INL/MIS-17-43197

Moving to Digital

Initial Experiences Developing Camera-Based Neutron Imaging Capabilities

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AUNIRA

Presented at TUM, FRM-II

August 30, 2017

www.inl.gov

Idaho National Laboratory

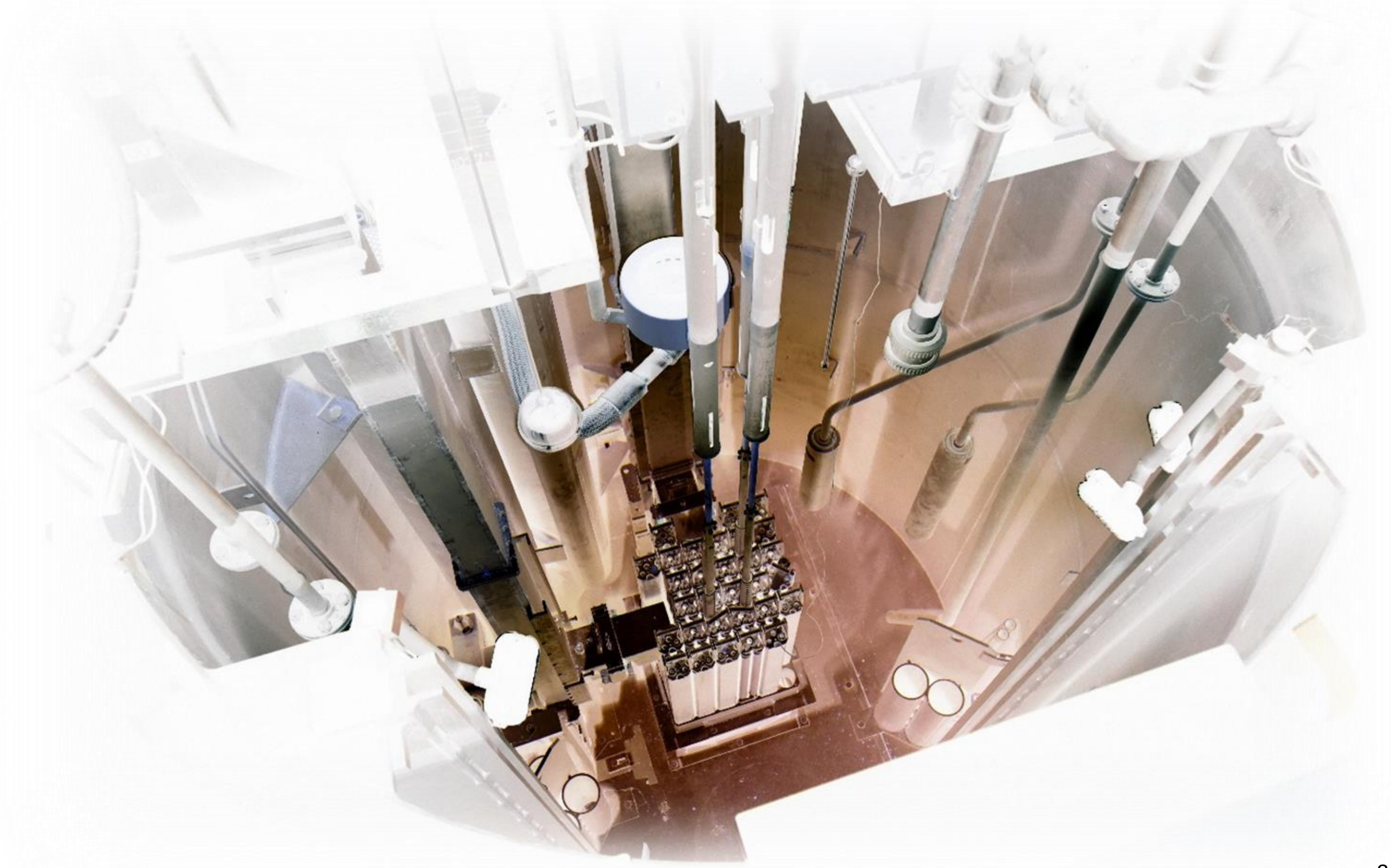
BRIEF Background

What we do at INL

How we currently do NR

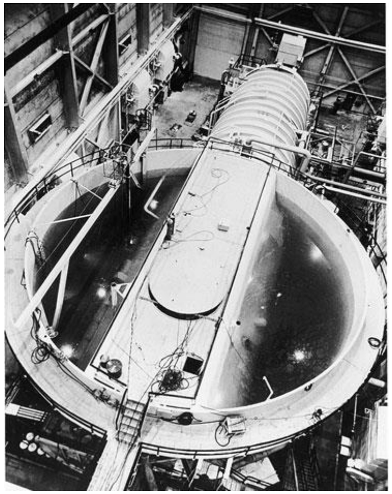
Why it is important

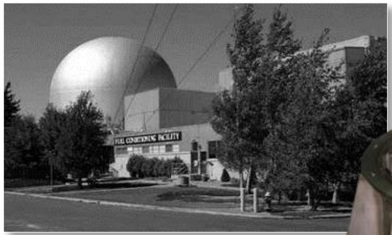
First experiments with a camera-based system

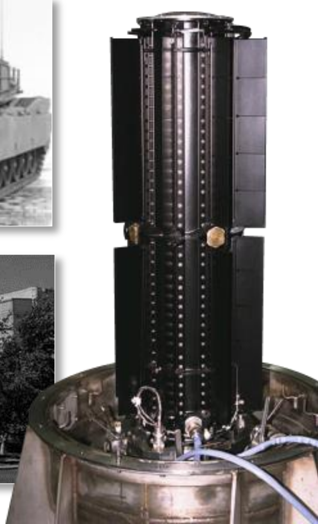


Idaho National Laboratory - Overview

- Est. 1949 as the National Reactor Testing Station and Argonne-West
- Location of the first nuclear power plant in 1951
- Developed Navy nuclear propulsion systems
- First demonstration of the breeder reactor concept
- Designed, constructed and operated 52 nuclear reactors
- The United States' leading nuclear **energy** laboratory

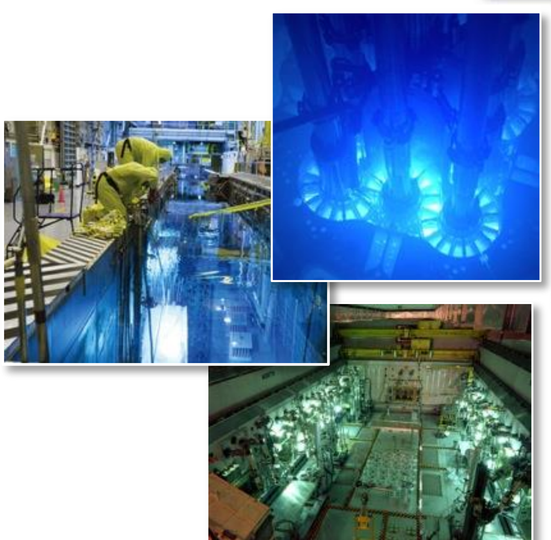






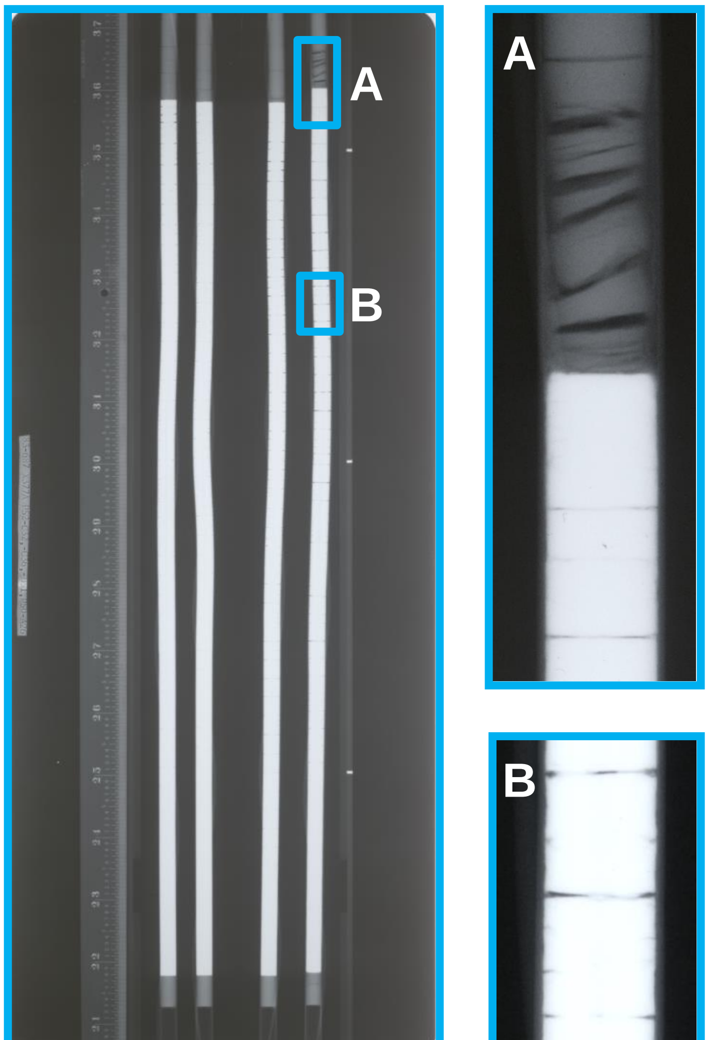
Idaho National Laboratory - Overview

- 2250 km^2 (~40× Manhattan, ~90% Luxembourg, 20× Paris, 37000× Louvre)
- 180 km of electrical transmission and distribution lines
- ~580 buildings
- 285 km of paved roads
- 300 metric tons of used fuel
- ~4000 employees
- 4 reactors

