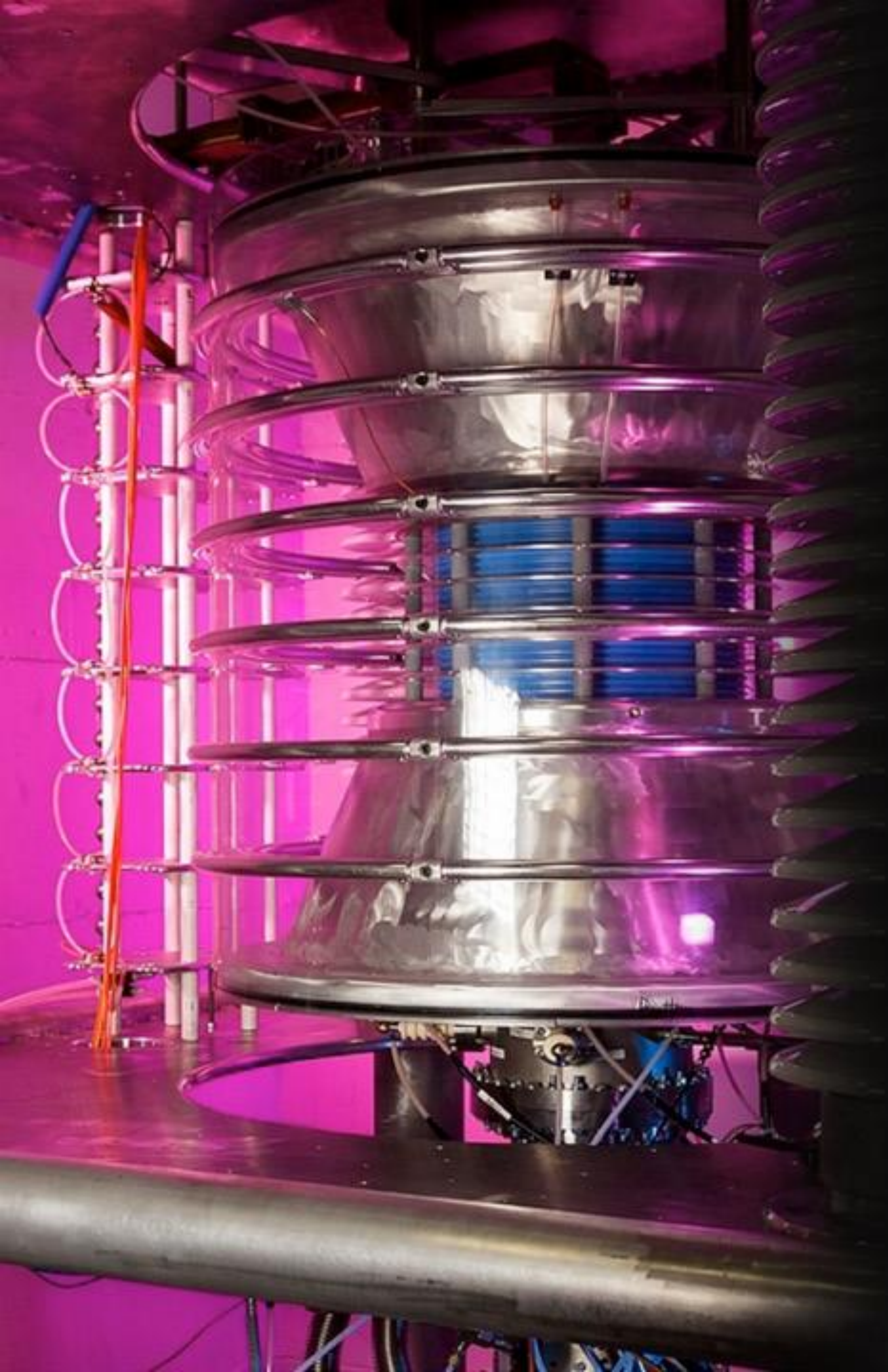

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# Current Status of Neutron Imaging at PNL

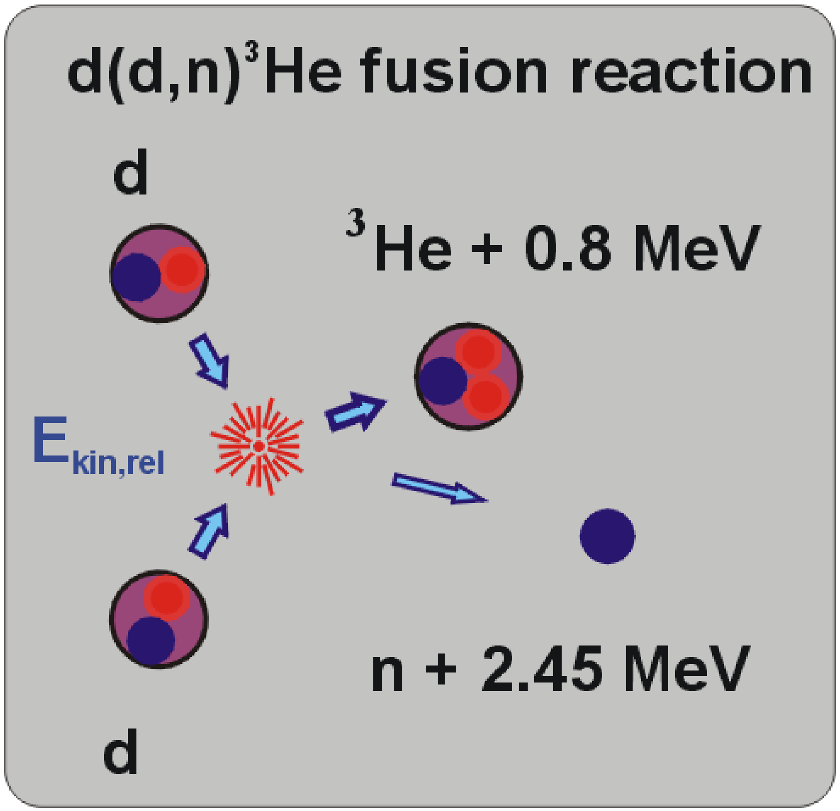
1 September 2017

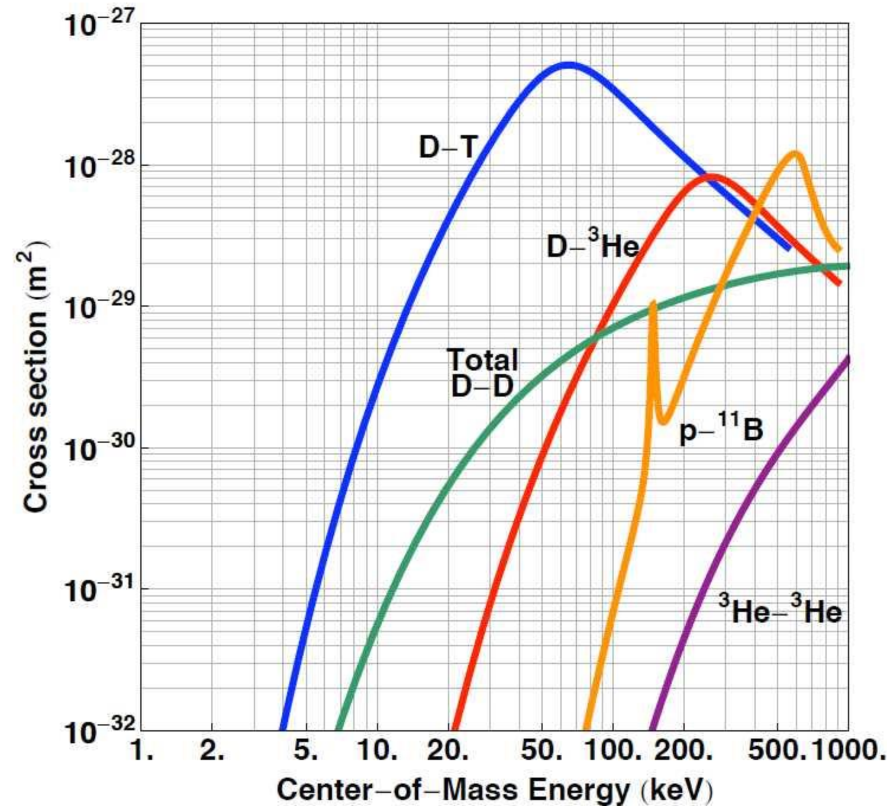
Michael Taylor

# Outline

- Physics of fusion neutrons
- Accelerators from PNL
- Film techniques
- Performance upgrades
- Digital imaging options
- Summary

