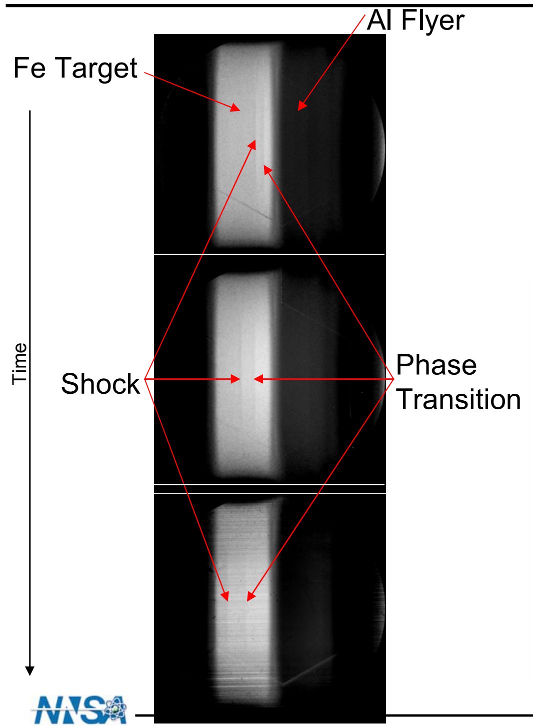
- Three imaging lens systems
  - –180 μm with 120 mm field of view
  - – 65 μm with 42 mm field of view
  - – 30 μm with 17 mm field of view
- 1-50 g/cm^2 object thickness.
- ~40 images, 100 ns exposure over < 1 ms

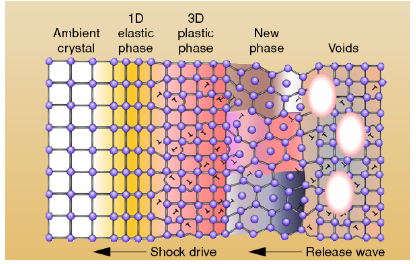
800 MeV pRad Facility at LANSCE

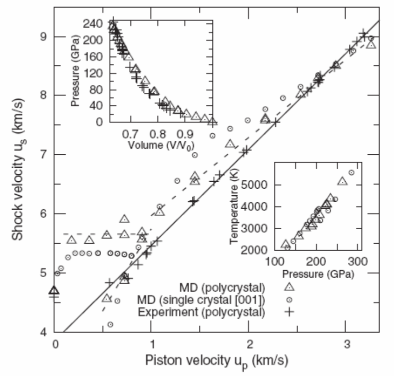
Rictmyer-Meshkov Instability Growth in Gasses



Solid-Solid Phase Transitions in Iron

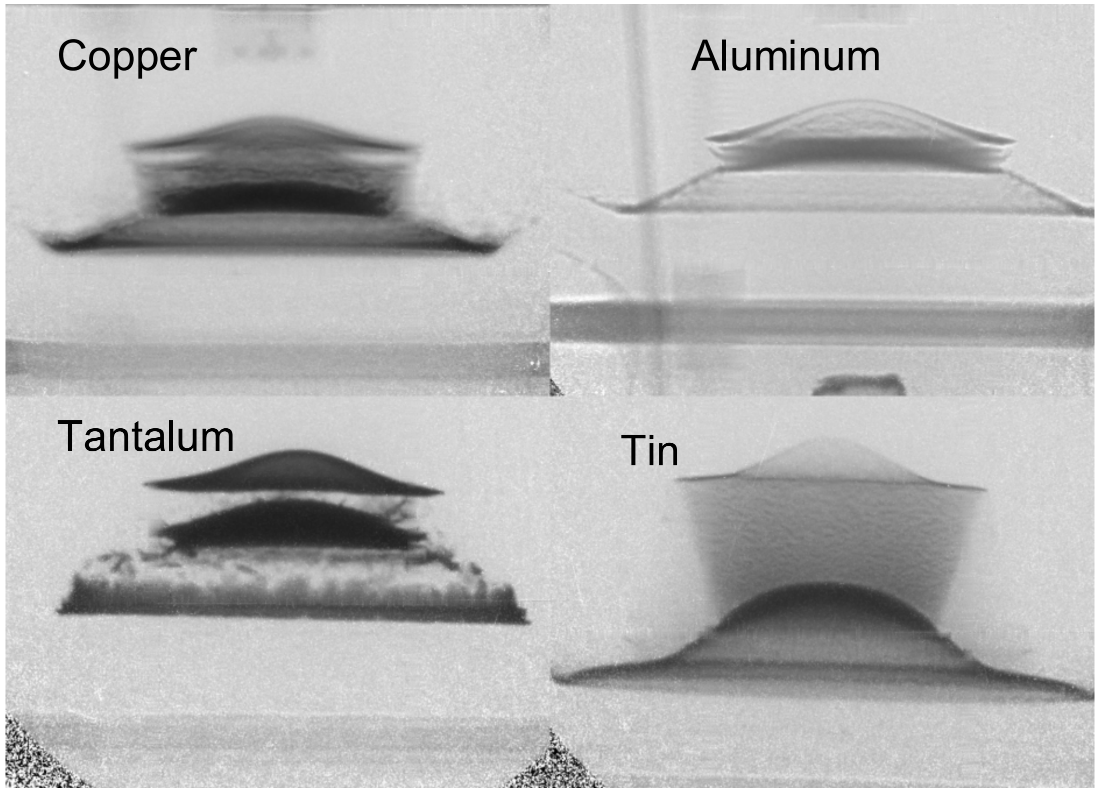


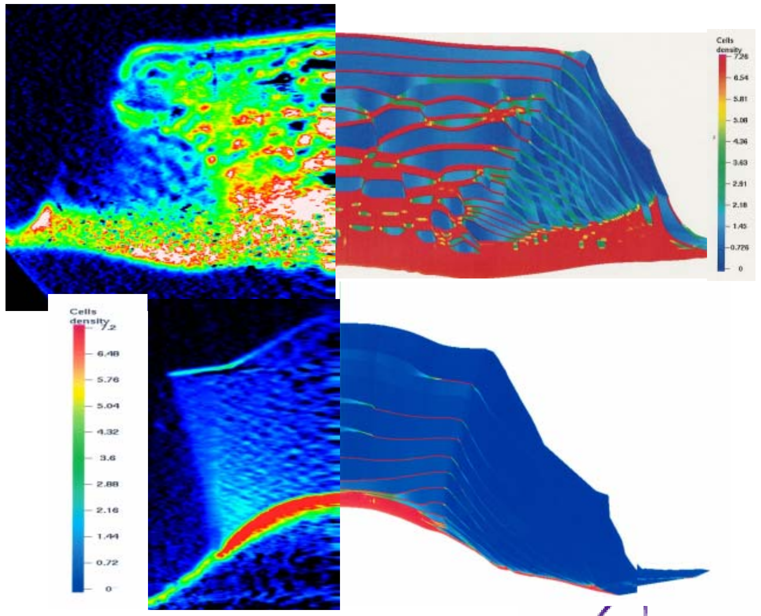




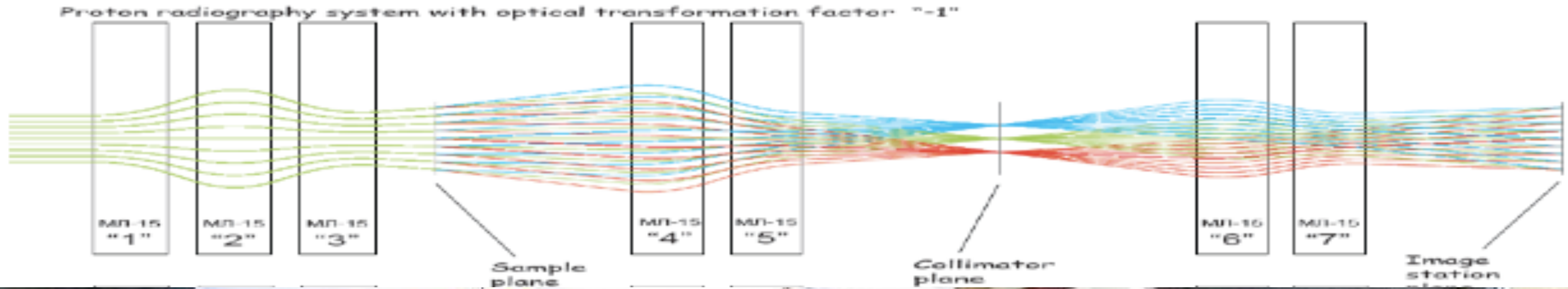
Phys. Rev. Lett. 98 135701 (2007)

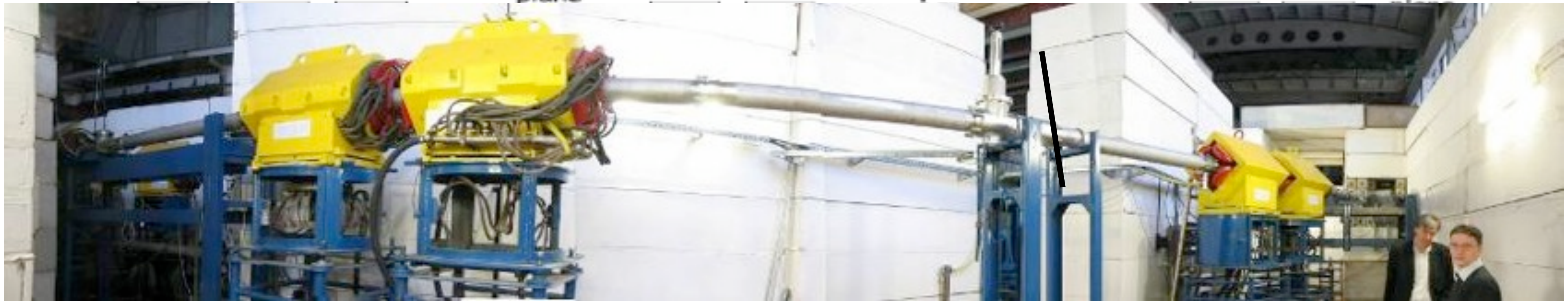
A comparison of spall for different materials