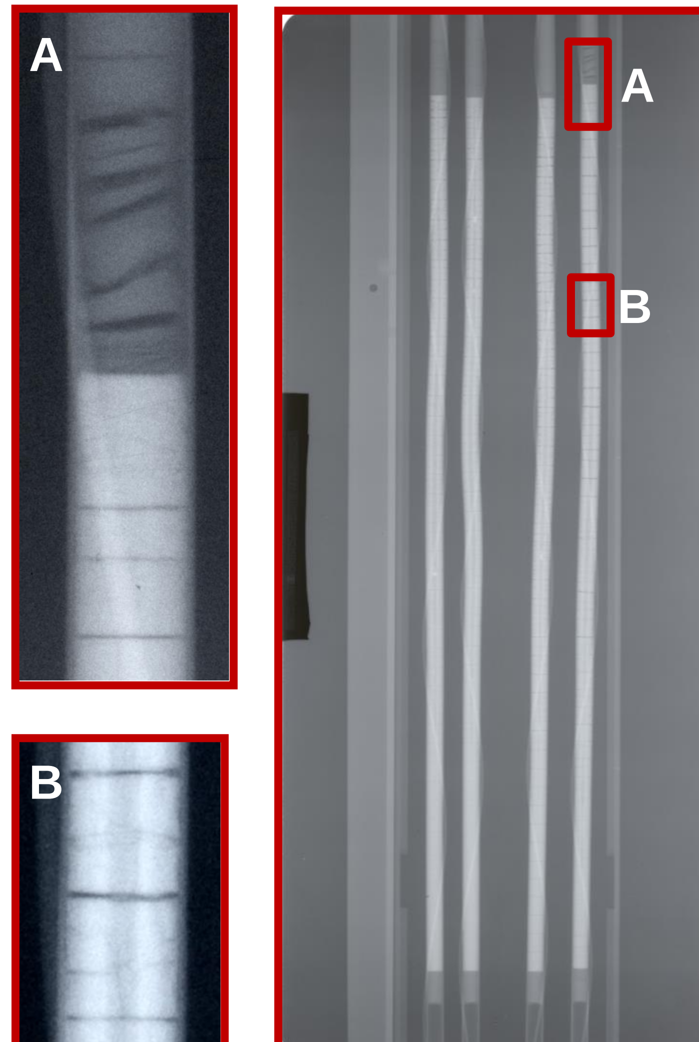


Current Neutron Radiography Capabilities

DYSPROSIUM

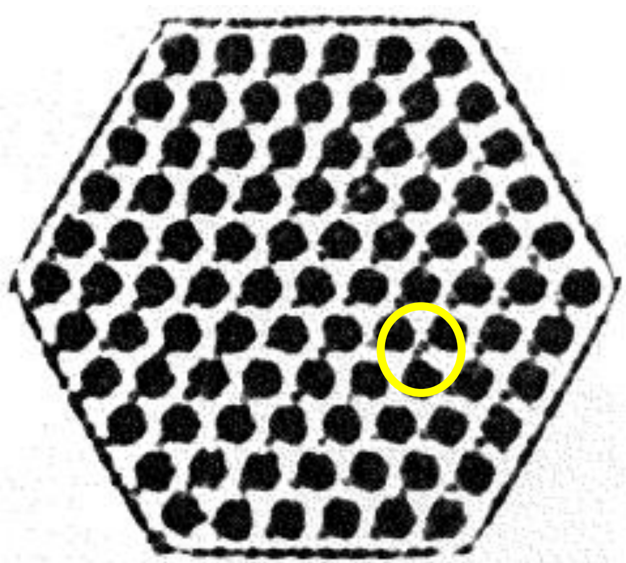


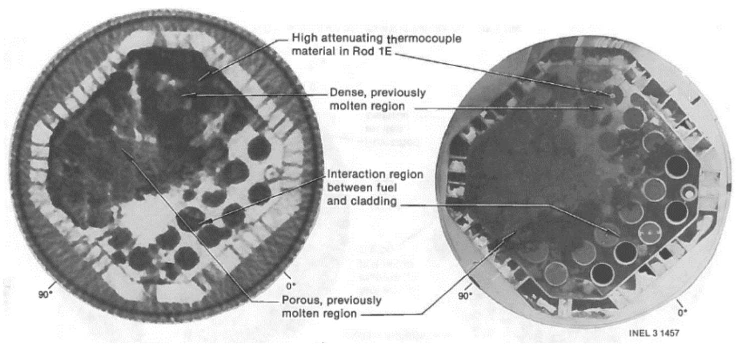
INDIUM

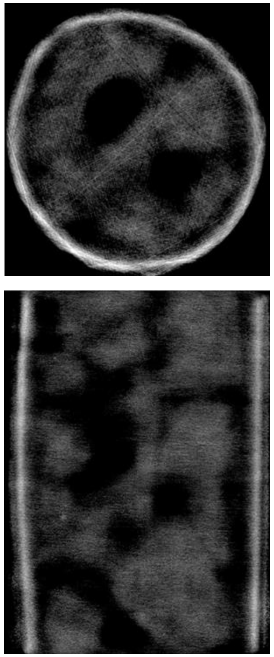


Neutron Tomography from Film Radiographs

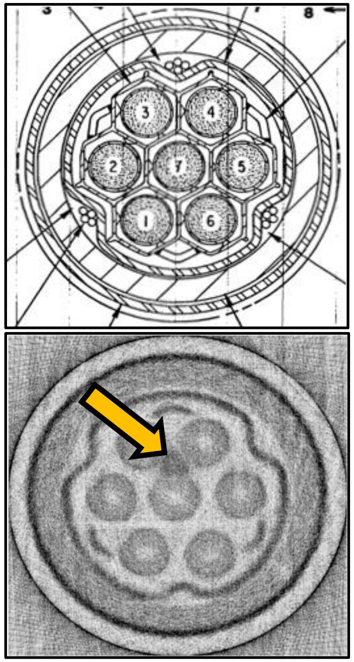
- Requires expensive and time-consuming acquisition of a full set of radiographs
  - Costly, but provides extremely valuable data



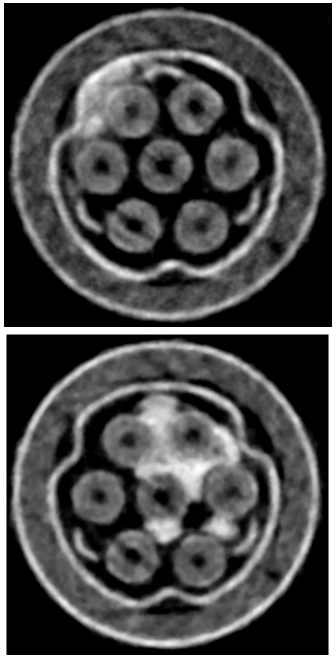




Jennsen et al., 2013, Prog. Nuc. En.



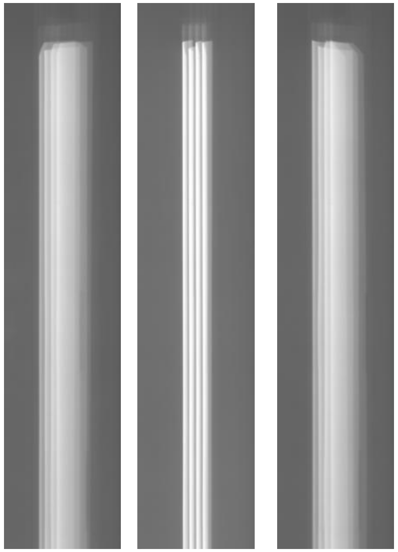
L07 Test, INL/EXT-13-30741-01



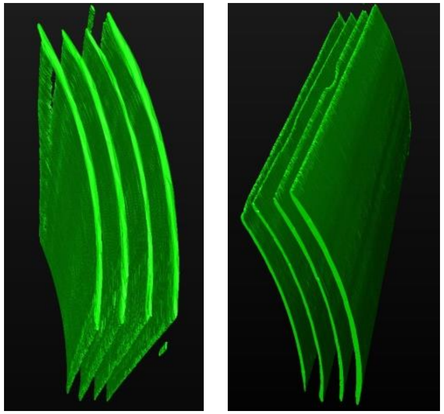
Abir, et al, Journal of Rad. & Nuc. Chem. (2016)

Development of Computed Tomography

- Computed tomography was performed to determine coolant channel gap widths of the AFIP-7 element
- Limited angle tomograph:
  - 42 projections at 1.25º increments,
  - Total of 252 radiographs (*very costly and time-consuming*)
- Illustrates the need for digital systems before CT can be used routinely
- Performing neutron computed tomography without a digital neutron imaging system is like "*having your cart before your horse;*" it may work but it's not recommended



Radiographs of AFIP-7 fuel assembly at three different angles.



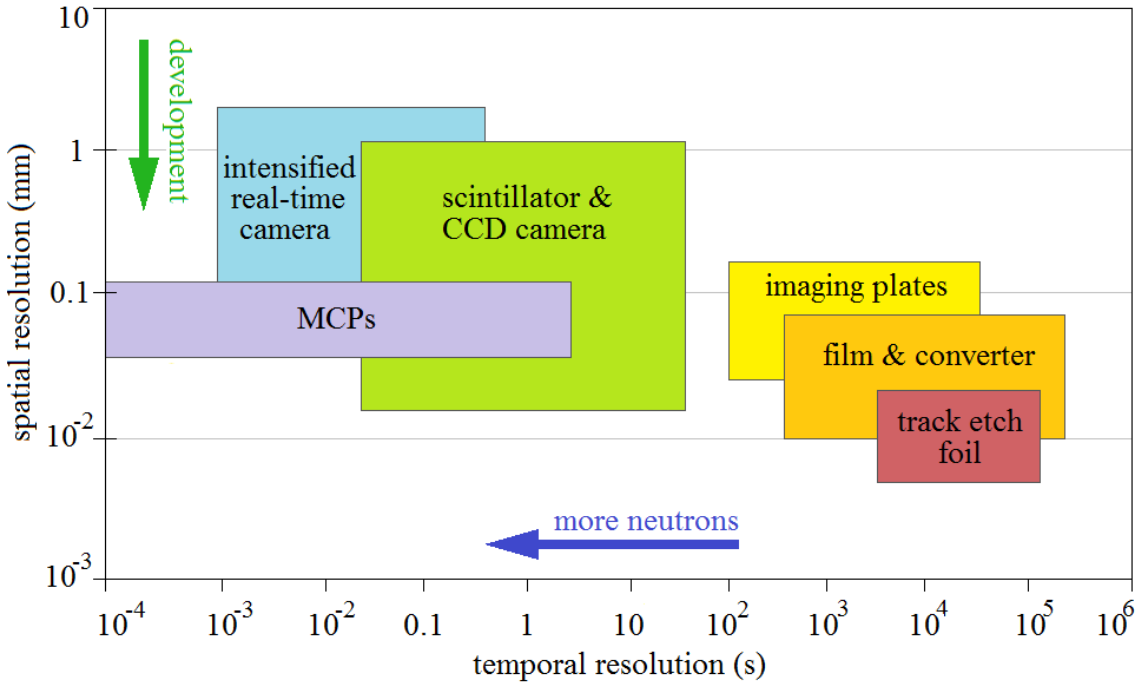
3D reconstruction of a 36 cm axial segment of 4 fuel plates inside aluminum cladding.

Neutron Imaging Goals

Make neutron tomography a *routine* PIE capability

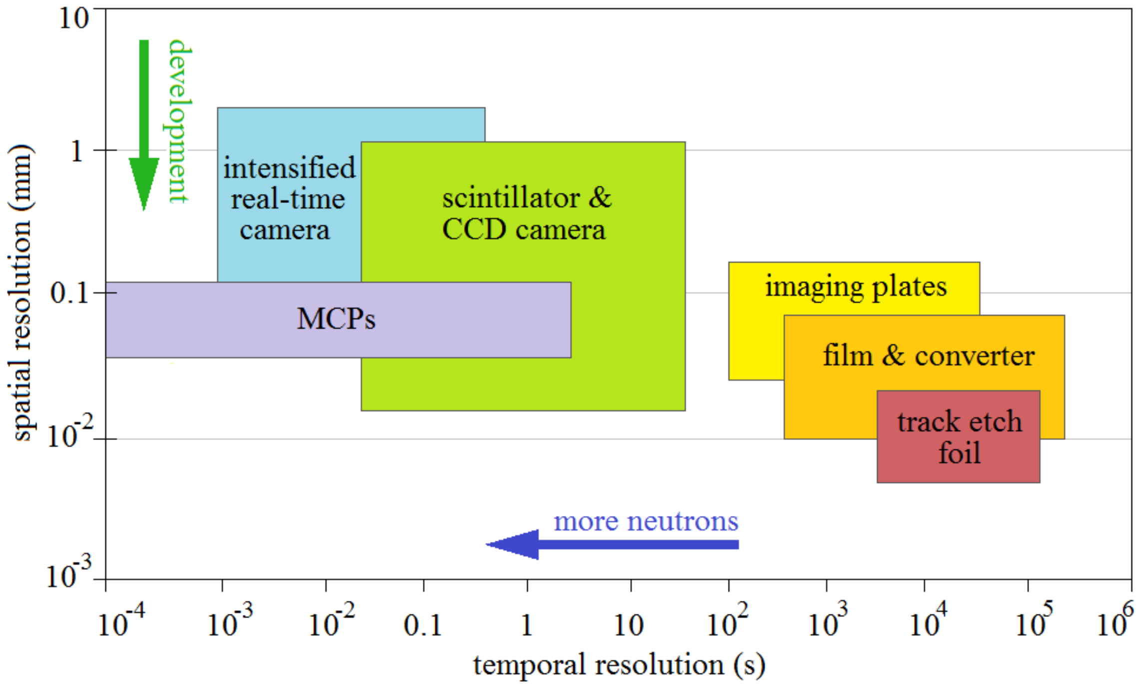
Need for CT	TODAY	FUTURE
rotation stage	single-use stage	universal stage
image acquisition	transfer technique	**digital**
image registration	semi-automatic	automatic
CT reconstruction	subcontract & postdoc	semi-automated
"*Will it work for my experiment?*"	"*Not sure. Maybe?*"	"*We can find out.*"

Radiography of Radioactive Specimens



- Some neutron radiography systems are <u>*not*</u> gamma sensitive
  - ☒ Direct method
  - ☑ Indirect (transfer) method ←Been doing for ~45 years
  - ☒ Scintillation screens and CCD camera
  - ☒ Multi-Channel Plate (MCP) detectors

Radiography of Radioactive Specimens



- Some neutron radiography systems are *not* gamma sensitive
  - ☒ Direct method
  - ☑ Indirect (transfer) method
  - ? Scintillation screens and CCD camera
  - ? Multi-Channel Plate (MCP) detectors

←Exploring other options

Developing a Scintillator-CCD System

- Digital capabilities in the North Radiography Station (NRS) will enable evaluation of non-rad objects developed at INL.
  - Fuel cells, batteries, homeland security, petroleum industry, material fabrication processes, hydridization of zircaloy, etc.
  - Could provide digital neutron imaging of dynamic processes.
- Purchased a system with a 10 cm × 10 cm FOV and a nice camera.
- Other activities showed high radiation background in the NRS, so we wanted to test a less-expensive system first to get some experience.