# Physics of Fission Neutrons

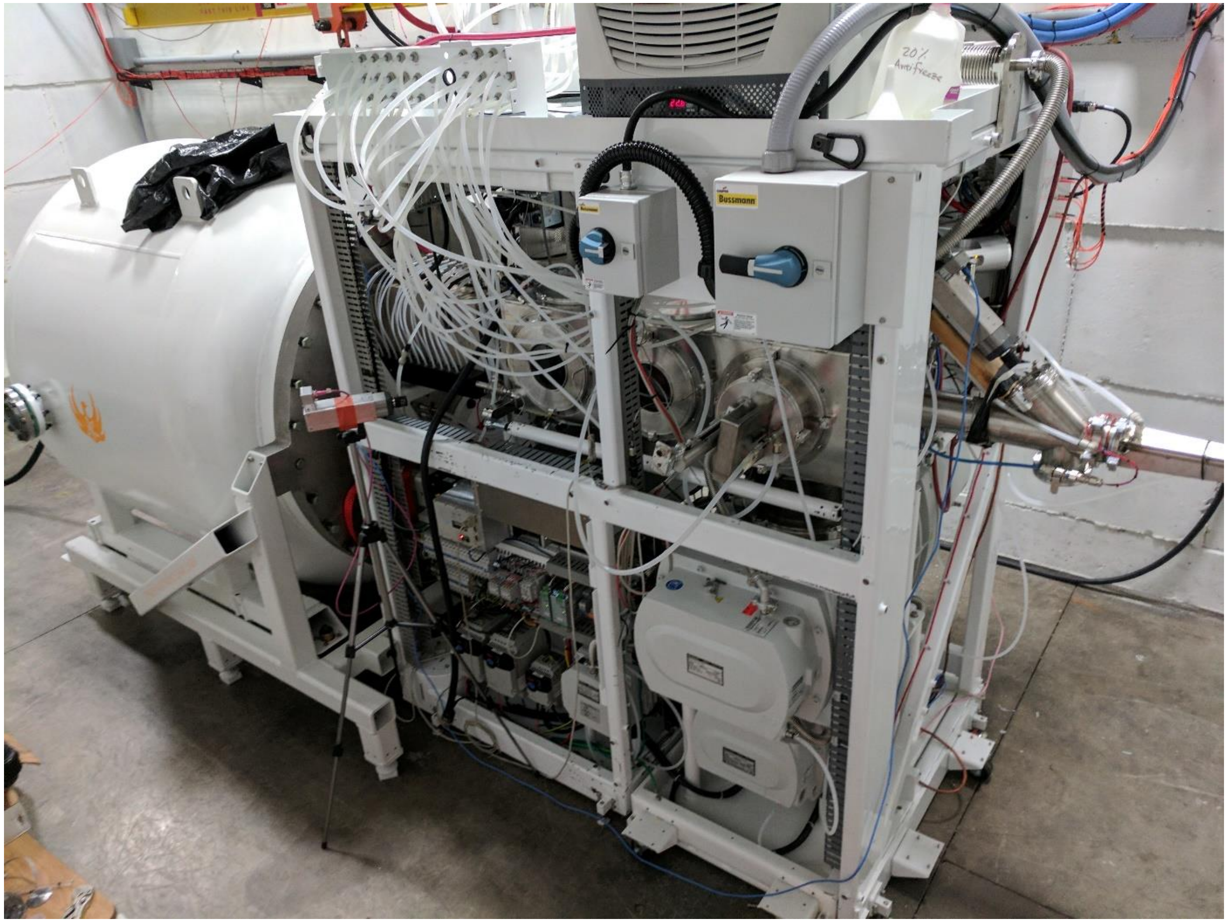


# Accelerator Technology

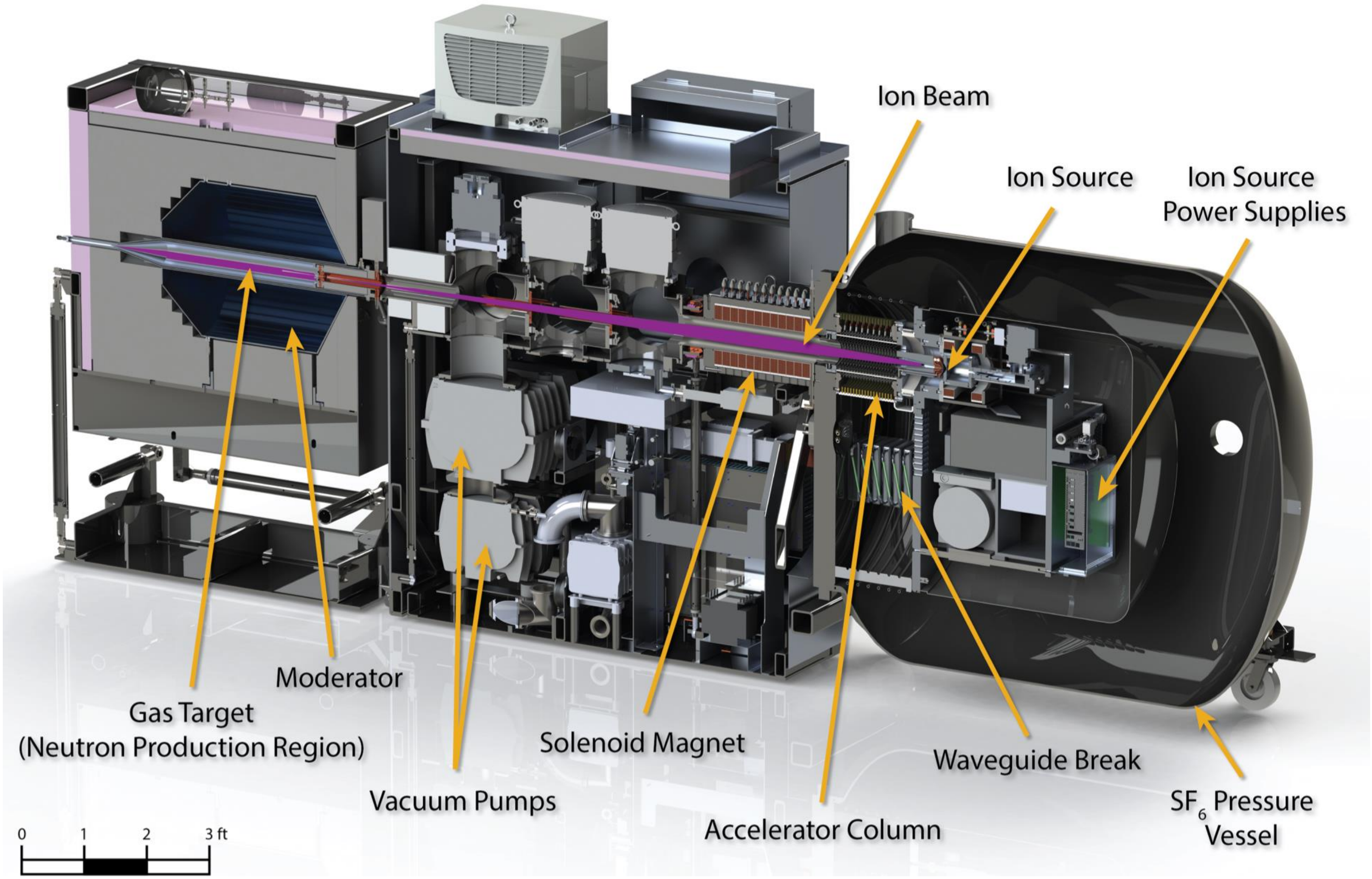
- Generation I: Installed and in use (horizontal)
- Generation II: Vertical