800 MeV proton radiography setup at ITEP

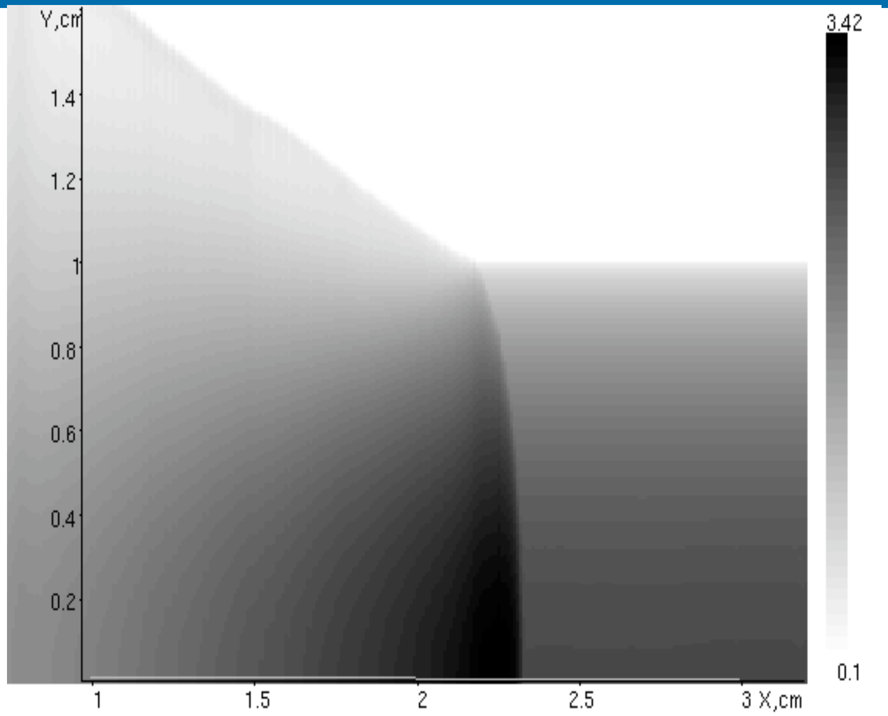




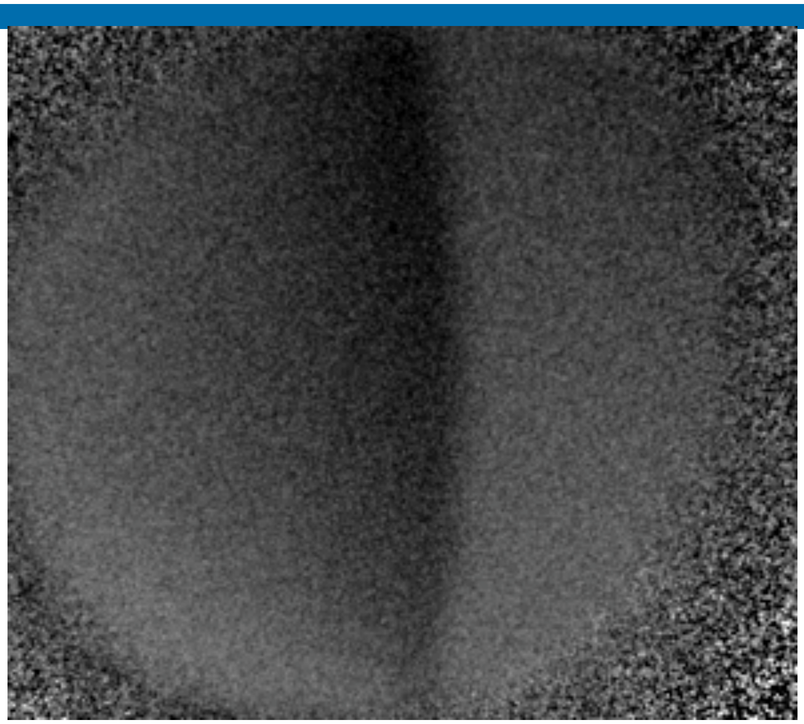
Field of View on object	up to 40 мм
Investigated objects	up to 60 g/cm2
Spatial resolution	0.5 p.lines/mm
Time resolution	4 bunches / 1 ms

Protective Target Chamber designed for:
Up to 80 g TNT
Pumped down to 10-3 Torr
Active ventilation system
Fiber for optical diagnostics (VISAR)

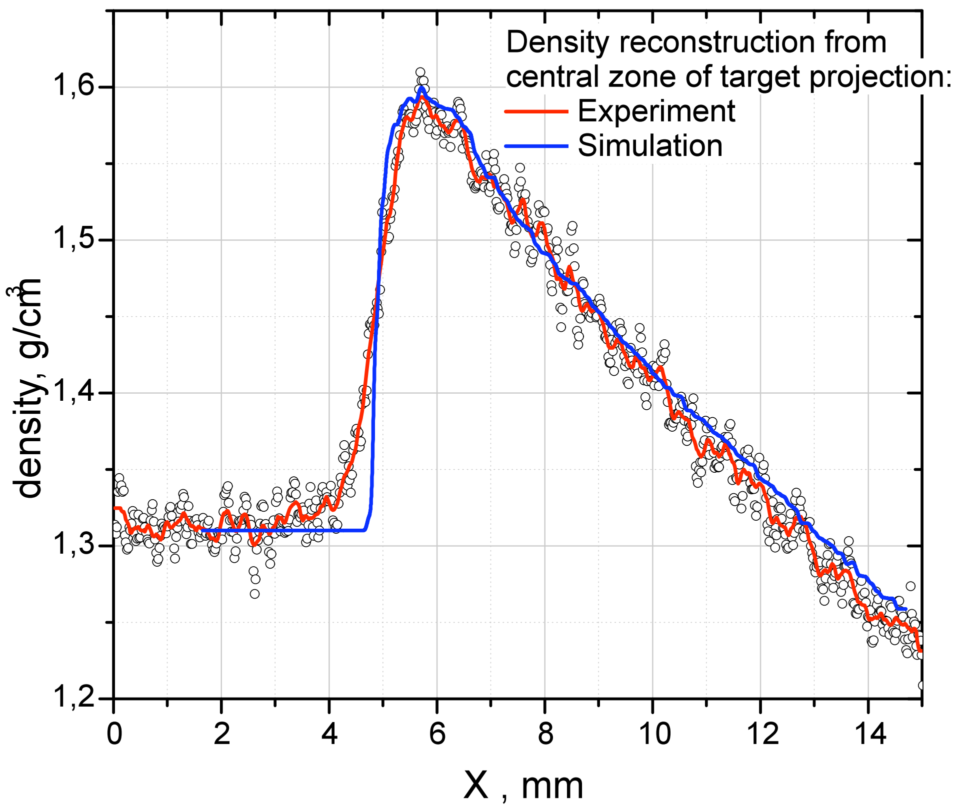
800 MeV proton radiography setup at ITEP: detonation wave in TNT

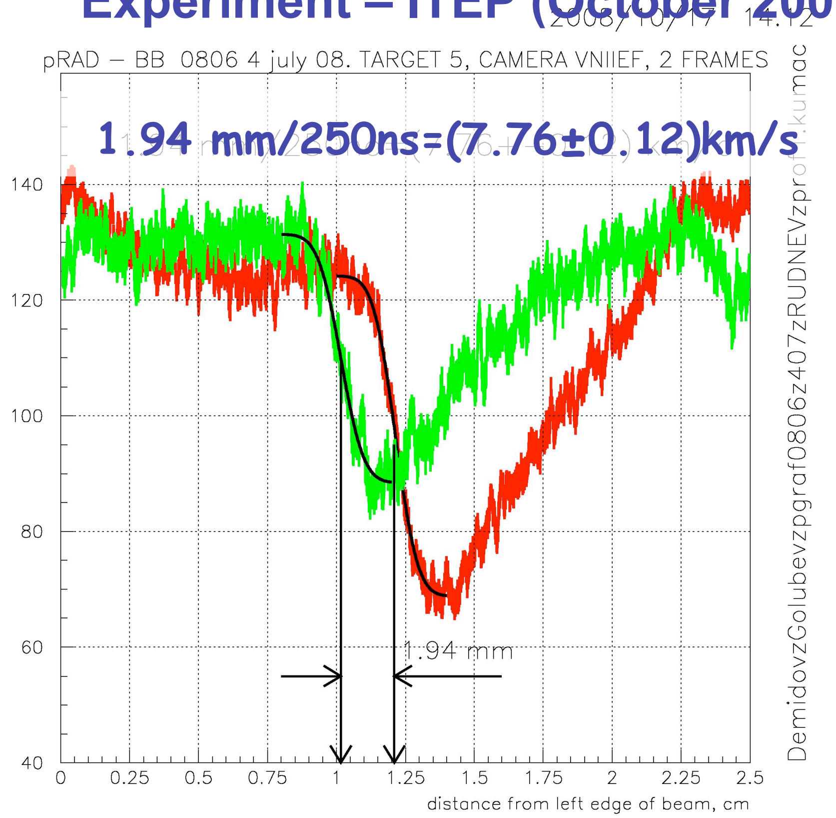


Areal density, (g/cm^2)
Simulation results – A. Shutov



Relative proton beam transmission, (%)
Experiment – ITEP (October 2008)