Andor iXon Ultra 888; Andor Technology Ltd.

ZWO 178 MM Cool

When Trying Something New, Talk to an Expert

Collaborations at INL

- Invited Burkhard Schillinger to visit INL.
- Prior to his arrival:
  - Ordered various equipment prior to activities.
    - Cameras, lenses and adapters, scintillator screens, cables, shielding materials, light-tight enclosure materials, stepper motors, et al.
    - We did not want to be limited by materials.
  - Built and prepared a few things ahead of time.
    - Avoid wasting time. Plan ahead as best possible.
  - Selected some important system variables.
    - Desired field of view (FOV).
    - Location of installation.
    - Prepare colleagues and required resources.
- Then it's time to get to work. (*i.e. Burkhard arrives*)

You have only three working days to build your system. Get started!

Overview of Tasks

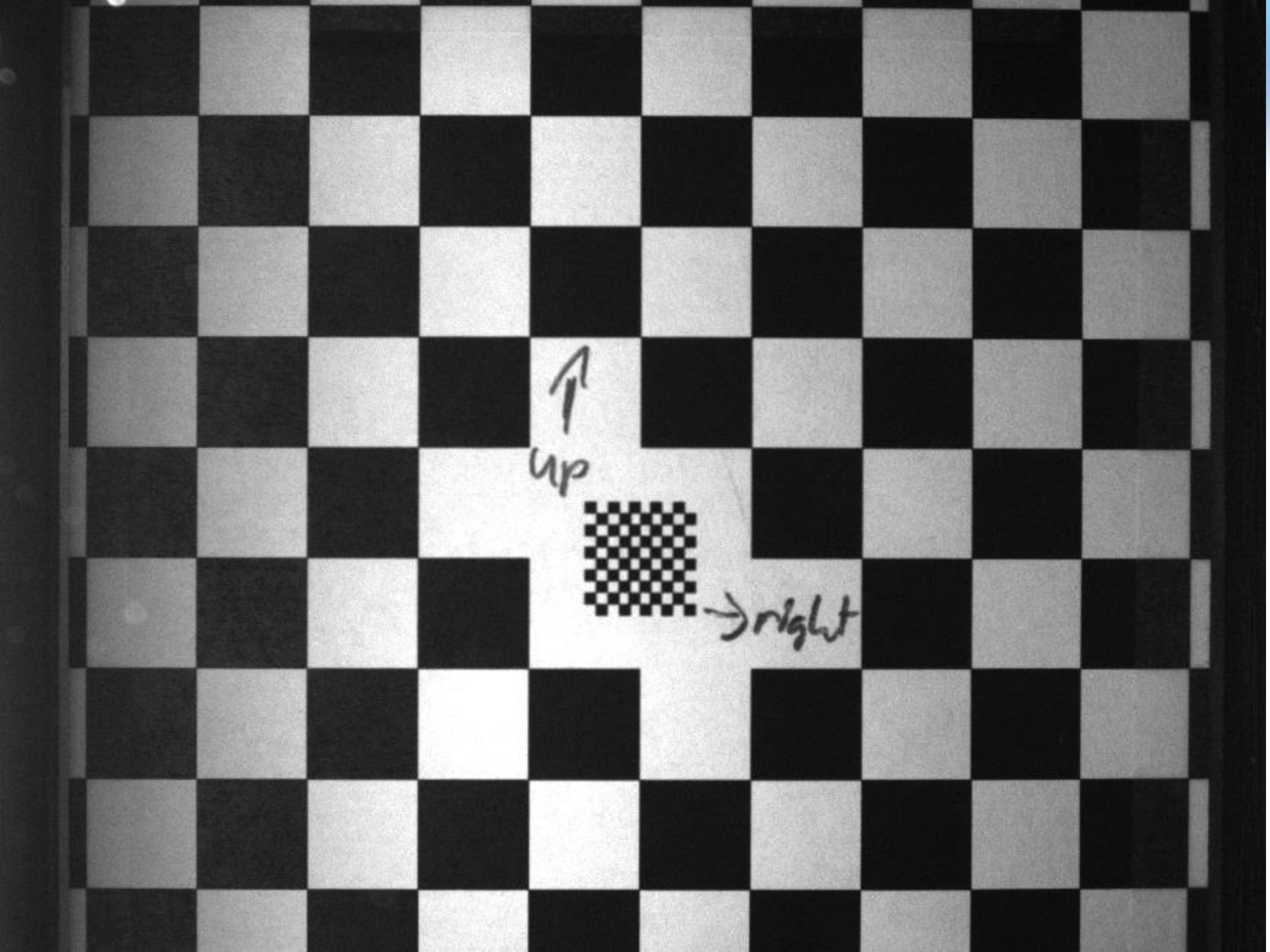
- Day 1:
  - Evaluate available materials. (Get any additional materials you need)
  - Take measurements with various camera and lens combinations.
  - Build and test a control system for integrating the motors and camera.
  - Choose a system configuration that works.
- Day 2:
  - Assemble the system and prepare for installation in the beam.
  - Troubleshooting.
- Day 3:
  - Install and test the system.
  - Troubleshooting.

- Success: Produce a digital neutron radiograph with a camera-based system for the first time.

Test Combinations of Cameras and Lenses

- Measured distance from the CCD chip (*not the lens*) to image plane for each combination.
  - Provides a coarse focus; fine tuning comes later.
  - This knowledge saves time later when designing a system or making adjustments.
- A lens has a range of object-detector distances (ODD) in which it can focus.
  - If the distance is less than this, the lens must move away from the CCD to focus.
  - Spacers (i.e. shims) can be placed between the camera and lens to provide the needed separation distance.
- Chosen system:
  - ZWO 178 MM Cool (~$700) 3096×2080 pixels, 2.4 µm pixels, 14-bit ADC
  - 25 mm lens
  - ODD ~762 mm
  - 1.0 mm spacer between camera and lens

Camera	Lens	Focus Distance (mm)
ATIK 414 EX	35 mm	825
	25 mm	626
	16 mm	375
ZWO 174 MM Cool	50 mm	940
	35 mm	692
	25 mm	495
ZWO 178 MM Cool	**25 mm**	**762**
	16 mm	445

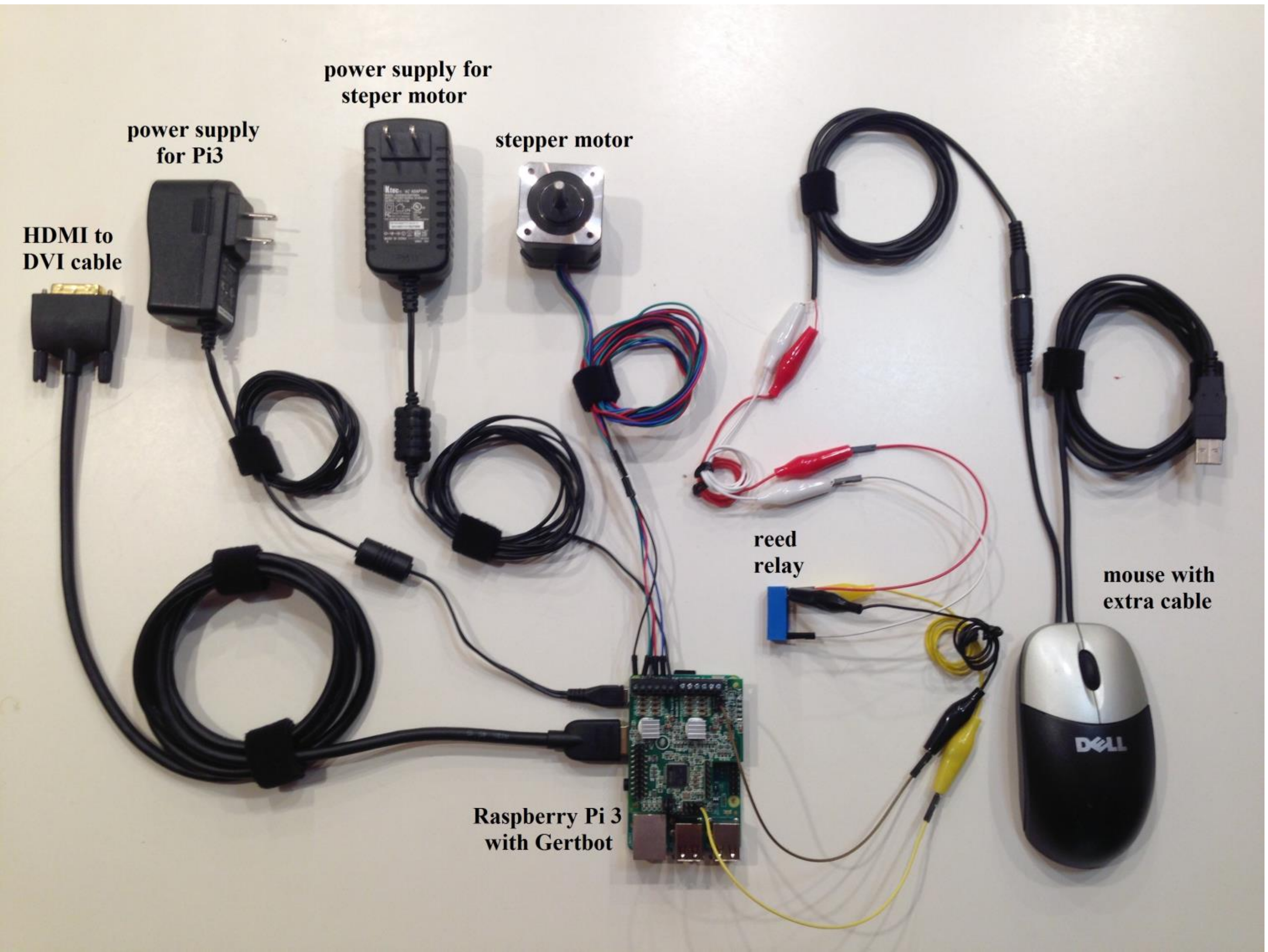

up
right

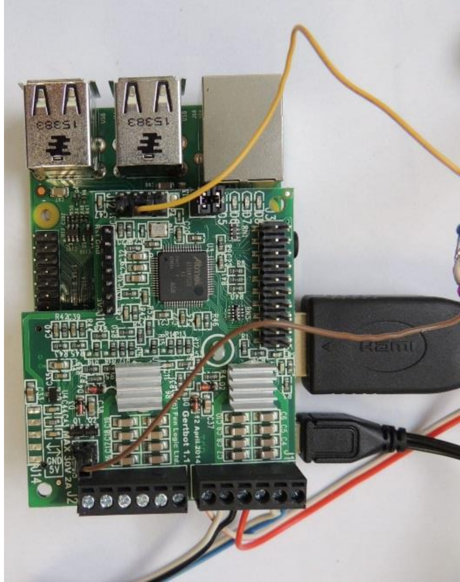
Overview of Tasks

- Day 1:
  - Evaluate available materials. (Get any additional materials you need)
  - Take some basic measurements with cameras and lenses.
  - Build and test a control system for integrating the motors and camera.
    - Need a way to simultaneously control the rotation stage and image acquisition.
  - Choose a system configuration that works.
- Day 2:
  - Assemble the system and prepare for installation in the beam.
  - Troubleshooting.
- Day 3:
  - Install and test the system.
  - Troubleshooting.
  - Produce a digital neutron radiograph with a camera-based system for the first time.