# Third Generation System

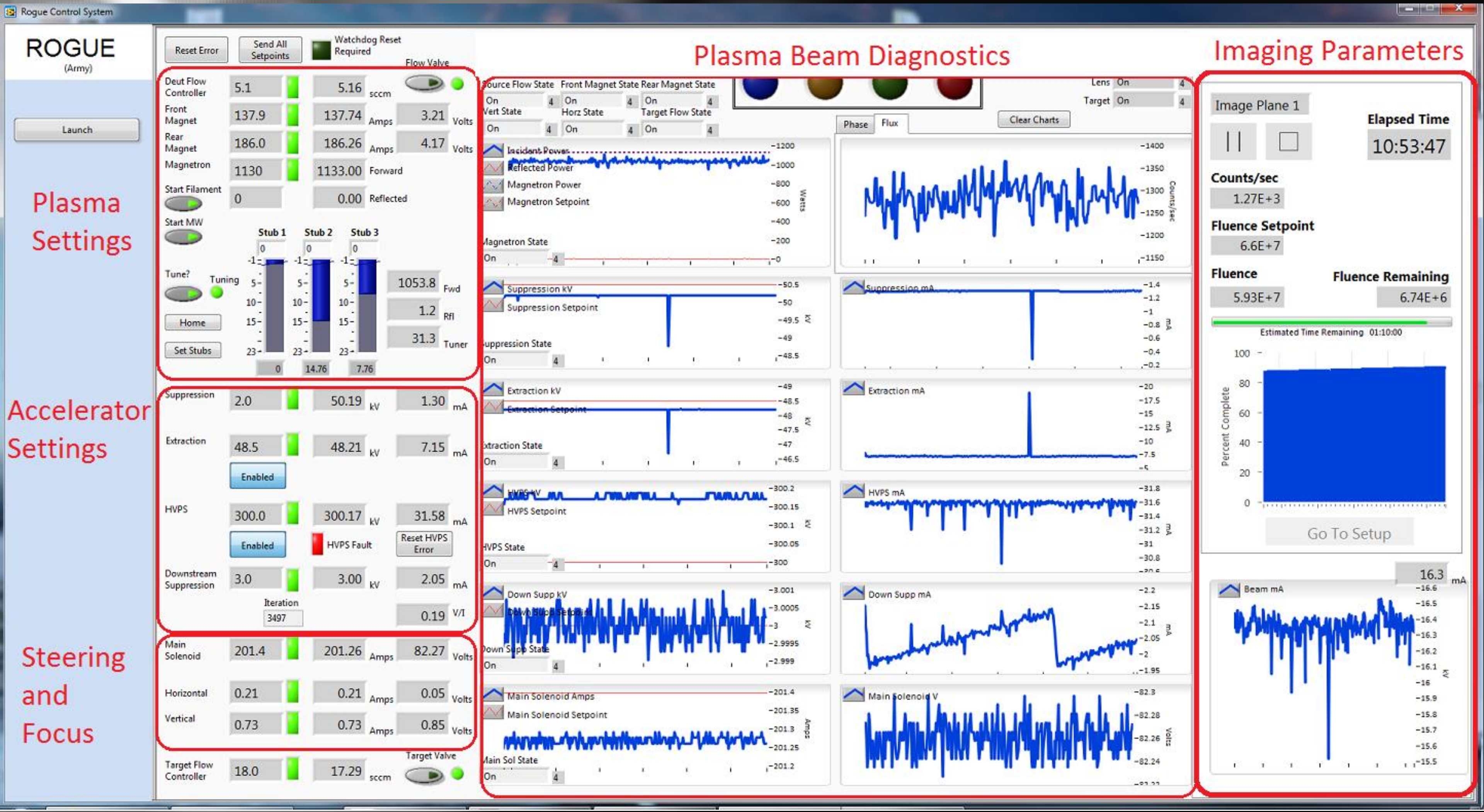


- Increased neutron output (3x$10^{11}$n/s)
- Increased Cd ratio (2.1)
- Lower gamma dose
- Faster images
- Higher image quality
- Engineered heavy water moderator

# Third Generation System



# LabVIEW User Interface

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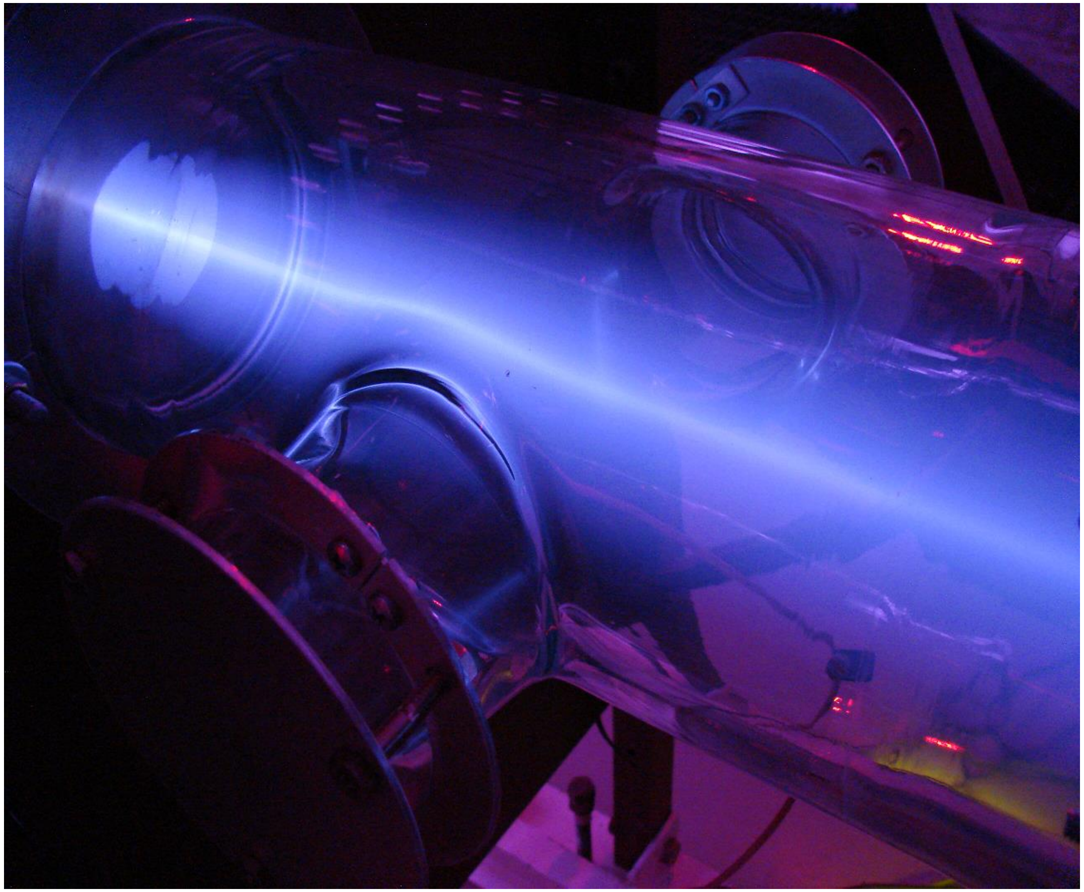
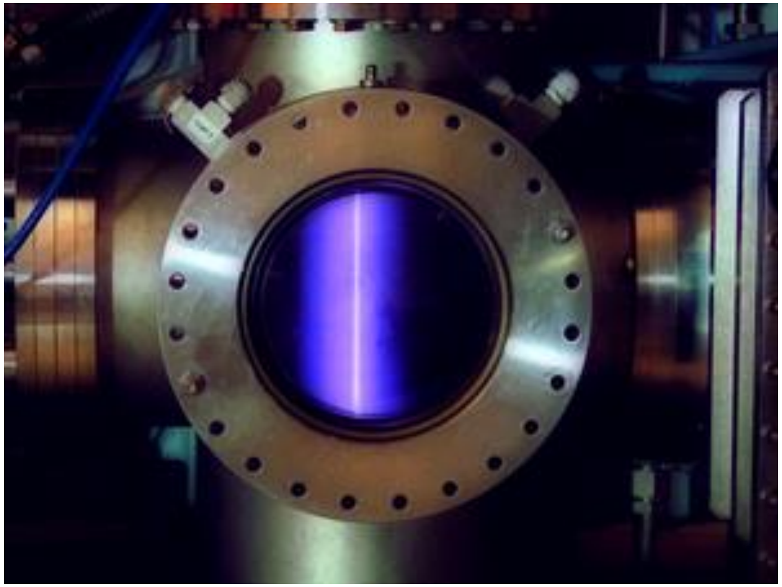
# Deuterium Beam Accleration