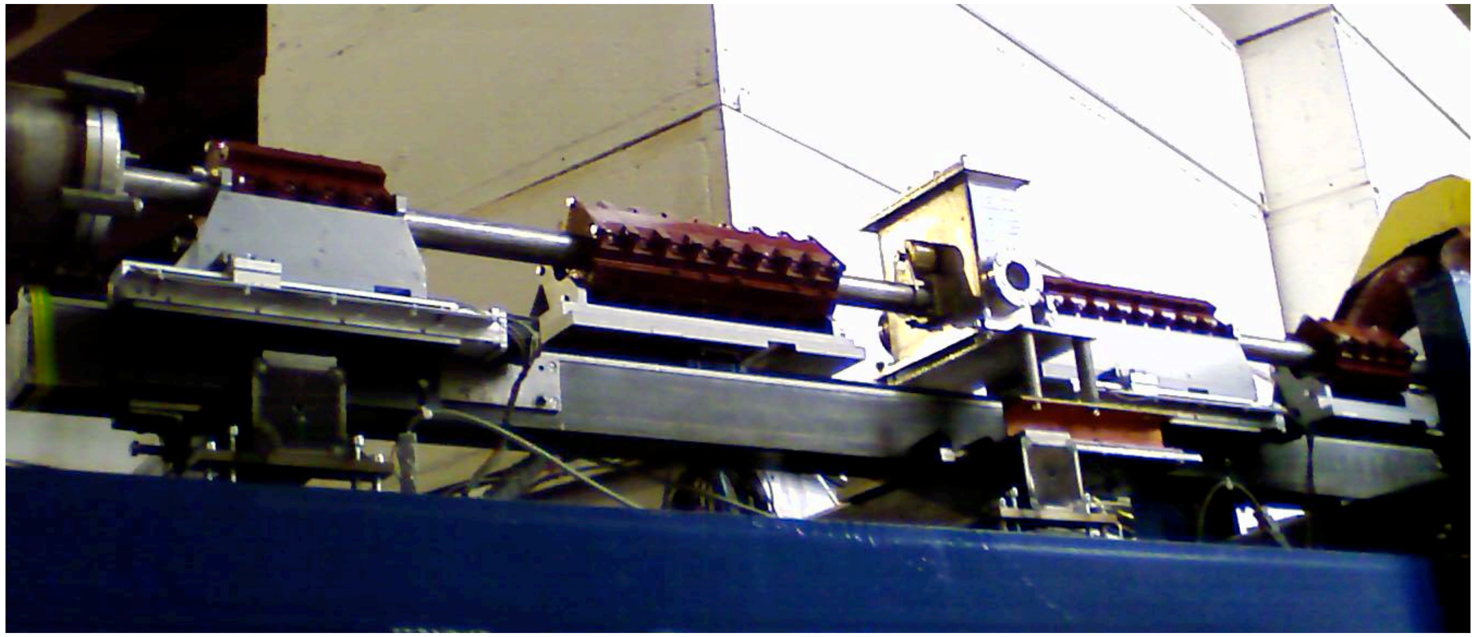
800 MeV proton radiography setup at ITEP: proton microscope

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

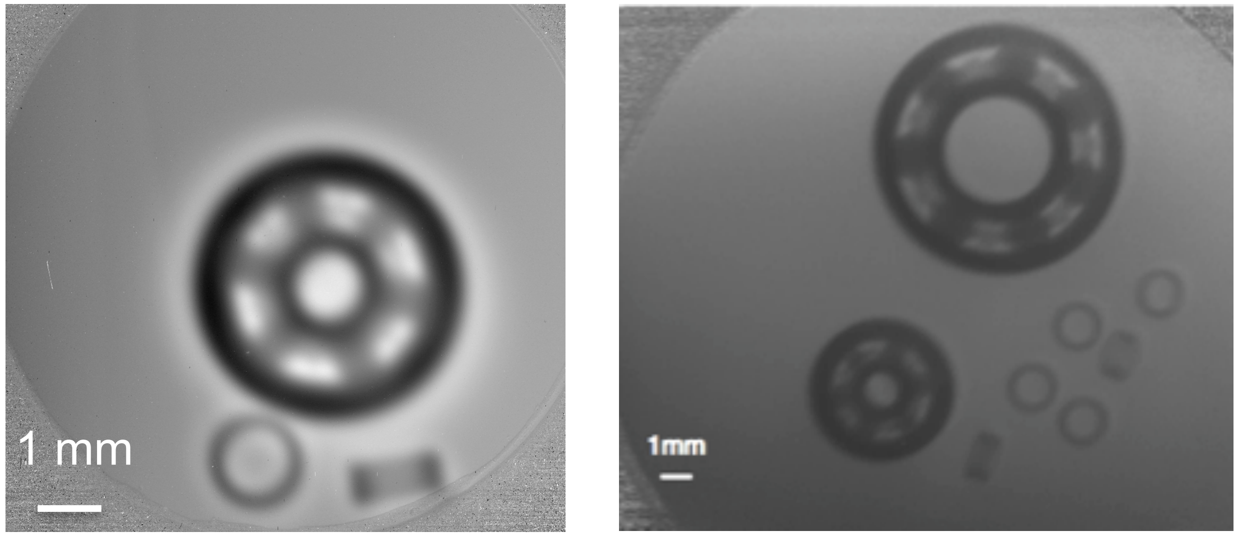
Magnification X = 3.92
Field of view < 22 mm
Spatial resolution σ = 60um

Density resolution ~ 6%

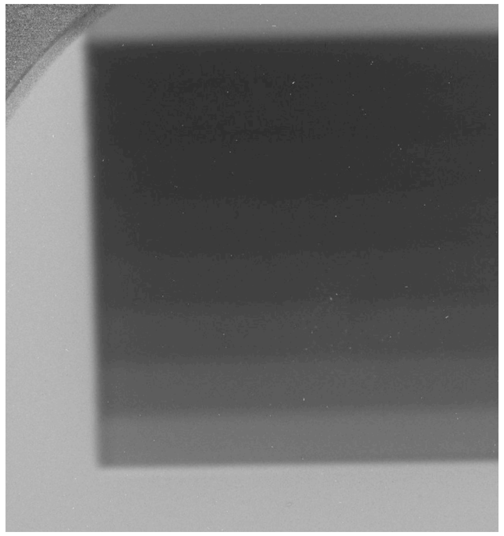
Beam structure – 4 bunches (FWHM=70ns) in 1 us



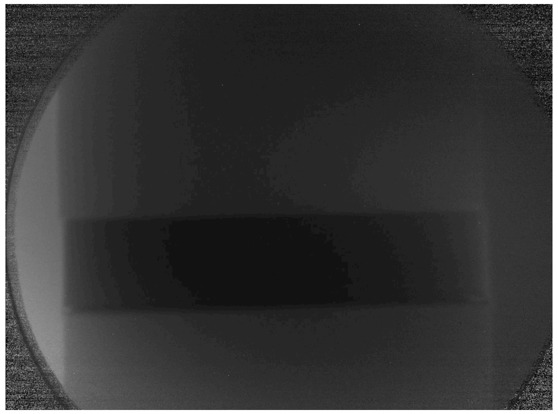
Static test-object images



Ball bearing and ferrite ring (X= 7.82 and X=3.92)



Brass stair 1 mm step Δρ=400um

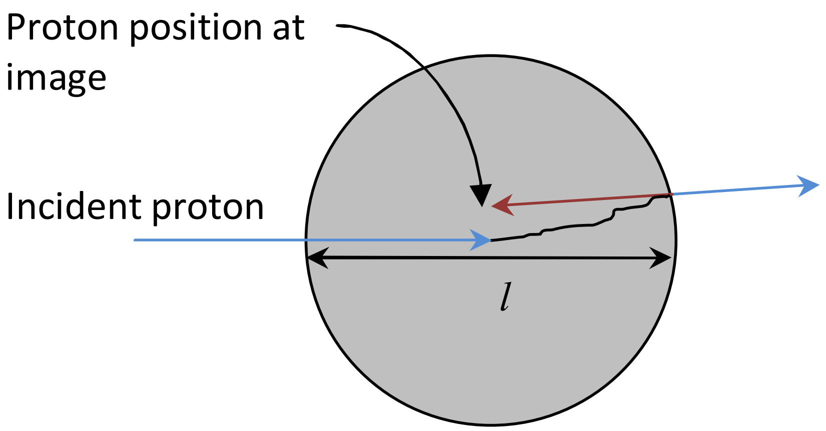


Detonation wave immitator d=15mm σ=100um

Resolution Limits of Proton Radiography

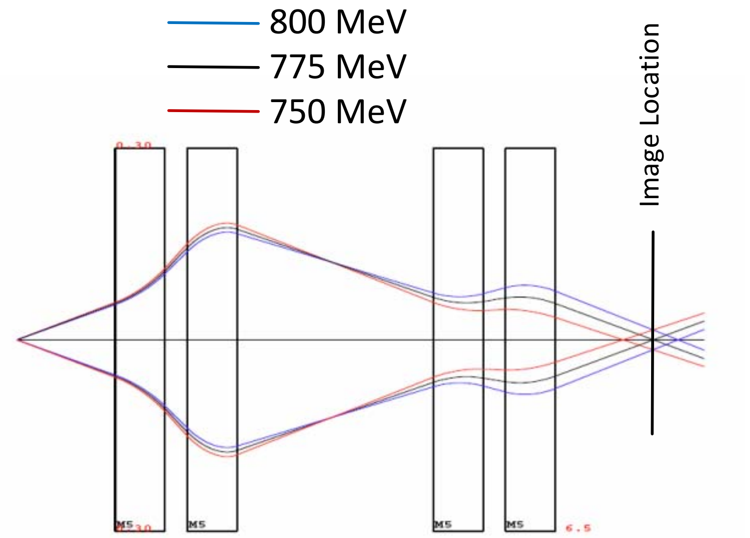
1. **Object scattering** - introduced as the protons are scattered while traversing the object.
2. **Chromatic aberrations**- introduced as the protons pass through the magnetic lens imaging system.