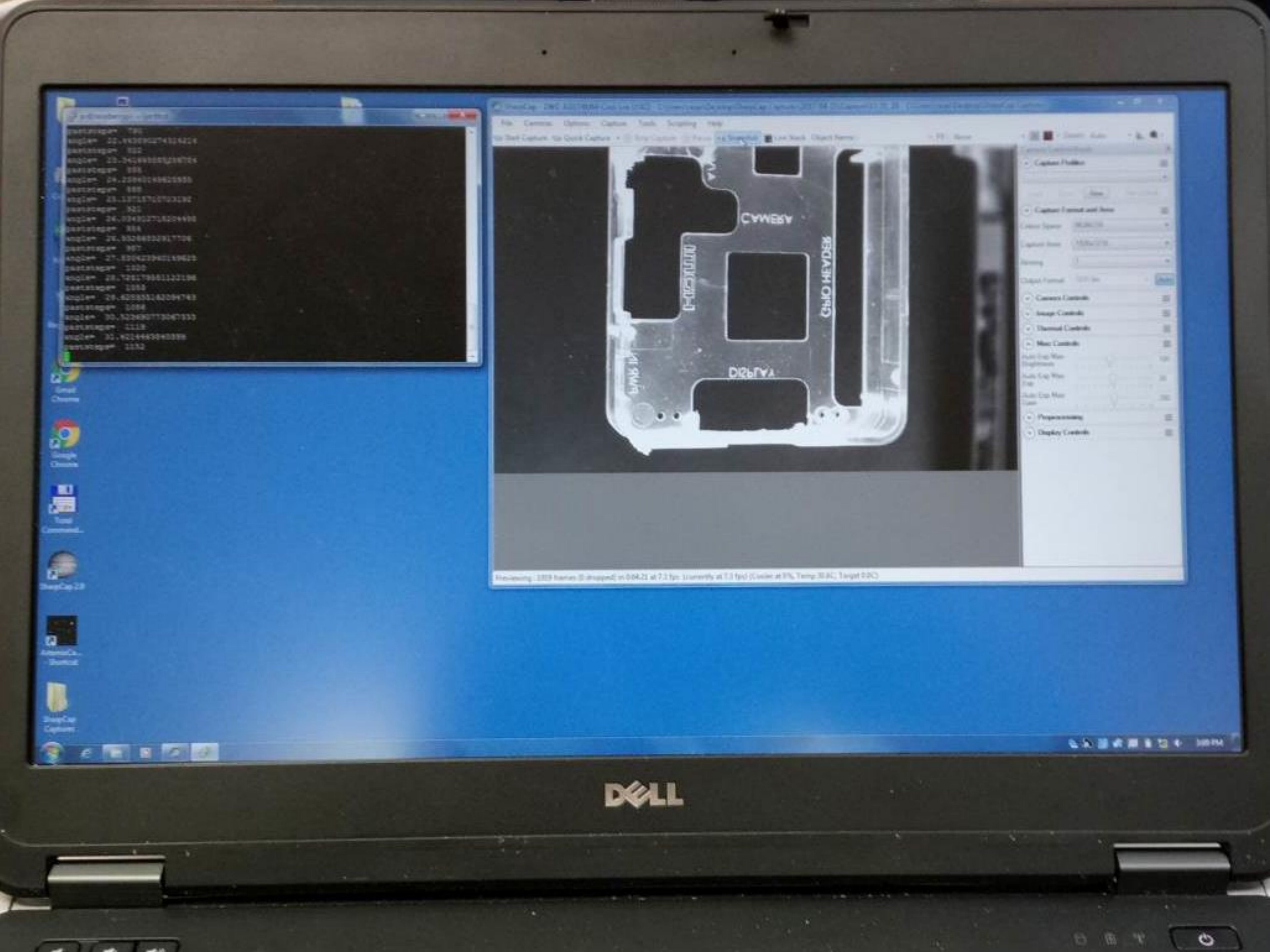
"How to set up the Raspberry Pi and Gertbot as a tomography controller"

Document available on ISNR website





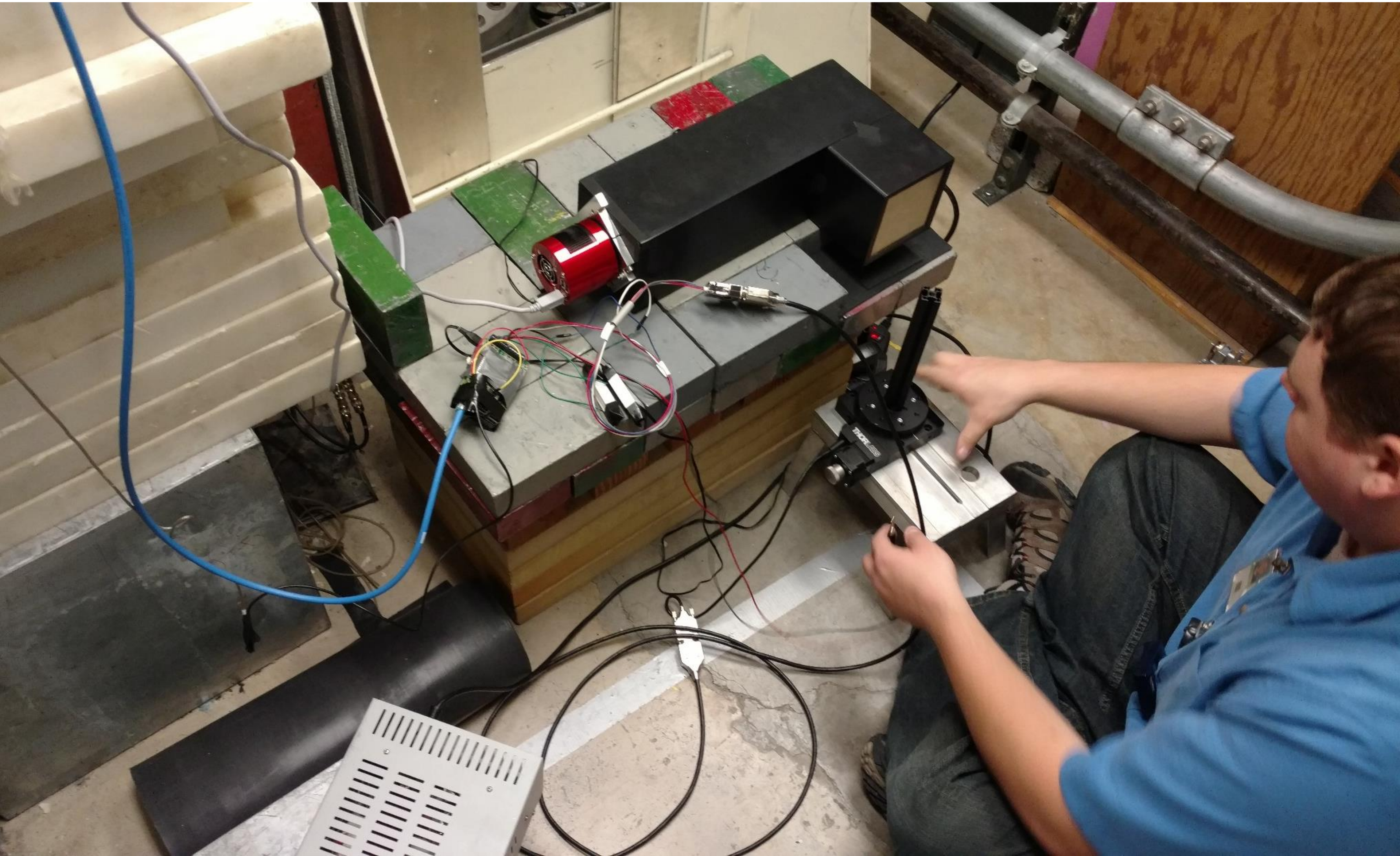

DELL
THORLABS


CAMERA
HDMI
GPIO HEADER
DISPLAY
DELL

A Few System Design Parameters

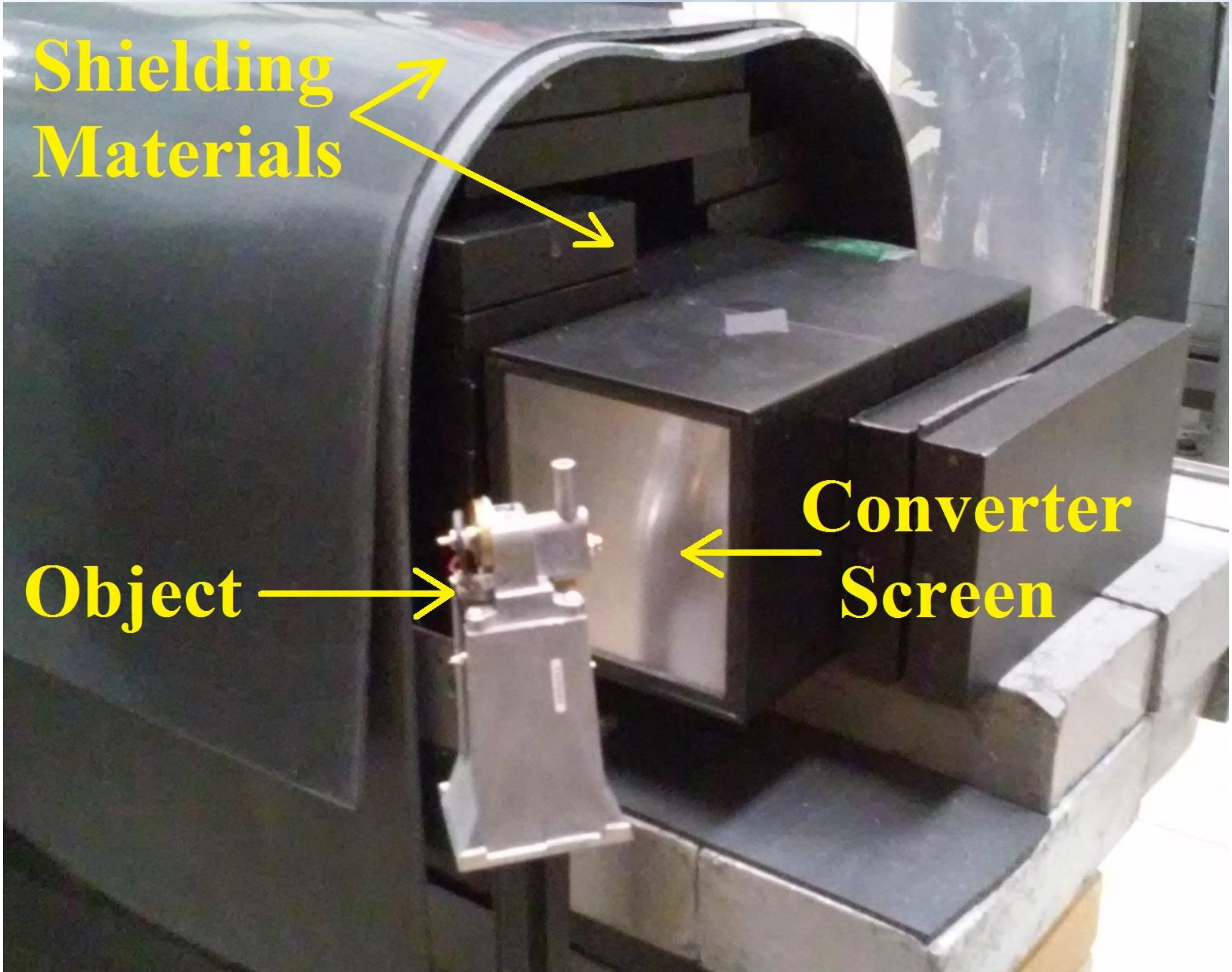
- Camera centered at the center of the beam, 53 cm above the floor
- Reactor at 250 kW, L/D_{eff}=270, $\phi \approx 2.0 \times 10^6$ $n/cm^2 s$
- Used an inexpensive *ZWO 178MM Cool* with *Sharp Cap 2.9* free software
- Radiation shielding for the camera and electronics
  - Lead bricks around the camera, at least 5 cm thick, preferably more
  - Borated poly (B_4C/silicone and B_4C/polyethylene)
  - Lithiated polyethylene purchased but not used because of fast neutron generation.
  - A particle transport model would be very beneficial for designing shielding