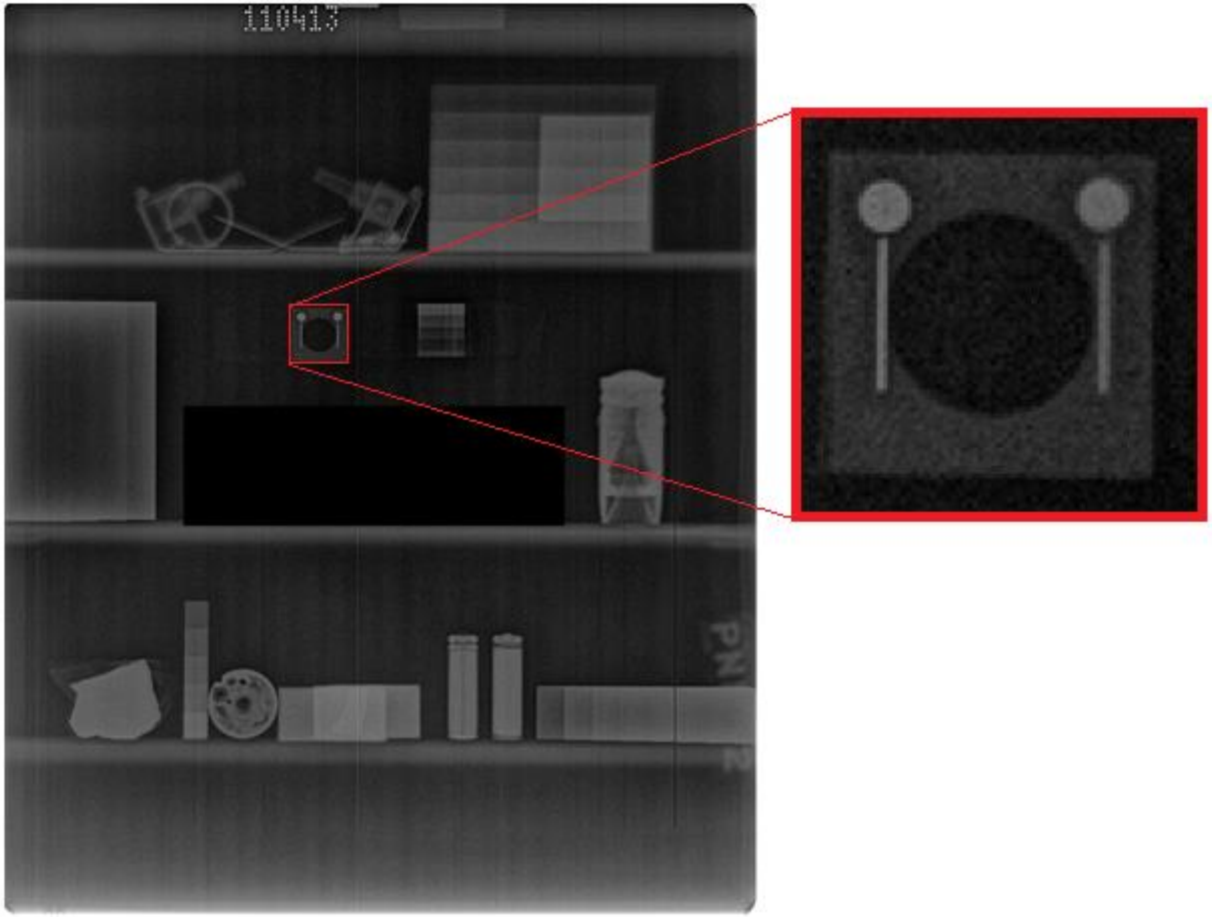




# Neutron Collimation


- With L/D=35 and L=62”, flux at imaging plane designed for $1.4\times10^4$ n/cm$^2$s
- L/D changed by aperture only
- Neutron/gamma dose ratio >$1\times10^5$ n/mrem
- Design Cd ratio >2.1, measure=1.9
- Field of view 22” diameter

# Examples




- Boron plugs easily visible
- Left plug and Cd wire more resolved – Low L/D
- Lead plugs not seen – low gamma
- Cd wires easily visible
- Long image time (8hrs)

*Image courtesy of Stephan Zuber at Picatinny Arsenal, Gen I PNL neutron generator*

# Description of Film Technique

- Films:
  - Industrial – Agfa D3 SC, Agfa D7, Kodak AA400
  - Medical – Carestream Min-R, Fuji AD-M, Agfa HDR-C
  - Photographic – Ilford Ortho Plus, Ilford Delta 100, Arista
- Main difficulty is the balance between image quality and time for exposure
- All films suffer from reciprocity failure at low exposure levels
  - Cool film to <-80°C to retain exposure
- Neutron conversion:
  - Industrial – Gd metal, GadOx, LiF:ZnS
  - Medical – GadOx (Agfa HD)

Summary: slower films and conversion screens can provide higher image quality.  Achieving Cat. III images might require industrial film.