Object Scattering



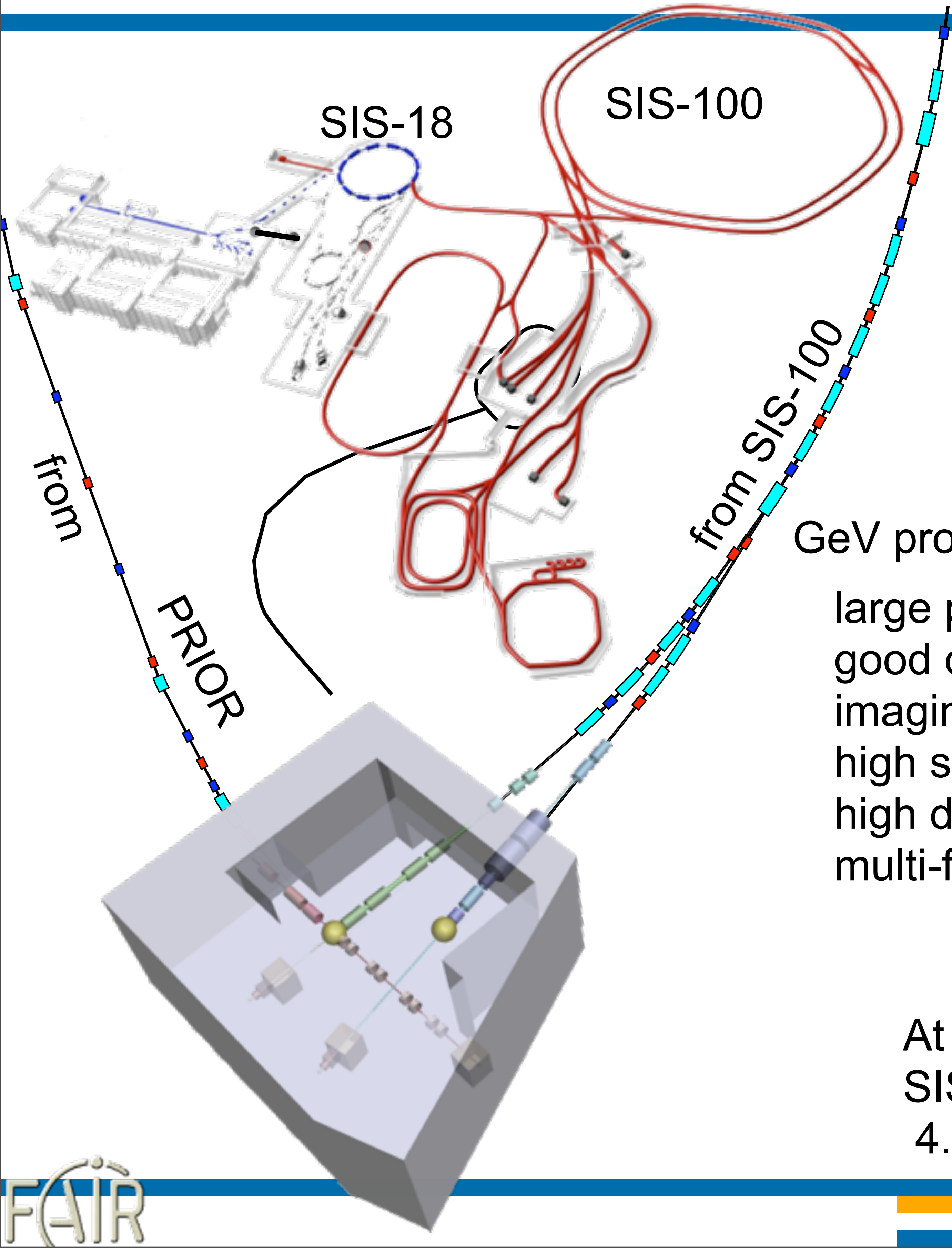
$$\sigma_o = \frac{1}{\sqrt{3}}\theta\frac{l}{2} = \frac{14.1}{\sqrt{6}}\frac{1}{P\beta}\sqrt{\frac{l^3}{x_o}} \boxed{\propto \frac{l^{3/2}}{P}}$$

Chromatic Aberrations



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

PRIOR – Proton Radiography at FAIR



Challenging requirements for density measurements in dynamic HEDP experiments:

- up to ~20 g/cm^2 (Fe, Pb, Au, etc.)
- ≤10 µm spatial resolution
- 10 ns time resolution (multi-frame)
- sub-percent density resolution

GeV protons:

- large penetrating depth (high ρx)
- good detection efficiency (S/N)
- imaging, aberrations correction by magnets
- high spatial resolution (microscopy)
- high density resolution and dynamic range
- multi-frame capability for fast dynamic events

At FAIR: a dedicated beam line from SIS-18 for radiography
4.5 GeV, 5·10^{12} protons

Technical specifications and resolution scalings

Spatial resolution scalings with proton energy:

- object scattering
- chromatic aberrations
- detector blur

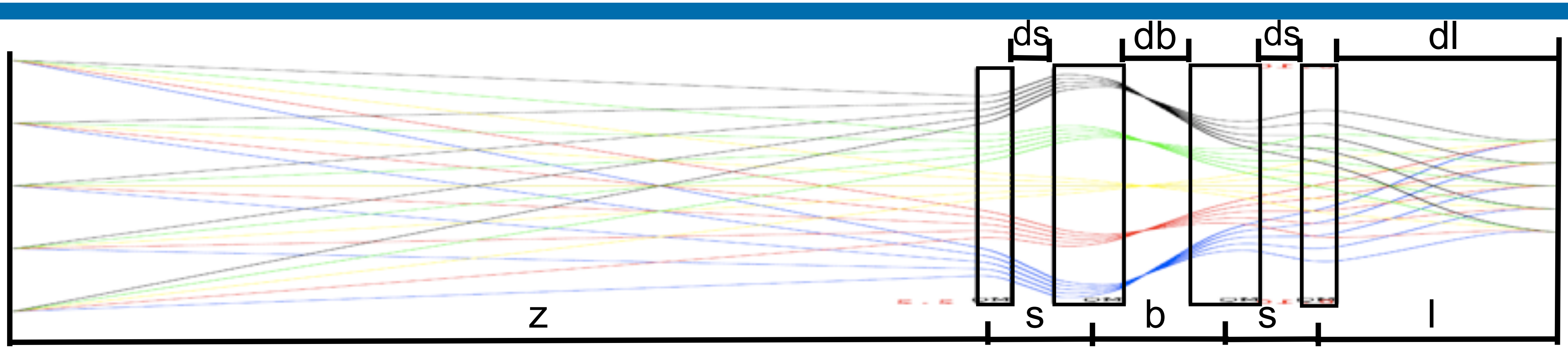
$$\sigma_o \propto \frac{\ell_t^{\frac{3}{2}}}{p} \qquad \sigma_c \propto \frac{\ell_t^{\frac{1}{2}}}{p^{\frac{3}{2}}} \qquad \sigma_d \propto \frac{\ell_s \ell_t^{\frac{1}{2}}}{p}$$

PRIOR technical specifications (for FAIR experiments):

proton energy:	4.5 GeV
spatial resolution:	≤10 μm
temporal resolution:	10 ns
multi-framing capability:	1 – 4 frames within 1 μs
target characteristics:	up to 20 g/cm^2
areal density reconstruction:	sub-percent level
field of view:	10 – 15 mm
stand-off distance:	1 – 1.5 m
proton illumination spot size:	3 – 15 mm
total length after object plane:	less than 15 m

- using permanent magnets or/and existing electromagnets

PRIOR magnetic lens design: thin lens approximation



$$\begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = \begin{pmatrix} 1 & z \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{-1}{df+f} & 1 \end{pmatrix} \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{k}{df+f} & 1 \end{pmatrix} \begin{pmatrix} 1 & b \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{-k}{df+f} & 1 \end{pmatrix} \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{1}{df+f} & 1 \end{pmatrix} \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} -m & 0 \\ M_{21} & \frac{-1}{m} \end{pmatrix}$$

Total length: $x = z + 2 \cdot s + b + l$

Quad focal length: $f = \sqrt{\frac{k^2ms^2}{km-m+k-1} - \frac{k^2s^2}{km-m+k-1} + \frac{2k^2lms}{km-m+k-1} - \frac{2klms}{km-m+k-1}}$

Last Quad to detector: $z = \frac{(km-k)\,s + (k-1)\,lm}{k-1}$

Distance 2d to 3d Quad: $b = \frac{(km-k)\,s^2 + (2k-2)\,lms}{(k^2-k)\,ms + (k^2-2k+1)\,lm}$

Chromatic length - complicated function of lens spaces:

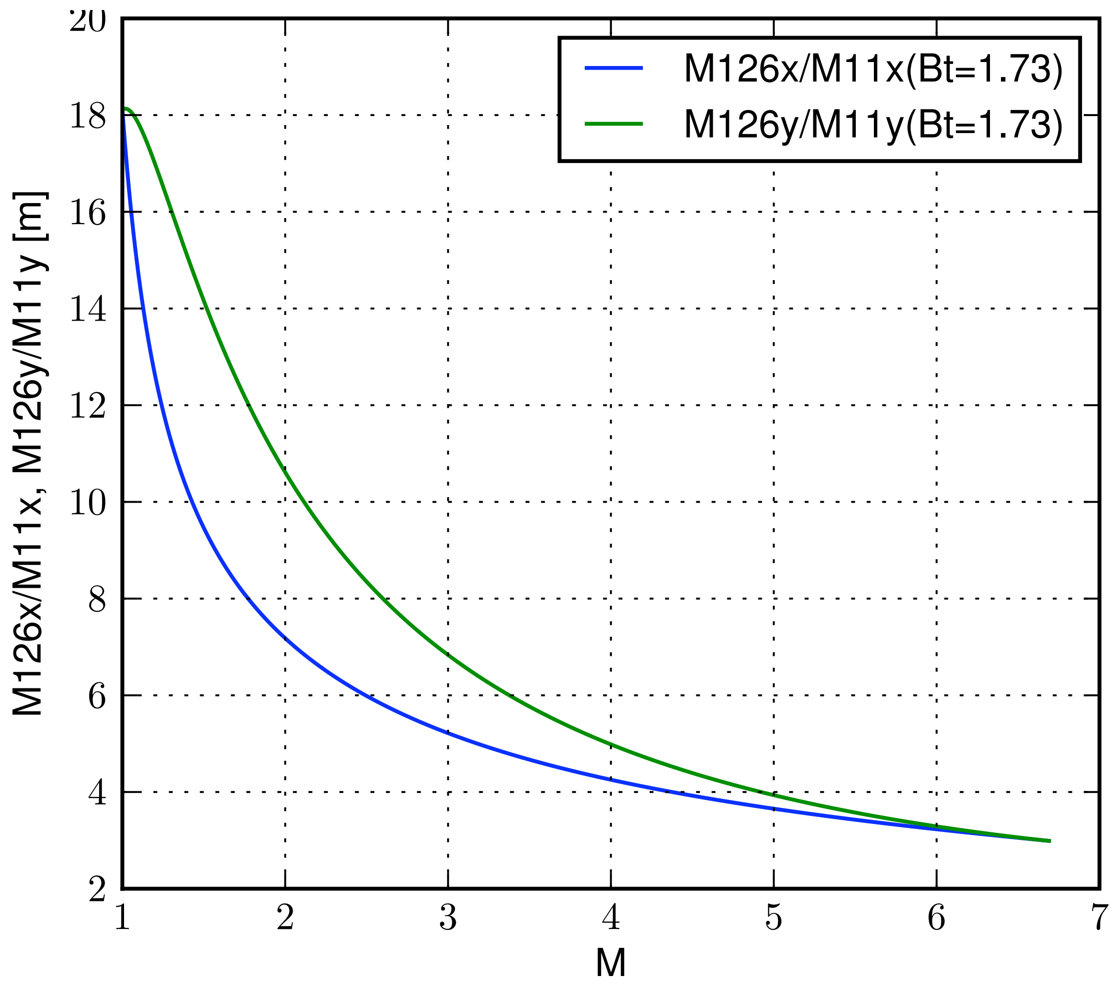
$$M_{126} = \frac{-4bk^2ls^2z}{f^4} + \frac{3bk^2s^2z}{f^3} + \frac{4lsz}{f^2} + \frac{2bk^2sz}{f^2} - \frac{2sz}{f} + \frac{2bk^2lz}{f^2} - \frac{4bklz}{f^2} + \frac{2blz}{f^2} + \frac{bkz}{f} - \frac{bz}{f} - \frac{3bk^2ls^2}{f^3} + \frac{2bk^2s^2}{f^2} + \frac{2bk^2ls}{f^2} + \frac{2ls}{f} - \frac{bkl}{f} + \frac{bl}{f}$$

$$M_{346} = \frac{-4bk^2ls^2z}{f^4} - \frac{3bk^2s^2z}{f^3} + \frac{4lsz}{f^2} + \frac{2bk^2sz}{f^2} + \frac{2sz}{f} + \frac{2bk^2lz}{f^2} - \frac{4bklz}{f^2} + \frac{2blz}{f^2} - \frac{bkz}{f} + \frac{bz}{f} + \frac{3bk^2ls^2}{f^3} + \frac{2bk^2s^2}{f^2} + \frac{2bk^2ls}{f^2} - \frac{2ls}{f} + \frac{bkl}{f} - \frac{bl}{f}$$

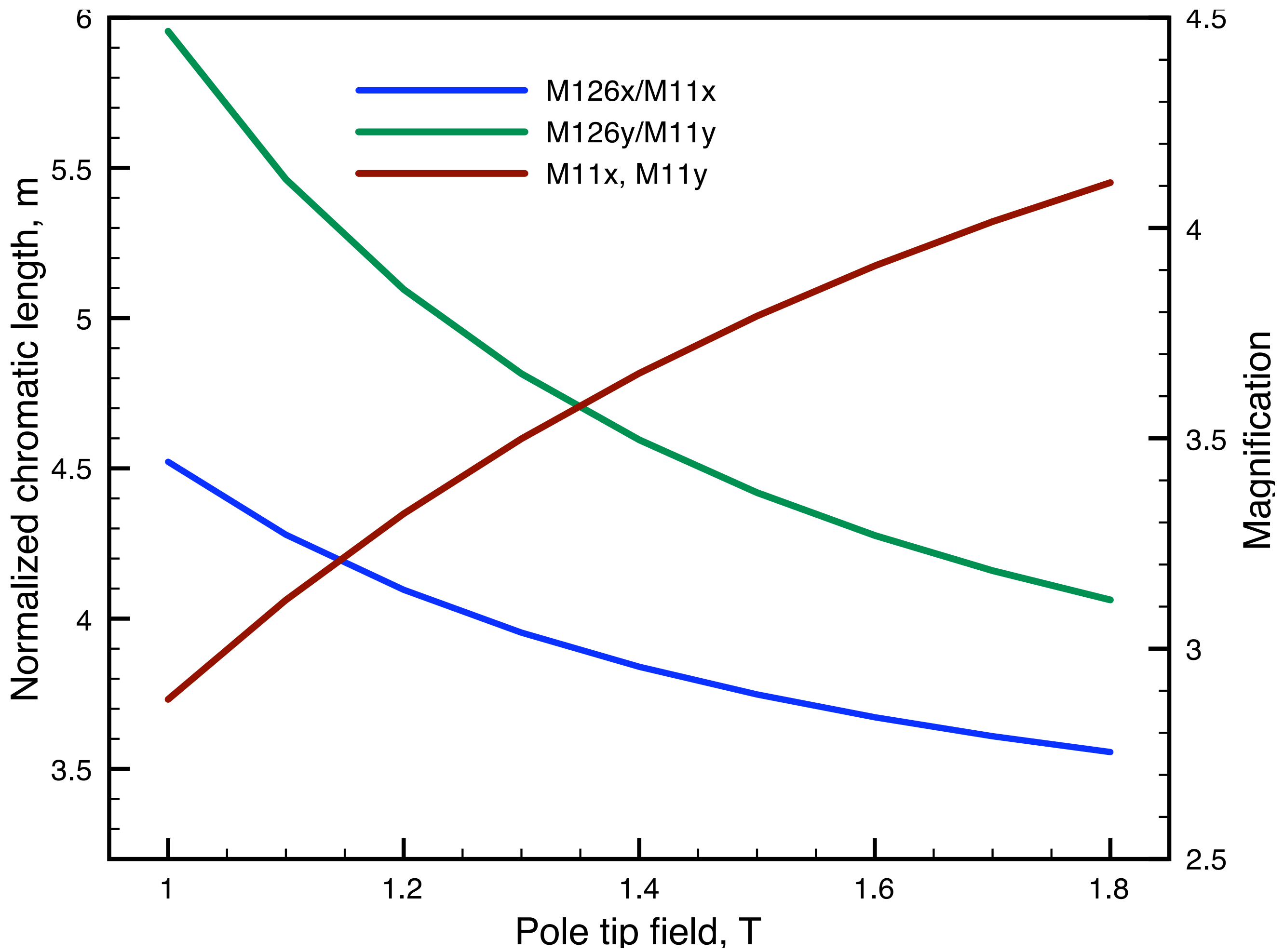
Chromatic blur:
(characterize spatial resolution) $x_0 - \frac{x_i}{M_{11}} = \frac{M_{126}\theta_A\delta}{M_{11}}; y_0 - \frac{y_i}{M_{33}} = \frac{M_{346}\theta_A\delta}{M_{33}}$ - for properly matched beam

PRIOR magnetic lens design: thin lens approximation

Normalized chromatic length vs magnification (Fixed total length x=10 m and pole tip field Bt=1.73 T)

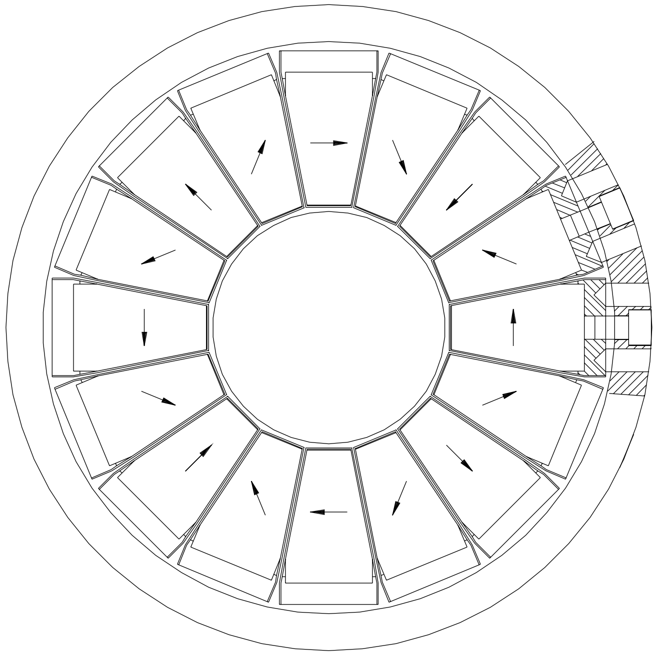


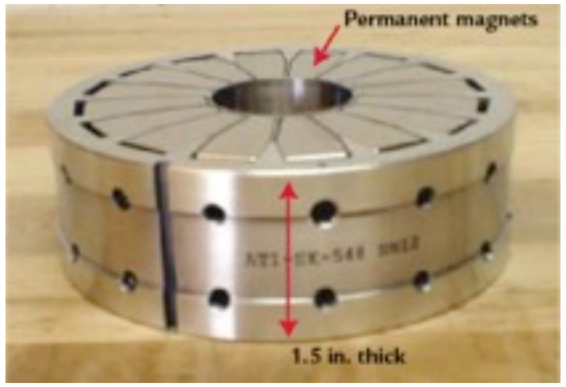
Normalized chromatic length and magnification vs pole tip field Bt (Fixed total length x=10 m)