Testing Connections and Focusing Camera

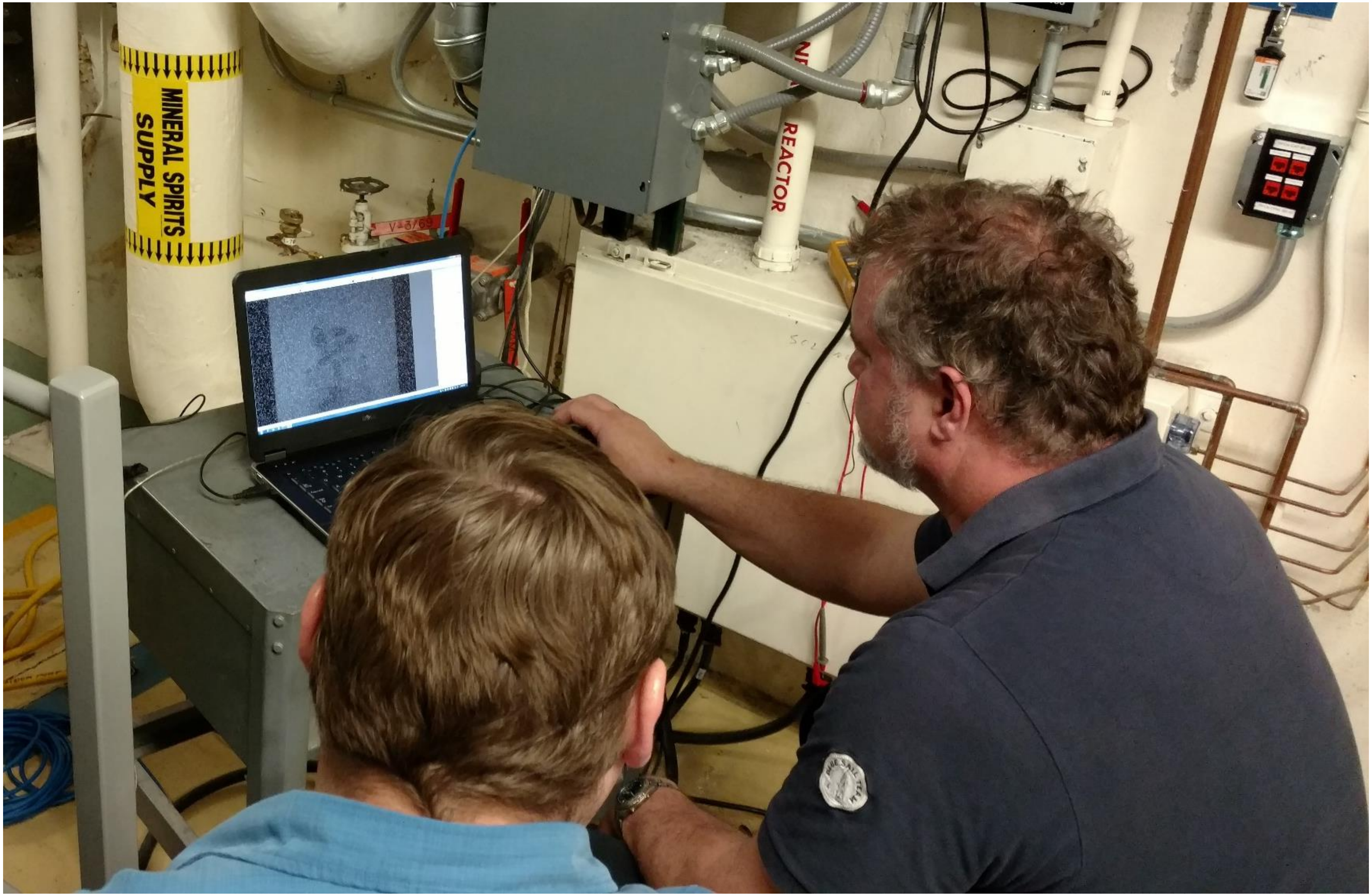


Shielding the power supply for the rotation motor

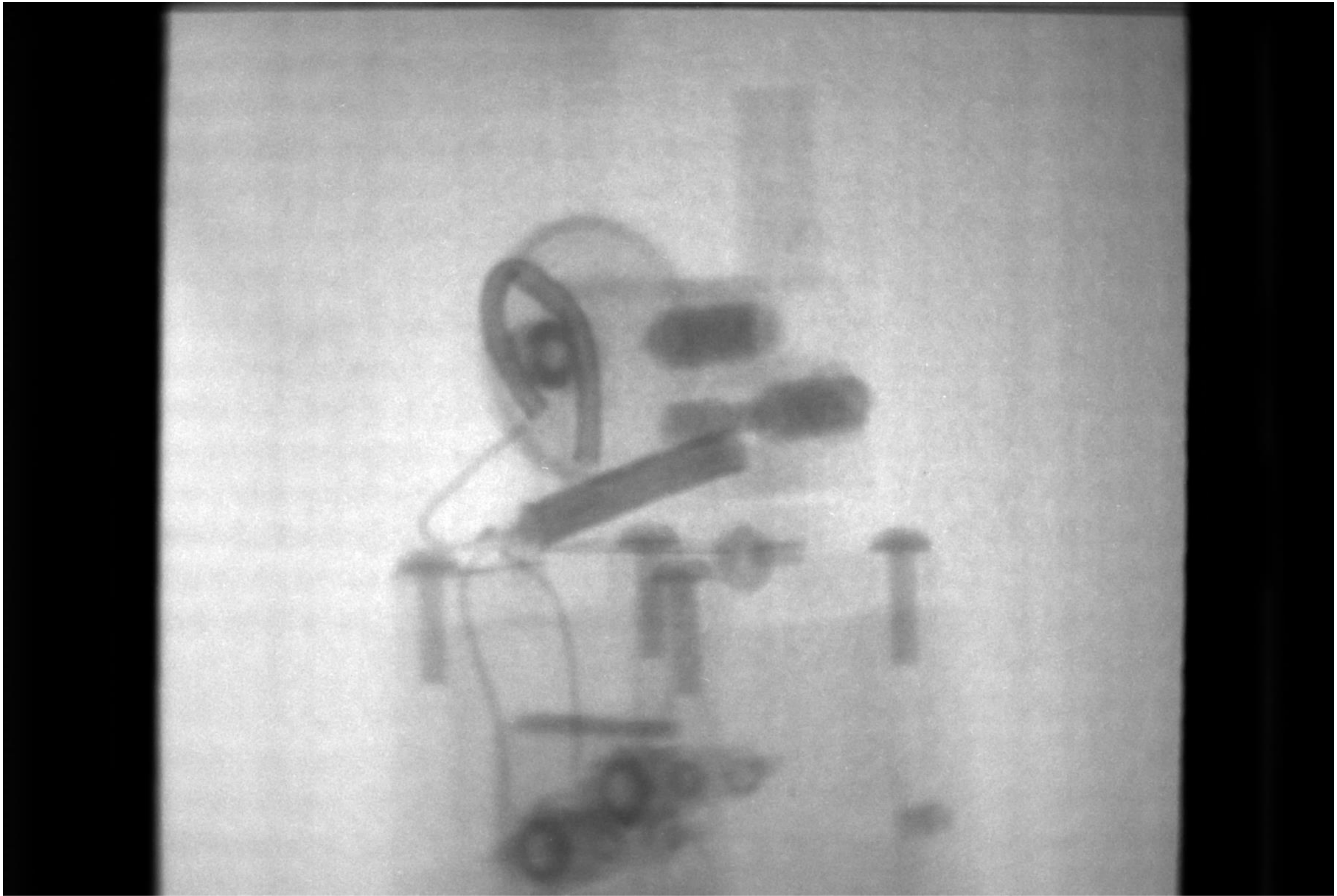
Stacking the shielding


Shielding
Materials
Object
Converter
Screen

First Light

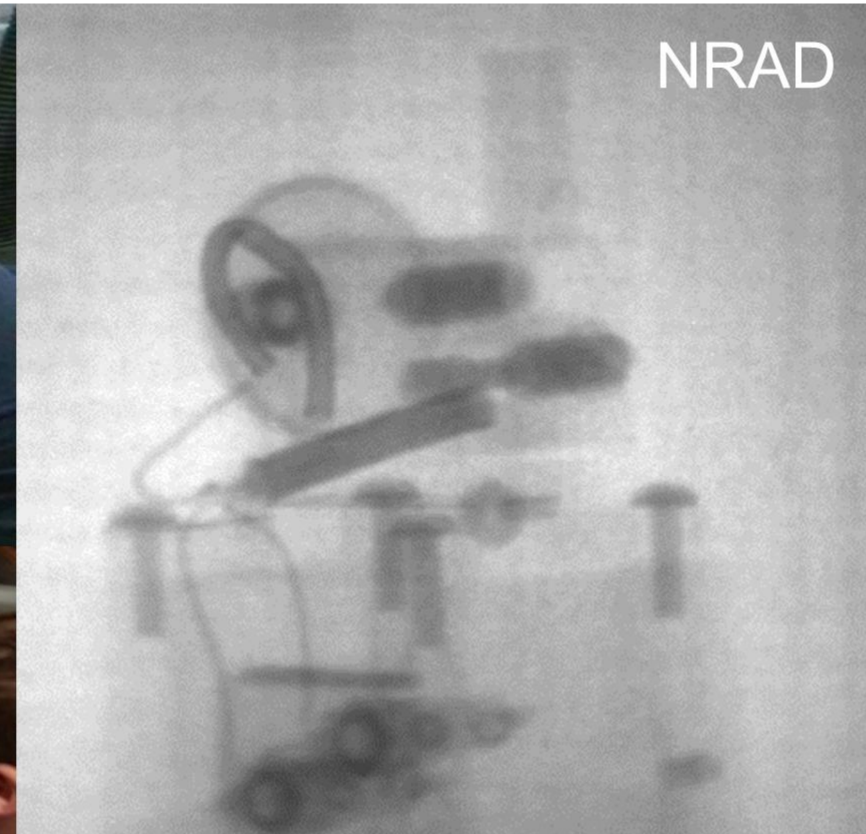


First Light



Celebrating Success

Got the system up and running with help from a colleague and learned many lessons