# Example Film and Analysis


- Carestream Min-R film with Agfa HD screen
- L/D=35
- Fluence: 1.3E7n/cm$^2$
- Time: 1.5hrs
  - Machine operating at only 1/3 power


Paint Marker
Camera Lens
Socket Wrench
50 Caliber BMG Rounds
ASTM Prototype Image Quality Indicator
ASTM Sensitivity Indicator
ASTM Beam Purity Indicator
Lighter
Shotgun Round
[redacted]
Serial Number and Date Marker
0 1 2 5 J U L 1 7
Magnets separated by Aluminum block
PNL Logo made from Aluminum and Gadolinium
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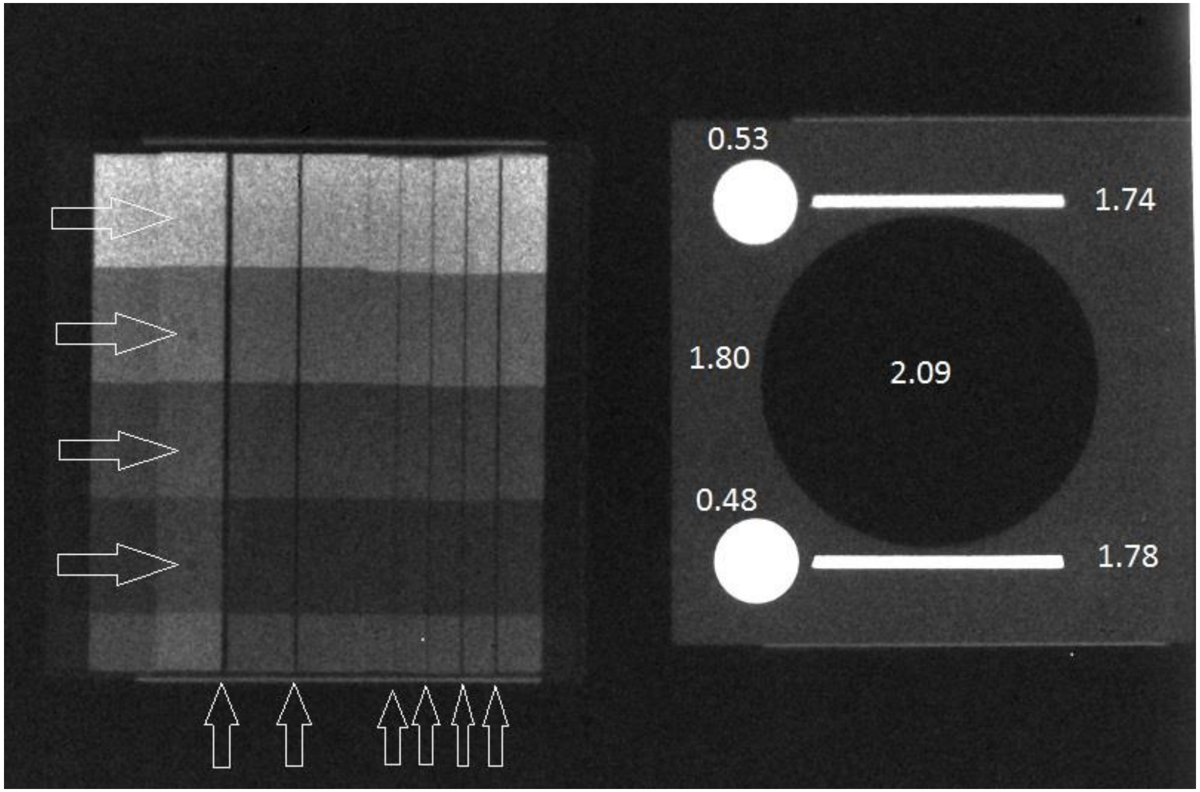
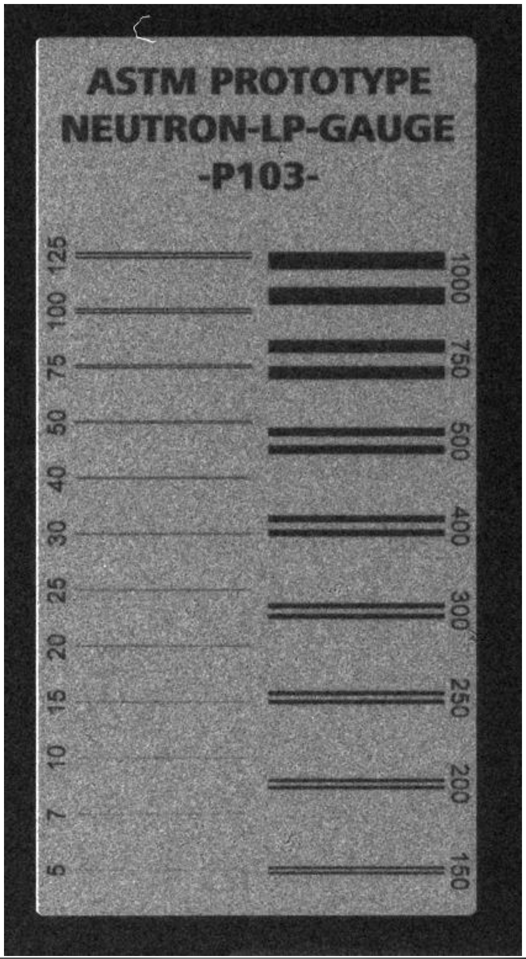
# Example Film and Analysis (L/D=35)

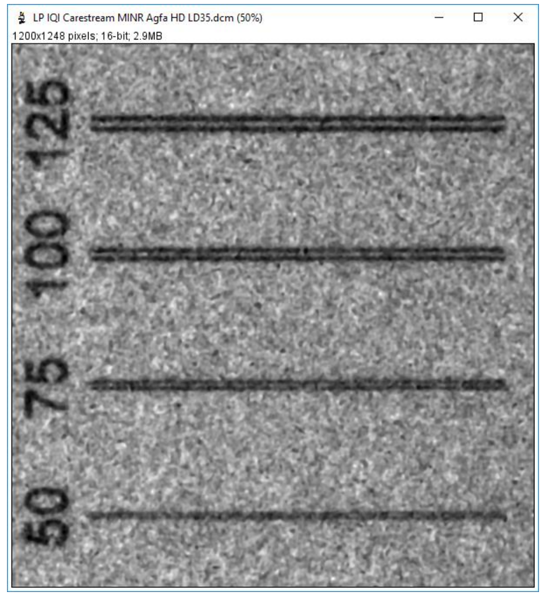



ASTM E545 Metrics

- 4th hole in SI visible on film but lost in digitization
- NC: 72.7 (Cat I)
- Scat: 2.4 (Cat I)
- Gam: 2.8 (Cat I)
- PP: 1.9 (Cat I)
- G: 6 (Cat I)
- H: 4 (Cat IV)
- Carestream Min-R
- Fluence = $1.3 \times 10^7 n/cm^2$