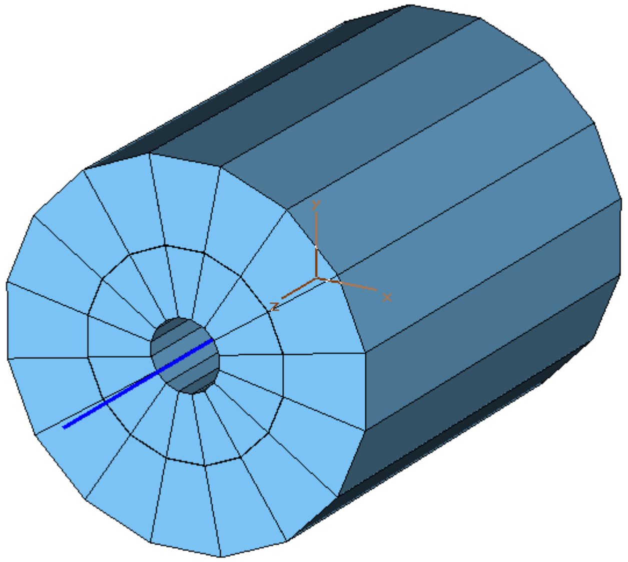


Permanent Magnetic Quadrupoles (PMQ) – design

High Gradient Split-Pole Quadrupole

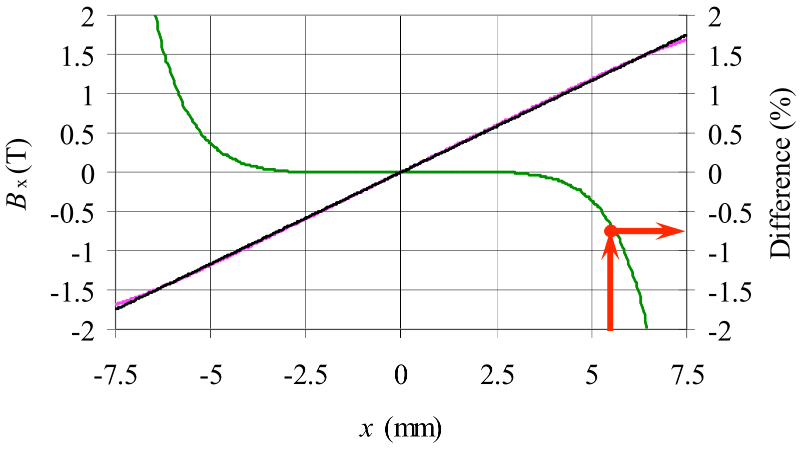


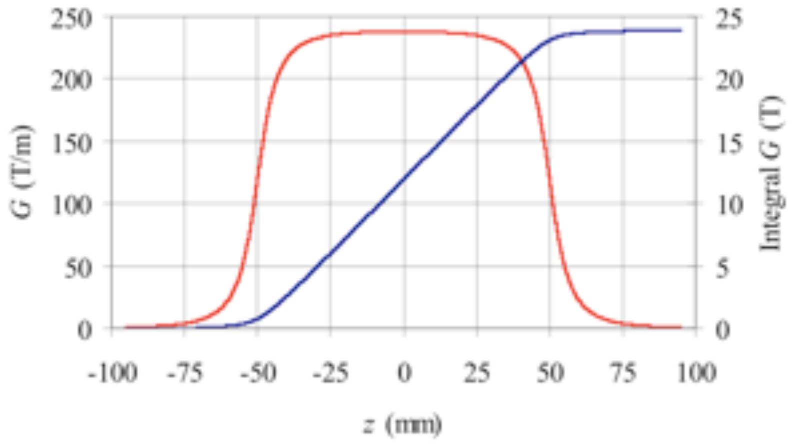




Extremely High-Level Gradient - Maximal Demagnetization Factor
Flexible Choice of the REPM Coercivity on Magnetization
Minimal Demagnetization in Median Planes (in Critical Spaces)
Gradient – Fixed

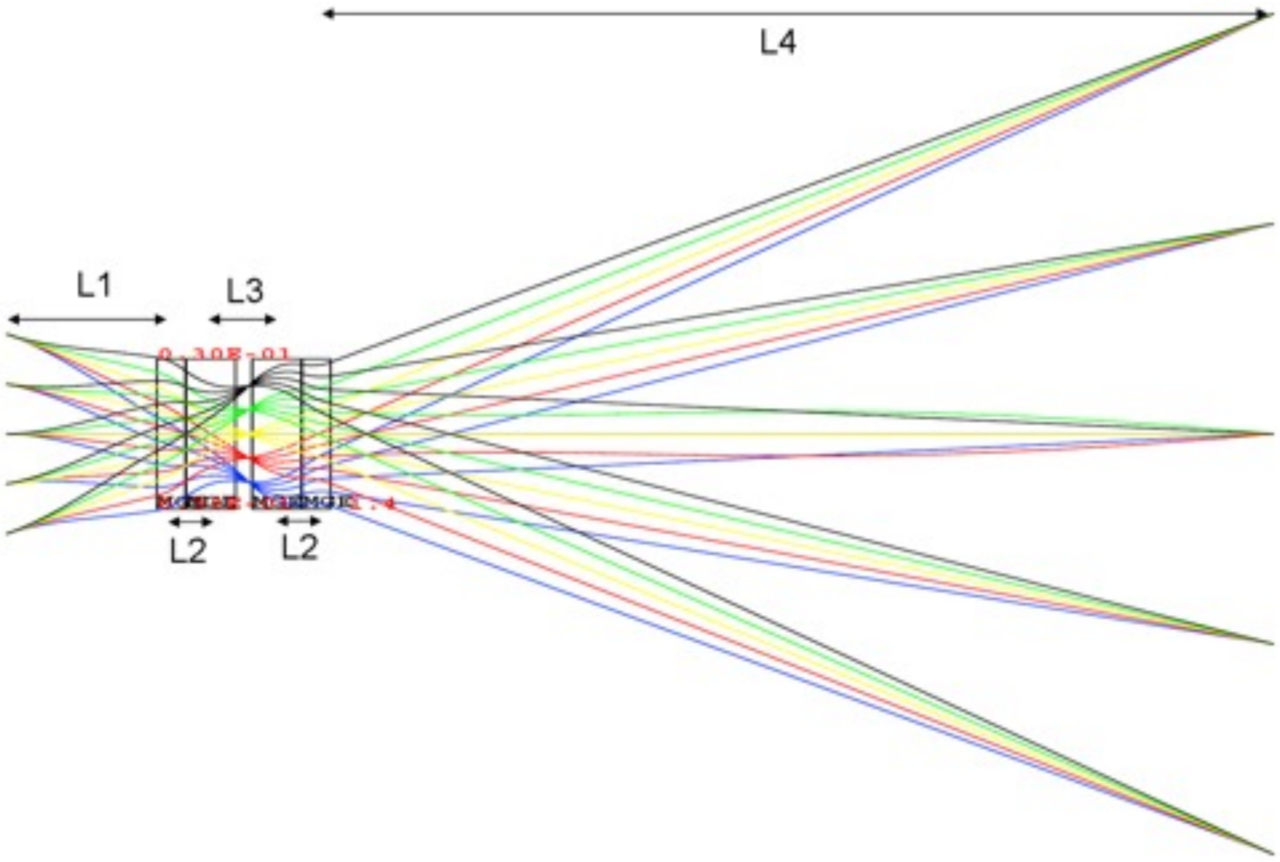
PMQ parameter	**Value**
Inner aperture, 2 · R_i	15 mm
Outer dimensions, 2 · Ro x L	79 x 100 mm
Internal ring magnetization	1.16 T
External ring magnetization	1.19 T
Pole tip field	1.7 T
Field non-linearity	< 0.75 %
Field gradient	238 T/m
Integrated field	23.8 T





PRIOR magnetic lens design – 15 mm PMQ aperture

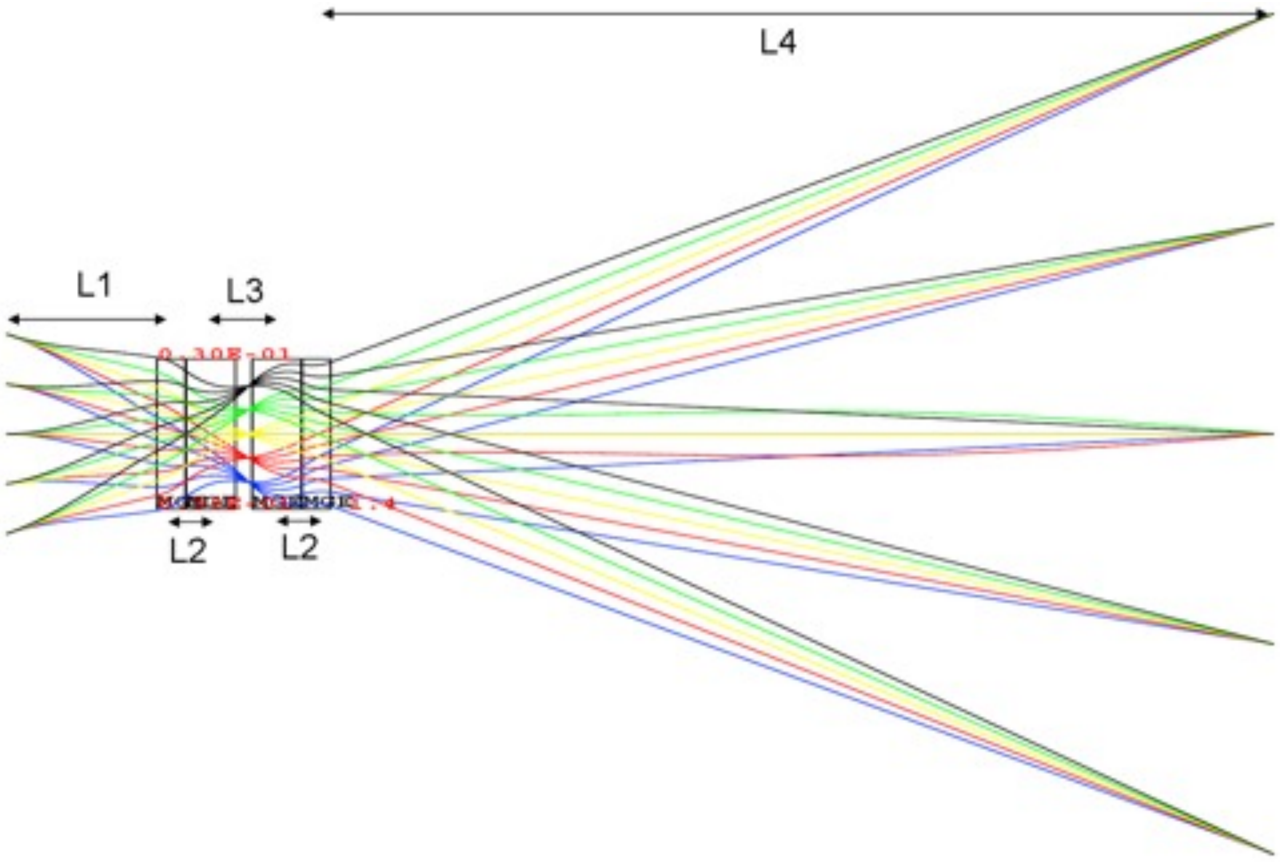
Parameter	**Value**
Proton energy	4.5 GeV
PMQ inner aperture, $2 \cdot R_i$	15 mm
PMQ outer aperture, $2 \cdot R_o$	79 mm
REPM remanent field	1.16 T
Field gradient	238 T/m
"Short" quadrupole length	110 mm
"Long" quadrupole length	220 mm
L_1 (object to first quad)	1.0 m
L_2 (first to second)	0.202 m
L_3 (second to third)	0.346 m
L_4 (last to image)	8.25 m
Total length	10.000 m