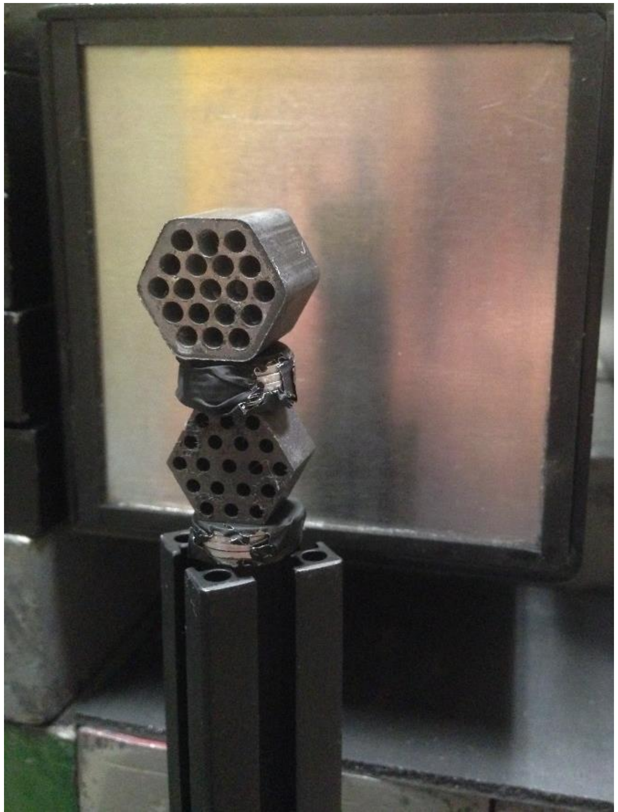


Digital improvements

INL researchers and a visiting German colleague produced the first digital neutron radiographs using a modern camera-based neutron imaging system at NRAD.

Running Solo Shortly After the Visit

- A second test using this system examined a surrogate prismatic fuel element with engineered flaws inside coolant channels.
- The sample rotation stage was mounted to a linear stage so it could be remotely positioned so a light image could be acquired.
- Widened the gap for somewhat improved ventilation.




THORLABS
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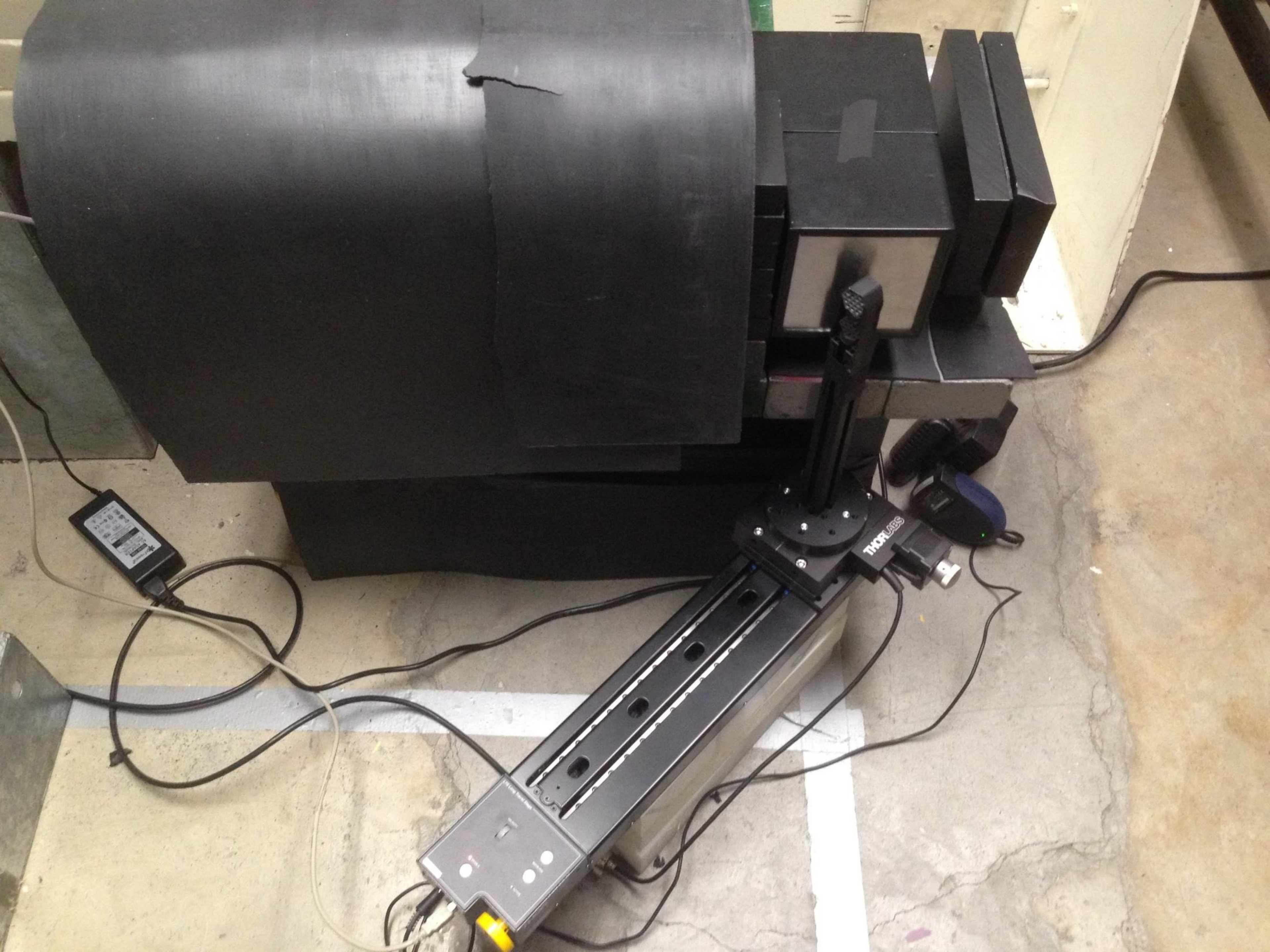
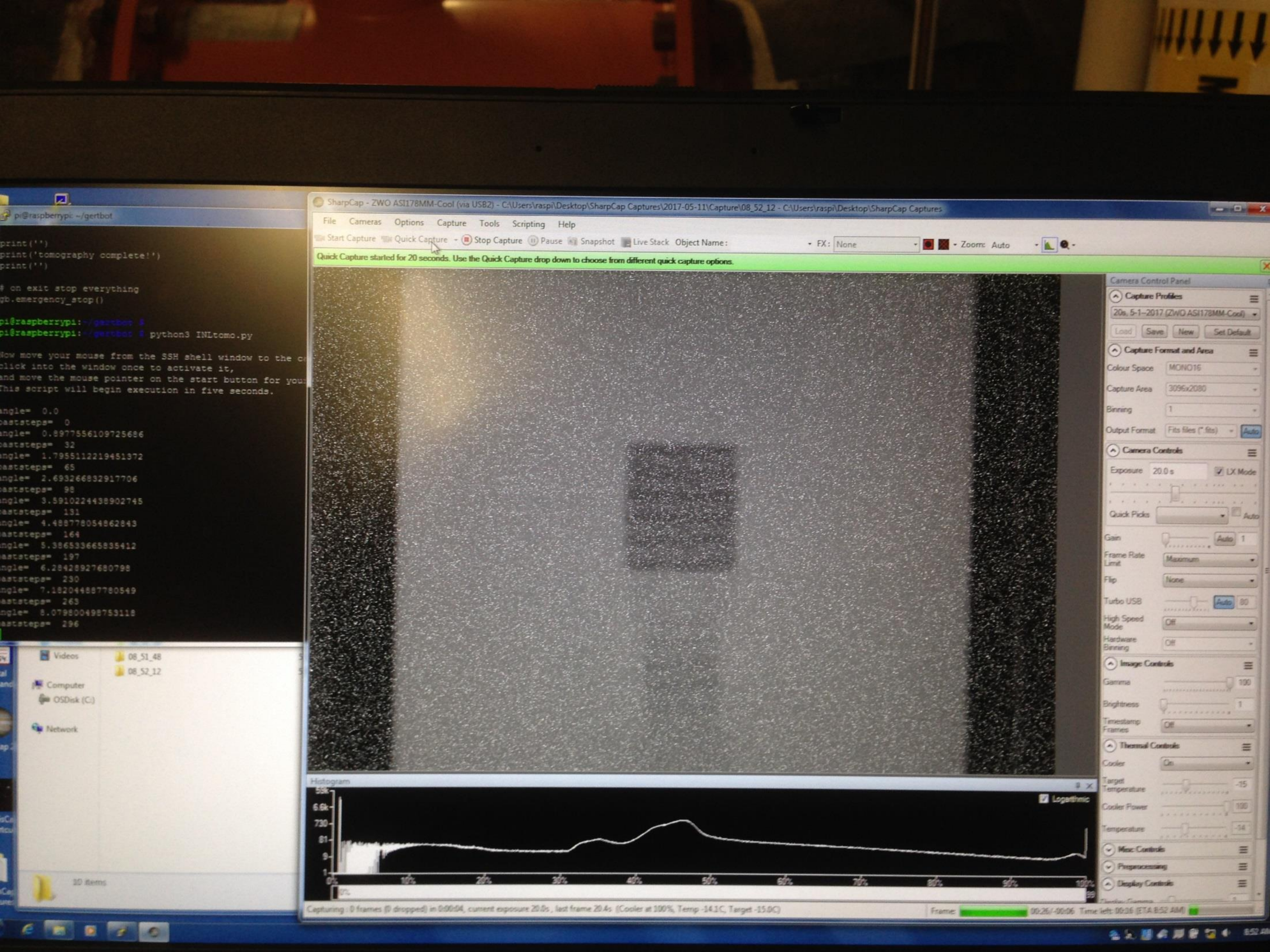
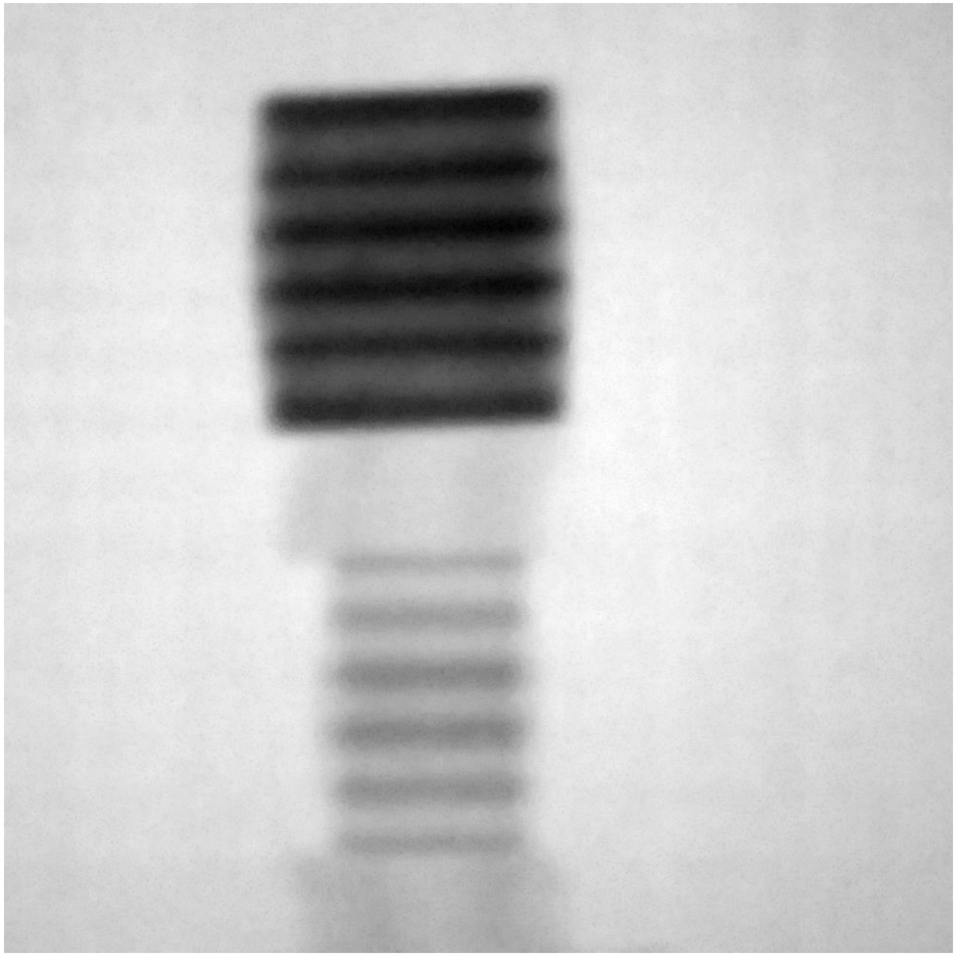
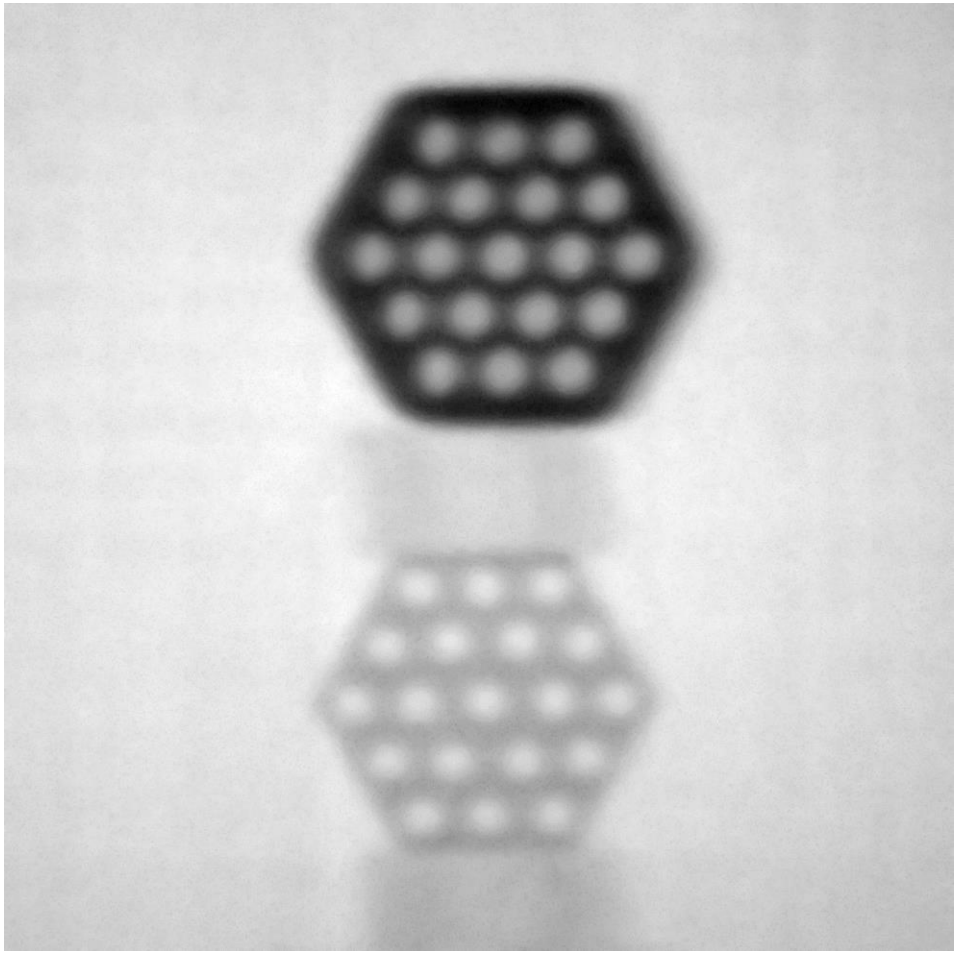