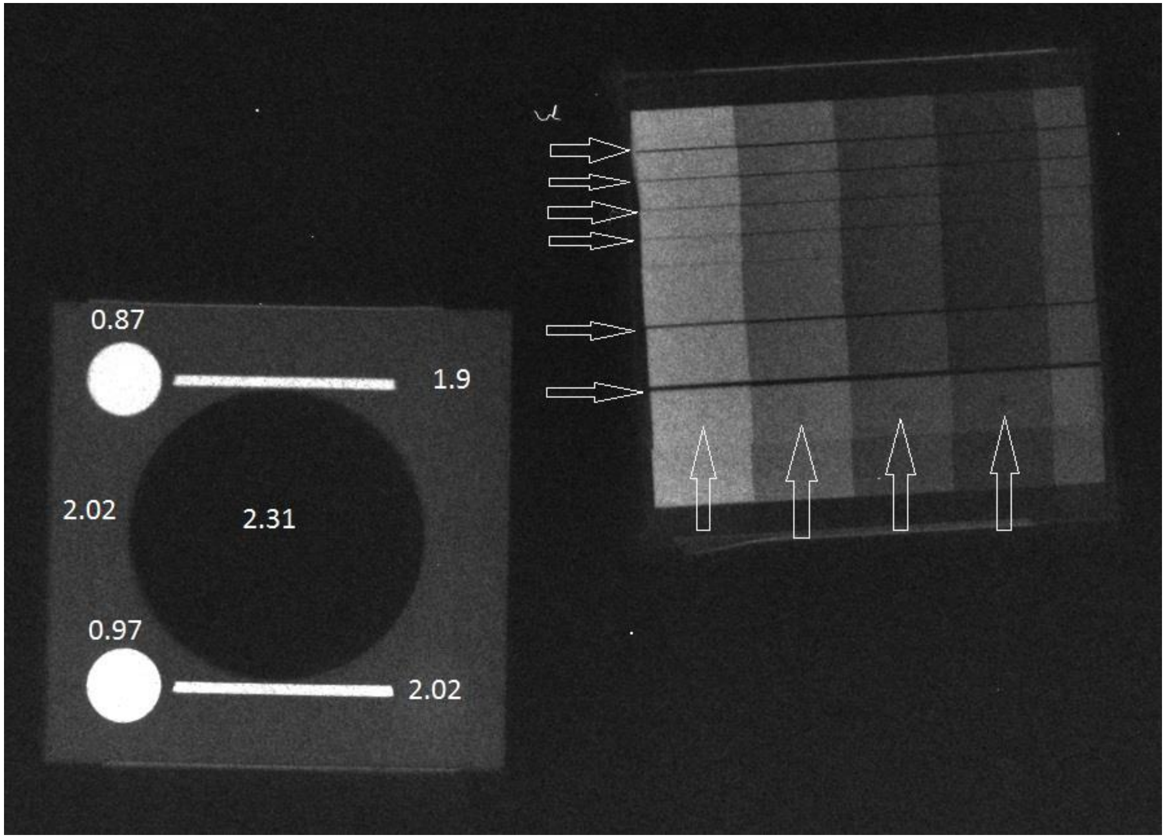
# Example Film and Analysis (L/D=35)




- Line Pair Gauge shows 75um LP clearly on film but loses some distinction in digitization
- Will discuss further in subsequent slides

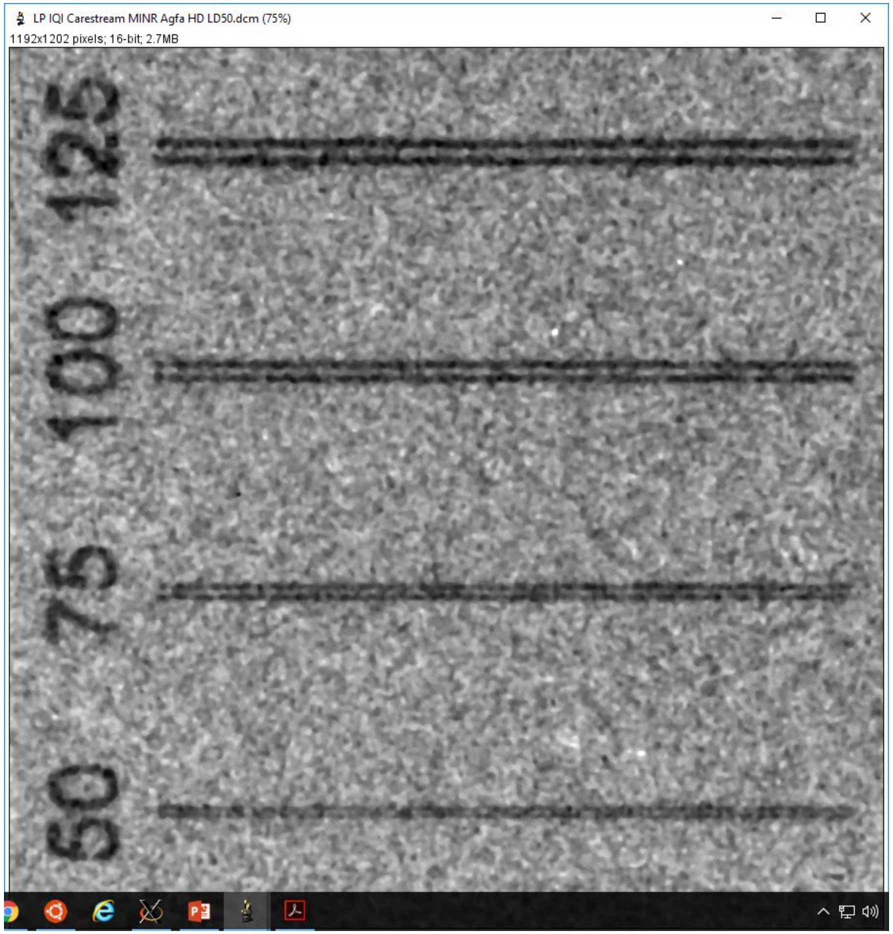
# Example Film and Analysis (L/D=50)




ASTM E545 Metrics

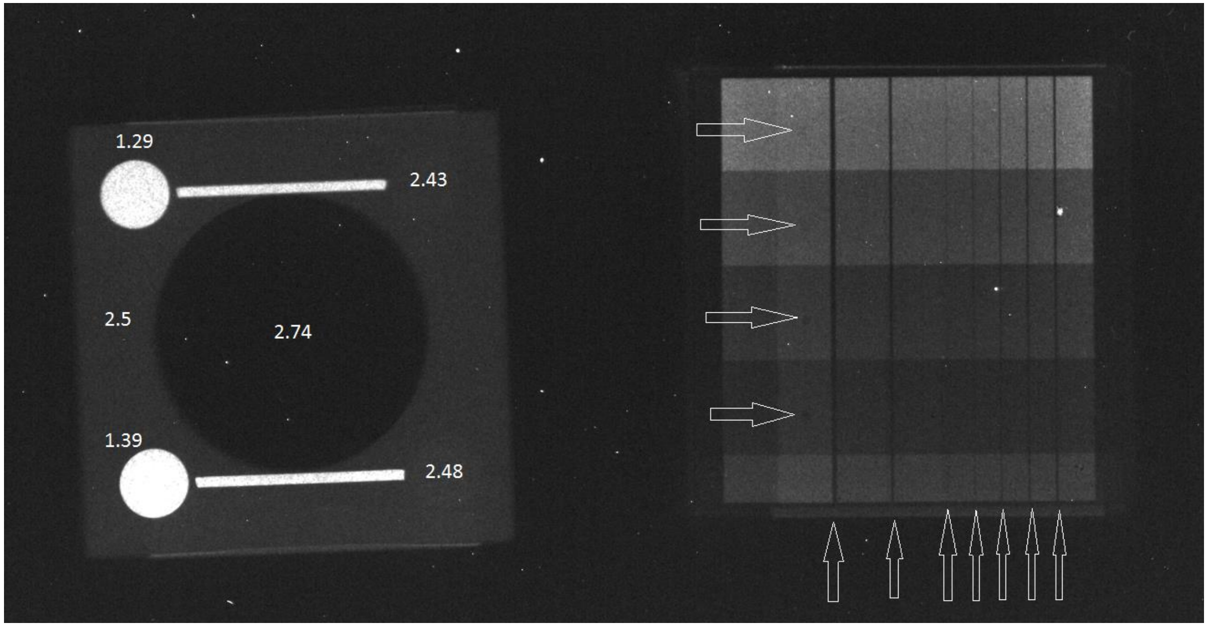
- $4^{th}$ hole in SI visible on film but lost in digitization
- NC:52.8 (Cat IV)
- Scat: 4.3 (Cat I)
- Gam: 5.2 (Cat IV)
- PP: 5.2 (Cat IV)
- G: 6 (Cat I)
- H: 4 (Cat IV)
- Carestream Min-R
- Fluence = $1.3x10^7 n/cm^2$