Parameter	**Value**
Magnification	6.12
Spatial resolution	6 – 7 µm
Horizontal chromatic length, C_x	2.74 m
Vertical chromatic length, C_y	2.40 m
Angular acceptance	5 mrad
Horizontal matching correlation, M_x	-0.42 mrad/mm
Vertical matching correlation, M_y	-0.53 mrad/mm

PRIOR magnetic lens design – 30 mm PMQ aperture

Parameter	**Value**
Proton energy	4.5 GeV
PMQ inner aperture, $2 \cdot R_i$	30 mm
PMQ outer aperture, $2 \cdot R_o$	100 mm
REPM remanent field	1.16 T
Field gradient	115 T/m
"Short" quadrupole length	165 mm
"Long" quadrupole length	330 mm
L_1 (object to first quad)	1.3 m
L_2 (first to second)	0.307 m
L_3 (second to third)	0.515 m
L_4 (last to image)	7.576 m
Total length	10.000 m



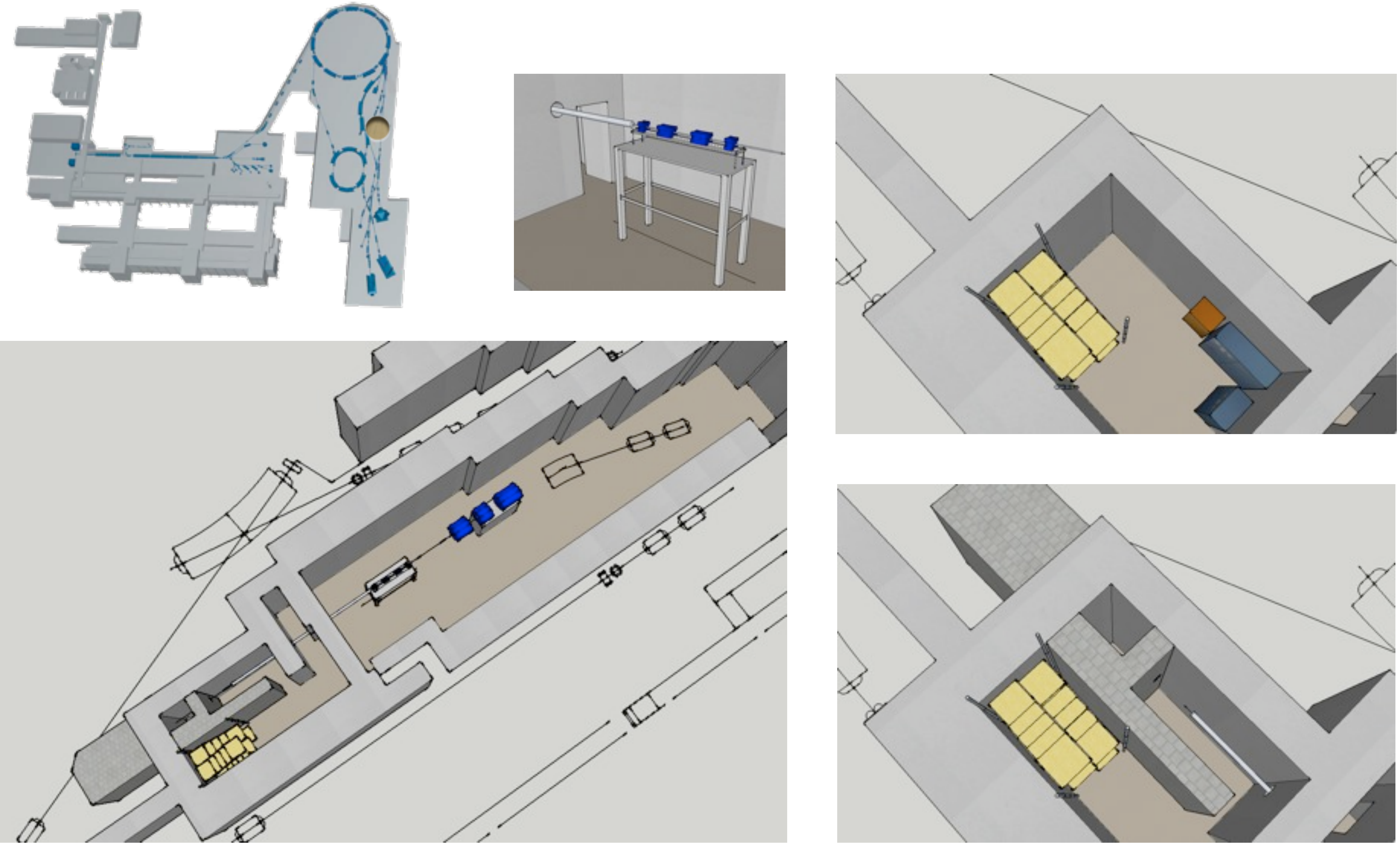
Parameter	**Value**
Magnification	4.1
Spatial resolution	8 – 10 μm
Horizontal chromatic length, C_x	3.99 m
Vertical chromatic length, C_y	3.41 m
Angular acceptance	5 mrad
Horizontal matching correlation, M_x	-0.45 mrad/mm
Vertical matching correlation, M_y	-0.55 mrad/mm

PRIOR setup features

- flexible design: can be optimized for a particular experiment:
  - proton energy can be reduced
  - standoff can be changed
  - magnification can be increased

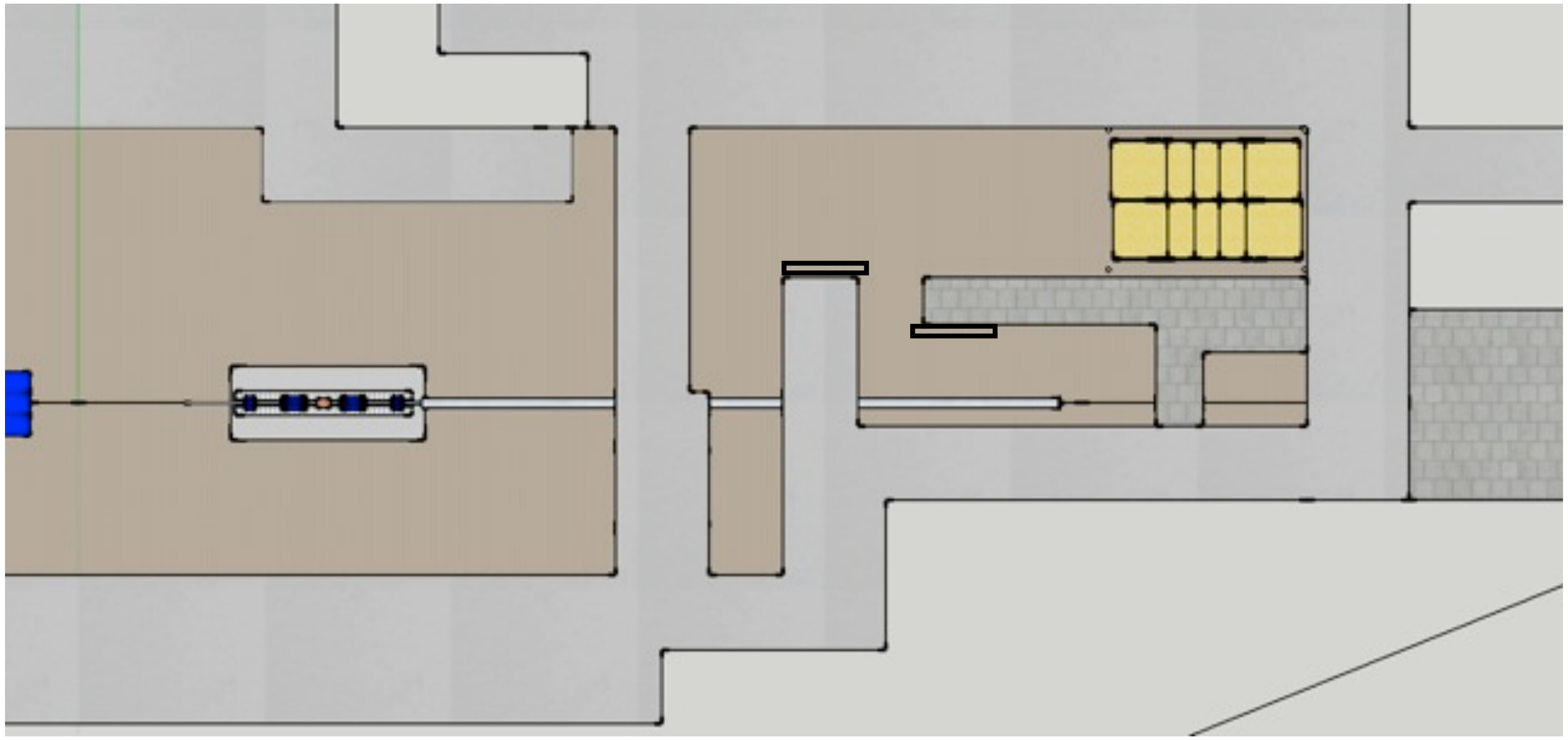
- SIS-18 electron cooler: both transverse (⇒ density resolution) and longitudinal (⇒ spatial resolution) emittances of the beam can be reduced by an order of magnitude or more