THORLABS


pi@raspberrypi: ~/gertbot
print('')
print('tomography complete!')
print('')
# on exit stop everything
gb.emergency_stop()
python3 INLtomo.py
Now move your mouse from the SSH shell window to the
click into the window once to activate it,
and move the mouse pointer on the start button for your
This script will begin execution in five seconds.
angle= 0.0
paststeps= 0
angle= 0.8977556109725686
paststeps= 32
angle= 1.7955112219451372
paststeps= 65
angle= 2.693266832917706
paststeps= 98
angle= 3.5910224438902745
paststeps= 131
angle= 4.488778054862843
paststeps= 164
angle= 5.386533665835412
paststeps= 197
angle= 6.28428927680798
paststeps= 230
angle= 7.182044887780549
paststeps= 263
angle= 8.079800498753118
paststeps= 296
SharpCap - ZWO ASI178MM-Cool (via USB2) - C:\Users\raspi\Desktop\SharpCap Captures\2017-05-11\Capture\08_52_12 - C:\Users\raspi\Desktop\SharpCap Captures
File Cameras Options Capture Tools Scripting Help
Start Capture Quick Capture Stop Capture Pause Snapshot Live Stack Object Name: FX: None Zoom: Auto
Quick Capture started for 20 seconds. Use the Quick Capture drop down to choose from different quick capture options.
Camera Control Panel
Capture Profiles
Load Save New Set Default
Capture Format and Area
Colour Space MONO16
Capture Area 3096x2080
Binning 1
Output Format Fits files (*.fits)
Camera Controls
Exposure 20.0 s
LX Mode
Quick Picks
Gain
Frame Rate Limit Maximum
Flip None
Turbo USB
High Speed Mode Off
Hardware Binning Off
Image Controls
Gamma
Brightness
Timestamp Frames Off
Thermal Controls
Cooler On
Target Temperature
Cooler Power
Temperature
Misc Controls
Preprocessing
Display Controls
Histogram
Logarithmic
0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Videos
08_51_48
08_52_12
Computer
OSDisk (C:)
Network
10 items
Capturing : 0 frames (0 dropped) in 0:00:04, current exposure 20.0s, last frame 20.4s (Cooler at 100%, Temp -14.1C, Target -15.0C)
Frame:

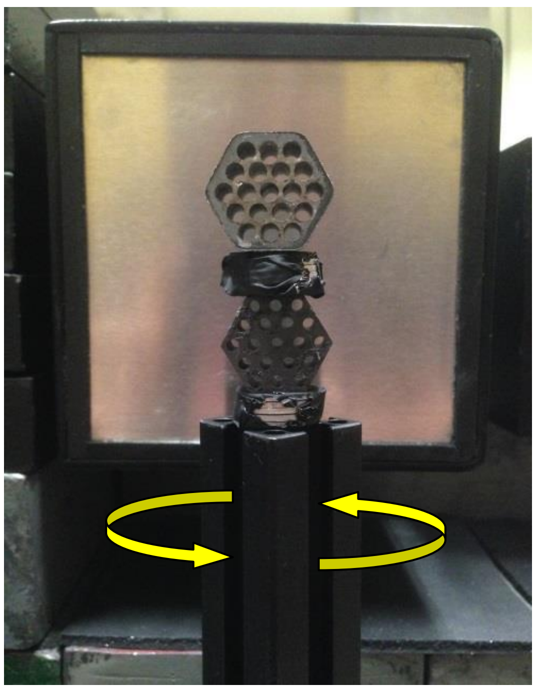
Orthogonal Views



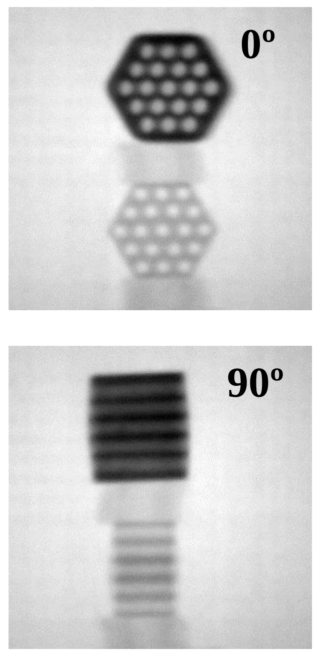


Running Solo Shortly After the Visit

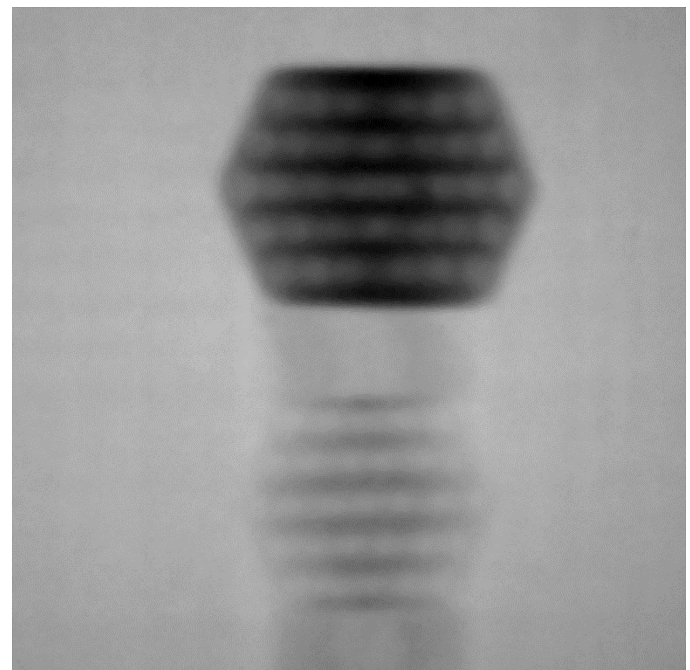
- The system was able to acquire 32 neutron radiographs in under 12 minutes.
  - Current production is limited to ~14 film radiographs per day.
- Radiographs acquired with specimen rotated at 10º increments.
  - An upset in the USB hub stopped acquisition after 32 radiographs.
- No single radiograph clearly shows the feature, but it becomes clear as the object rotates. Tomography should provide additional and higher-quality information.



Close-up view of the object positioned in front of the scintillator screen.



Orthogonal neutron radiographs of the surrogate prismatic fuel element.



Example radiograph at 45º (*link to video*)

Challenges

- Access to the beamline hutch should be made as simple a procedure as possible. Multiple entries are inevitable.
  – Iris needs adjusted or lens refocused.
- Very high background radiation causes upsets in electronics.
  – *Very high gamma and epithermal neutron content.*
  – Need to improve the shielding approach for camera.
  – Perhaps modification of the neutron beamline.
  – Move all nonessential electronics outside the bunker.
- Cooling the camera.
  – Initially -15°C, but could only get to -10°C after an hour due to heat building up in the lead shielding.
  – Need more ventilation through camera shielding or water cooling.
- This valuable experience helped us to be able to operate the system on our own.