# Example Film and Analysis (L/D=50)




- At L/D=50 Line Pair Gauge shows 50um LP clearly on film but loses some distinction in digitization
- Will discuss further in subsequent slides

# Example Film and Analysis (L/D=50)



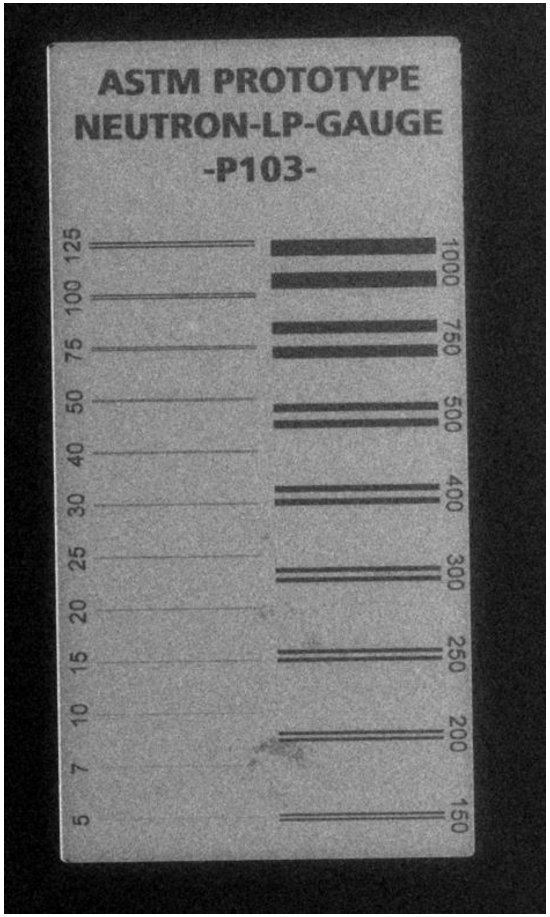

ASTM E545 Metrics

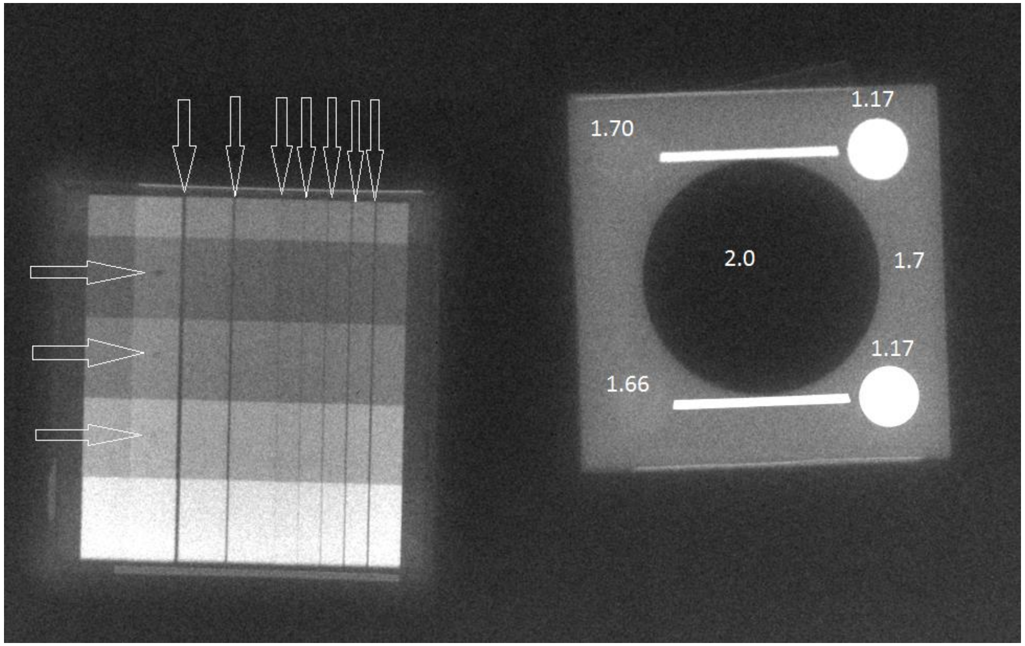
- 4th hole in SI visible on film but lost in digitization
- NC:47.4 (Cat V)
- Scat: 3.6 (Cat I)
- Gam: 2.6 (Cat I)
- PP: 1.8 (Cat I)
- G: 7 (Cat I)
- H: 4 (Cat IV)
- Fuji AD-M
- Fluence = $3.3 \times 10^7 n/cm^2$

# Industrial Film Technique

- Industrial film, such as Agfa D3 SC (single coated emulsion) are sensitive to electrons or blue light but not green light from GadOx conversion screens
  - Requires Gd vapor deposited vacuum cassette
  - Agfa D3 SC is much slower than D7; D7 explored first
  - Film cooled to -60°C to mitigate reciprocity failure