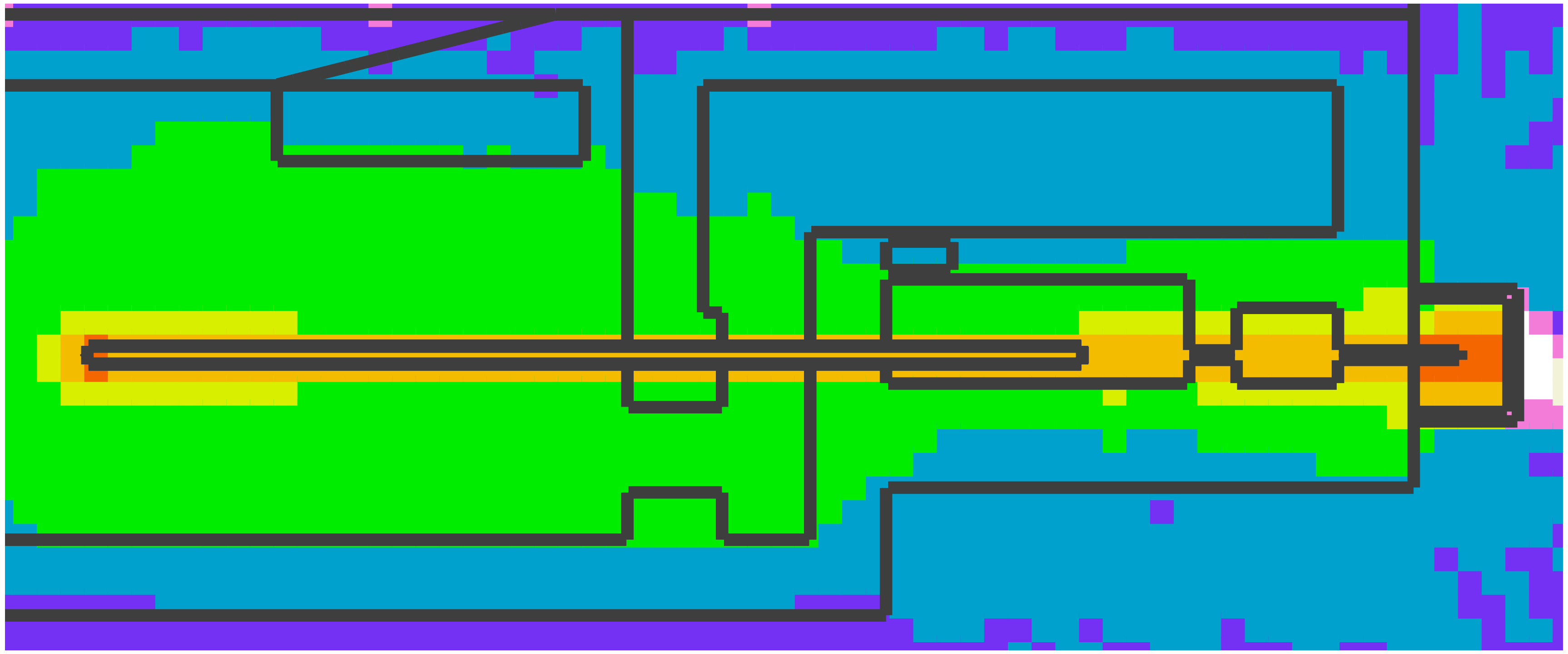
Fielding at GSI – a minor reconstruction of the HHT cave



a compact system but long drift is needed for the microscope

Radiation safety – preliminary simulations

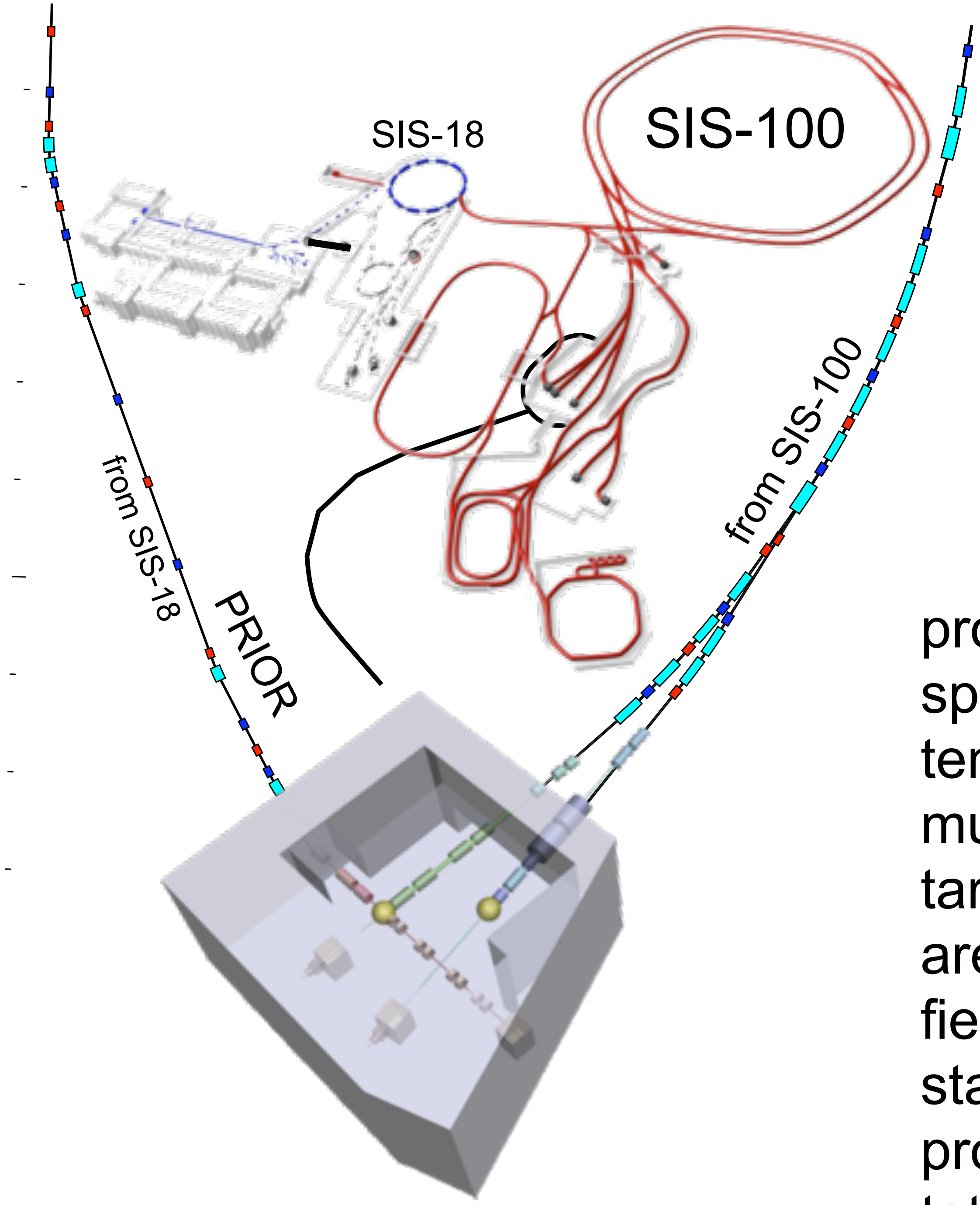


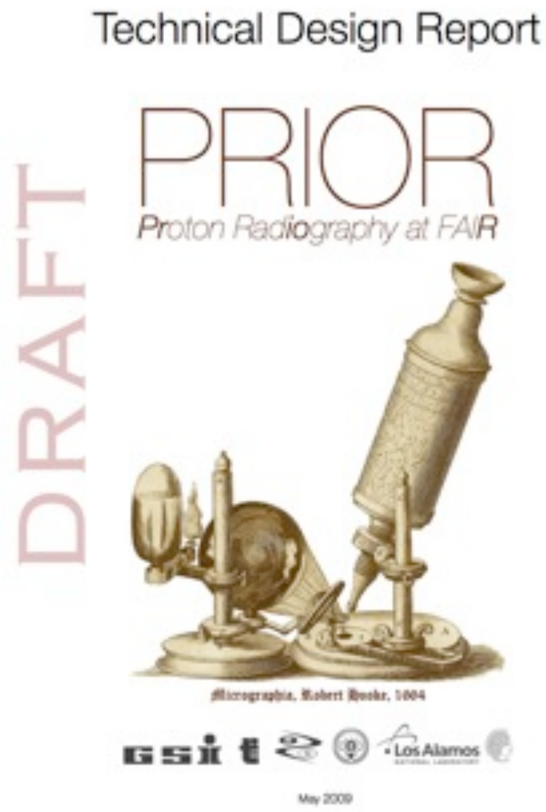


4.5 GeV protons
5·1010 / pulse, 107 / s
beam dump:
150 cm Fe,
350 cm concrete

< 0.5 μSv/h

PRIOR – Proton Radiography at FAIR




Technical Design Report

DRAFT

PRIOR

Proton Radiography at FAIR

Micrographia, Robert Hooke, 1664

May 2009

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spatial resolution:	≤10 μm
temporal resolution:	10 ns
multi-framing capability:	1 – 4 frames within 1 μs
target characteristics:	up to 20 g/cm2
areal density reconstruction:	sub-percent level
field of view:	10 – 15 mm
stand-off distance:	1 – 1.5 m
proton illumination spot size:	3 – 15 mm
total length after object plane:	less than 15 m