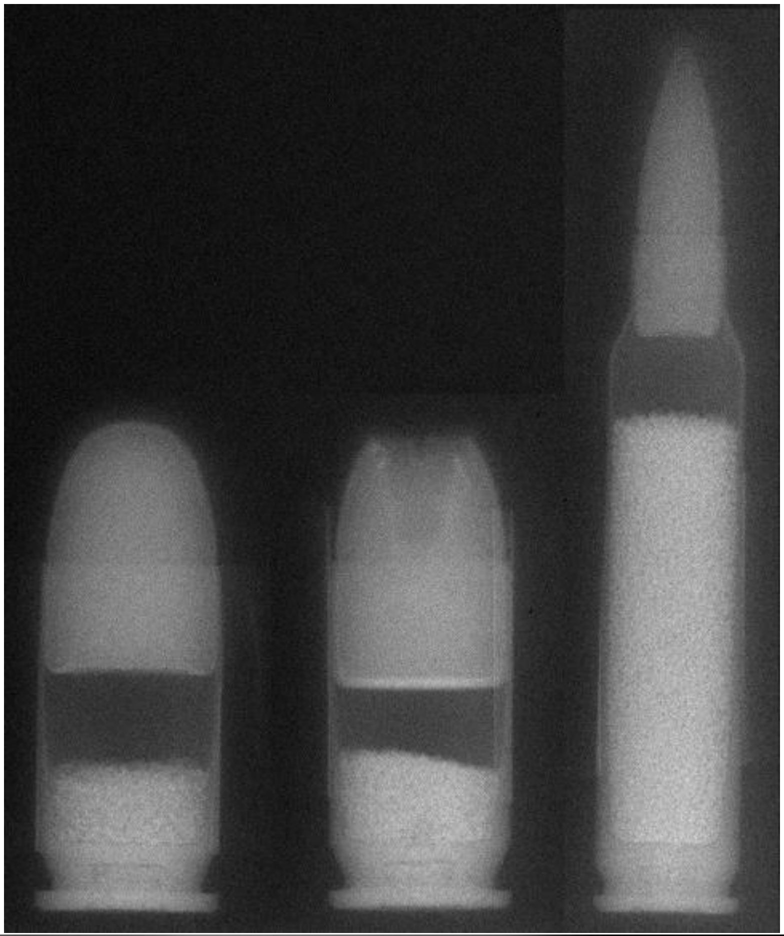
# Industrial Film Technique

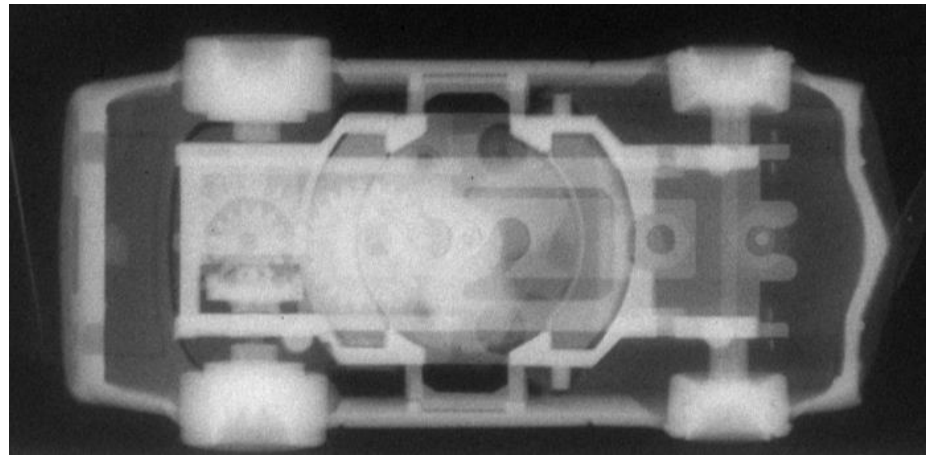


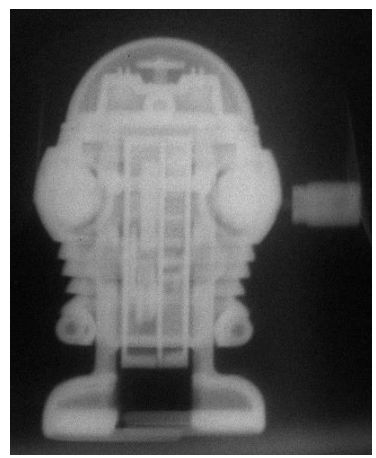



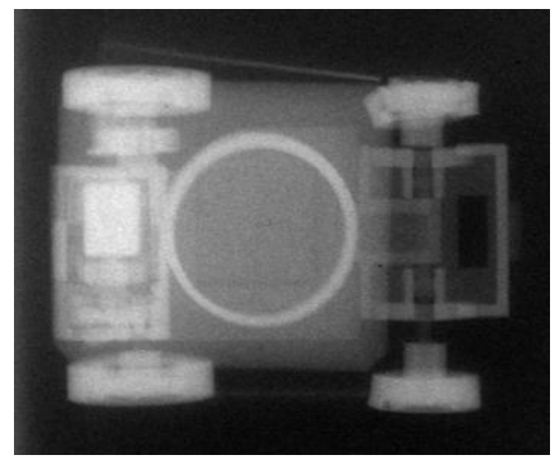

- Similar Line Pairs, gaps and holes in SI
- Much lower neutron content due to long exposure to epithermals

# Industrial Film Technique









# Differences

- L/D of 50 takes 2x as long for similar film density
- During the longer run time, total background gamma contamination and epithermal/fast neutron contamination goes up while total thermal neutron exposure remains constant
  - Increased values for gamma and pair production
  - Decreased value for thermal neutron content

# Performance Upgrades

Gamma Contamination

- *Use a conversion screen that is less sensitive to gammas that might fog the image (BPI still indicates low gamma exposure)*
- *Additional shielding against gammas for longer run times (lead 2”)*
- *Fuji medical film appears to have lower gamma content in E545 evaluation*

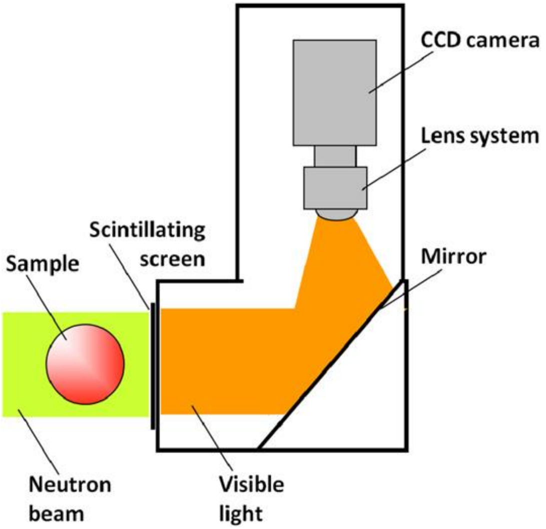
Thermal Neutron Content

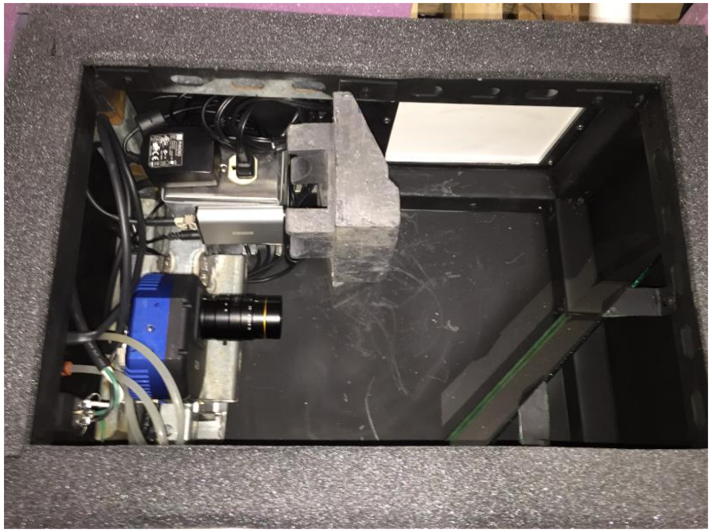
- *Moderator design changes for a more thermalized beam*
- *Sapphire crystal for filtering epithermal neutrons*

# Detector Technology

## Neutron Conversion Screen

- $^{6}LiF/ZnS{:}Cu,Al,Au$ and $Gd_2O_2S$ mixture captures neutrons and emits blue or green light (~450-600 nm)
- Light captured by CCD camera offset from beamline
- Must be sealed in light tight box, well shielded from stay neutrons and gamma rays



# Detector Technology

## Solid State Detector

- Amorphous silicon substrate with Li/B mixture surface coating
- Digital readout every 1 second
- Images stacked to reduce noise
- Must be shielded from stay neutrons but otherwise insensitive to gamma rays

# Detector Technology

## Solid State Detector

- Amorphous silicon substrate with LiF/ZnS or GdOS
- Digital readout variable
- Images stacked to reduce noise
- Must be shielded from stay neutrons
- 200um pixel pitch, 16 bit

# Detector Technology

## Computed Radiography

- Image plate/storage phosphor ($BaFBr:Eu^{2+}$ with $Gd_2O_3$)
- 14”x17” neutron sensitive image plates available
- 14 bit, selectable spot size down to 25um

# Summary

- PNL has demonstrated neutron imaging using many different films/conversion screens as well as digital images using DR, CR and CCD
- Best images taken have been with Carestream medical film and Agfa HD conversion screen (all metrics at Category I per ASTM E545 except for holes in SI)
- Next steps with industrial film at L/D of 35 and 50.  Expect Category III or better per ASTM E545
- Chiller expected in 2 weeks to control film temperature more consistently – might also reduce image time
- Ongoing research for optimal image detection (Film and digital detectors)
- Ongoing research for beam filtering for increased image quality (lead, bismuth, sapphire)

# Thank You!