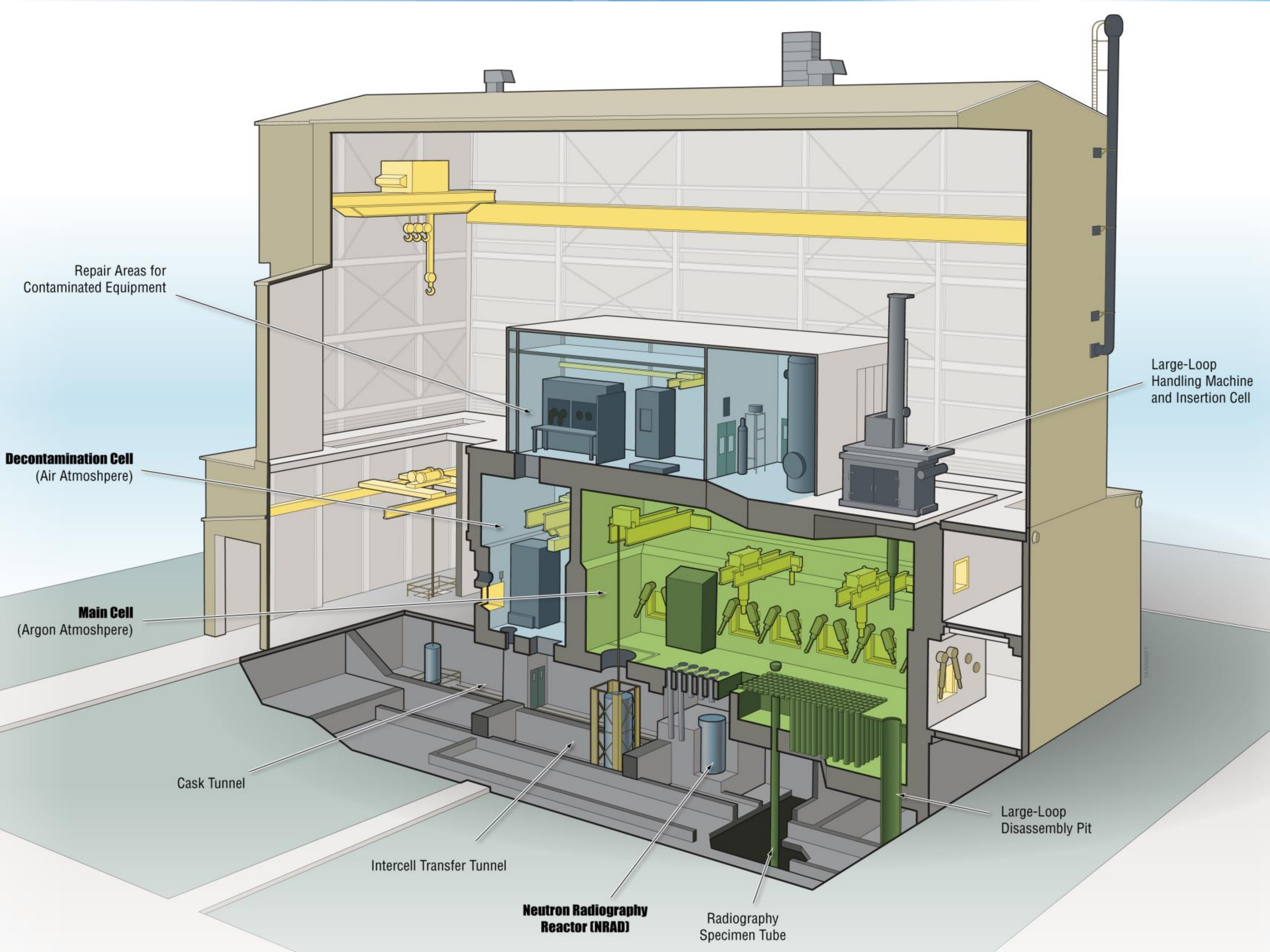
Upcoming Activities

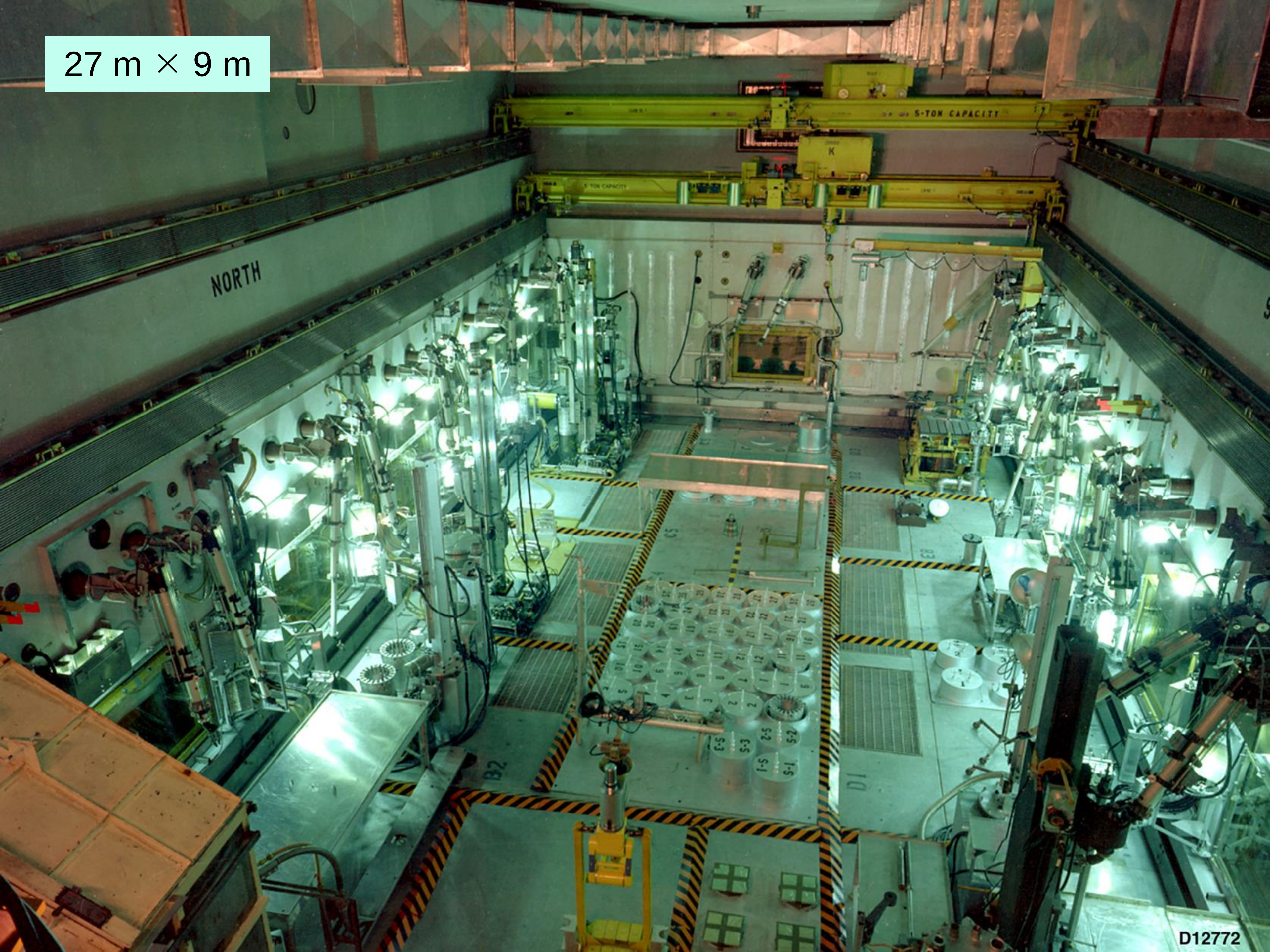
- Building two new systems with FOV's of 20 cm and 10 cm square.
- A double-mirror system should reduce scattered radiation to the camera.
- Camera mounted to a linear stepper motor for remote focusing.
- Radiation transport models under development to assess shielding options.

Supplemental Slides:
More About NRAD

Hot Fuel Examination Facility (HFEF)

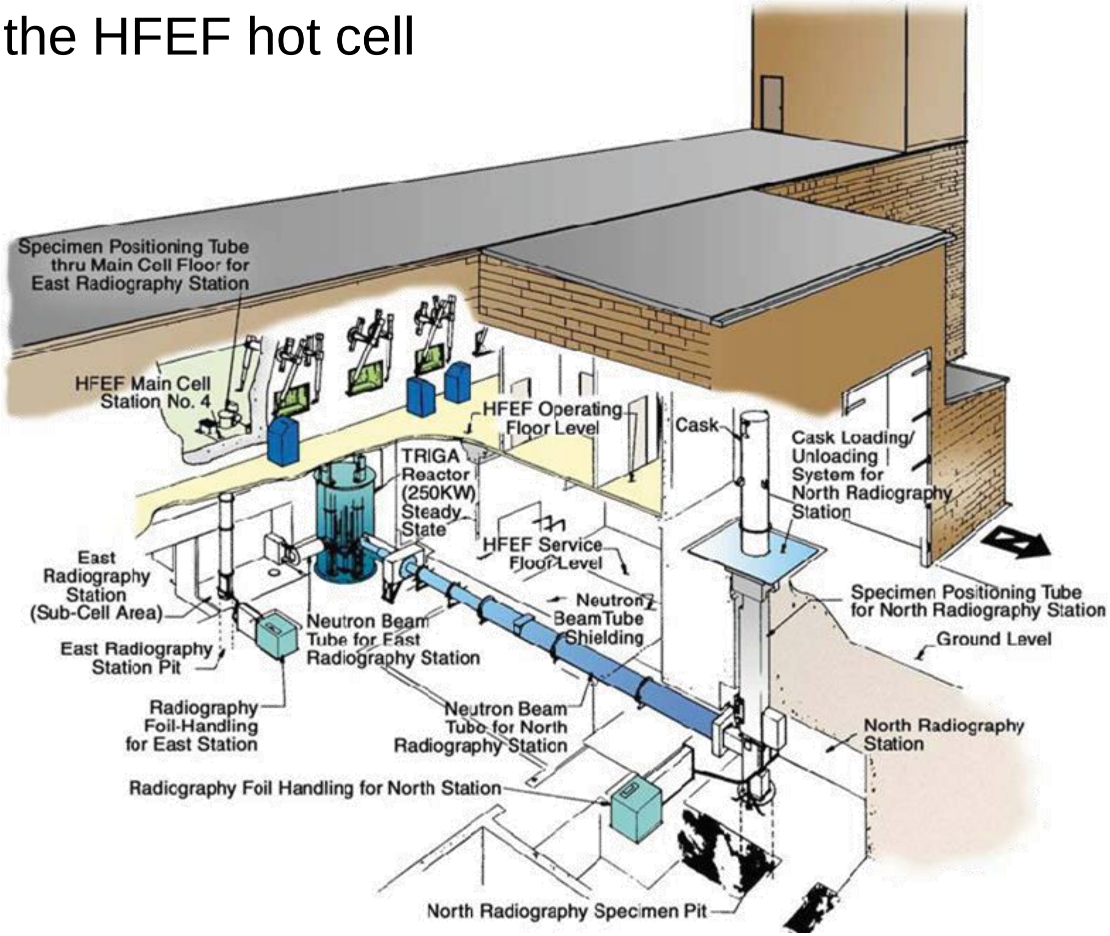
- One of the world's largest inert atmosphere hot cells
- Primarily used for post-irradiation examination (PIE) of irradiated nuclear fuel experiments


Repair Areas for
Contaminated Equipment
Decontamination Cell
(Air Atmoshpere)
Main Cell
(Argon Atmoshpere)
Cask Tunnel
Intercell Transfer Tunnel
**Neutron Radiography
Reactor (NRAD)**
Radiography
Specimen Tube
Large-Loop
Disassembly Pit
Large-Loop
Handling Machine
and Insertion Cell

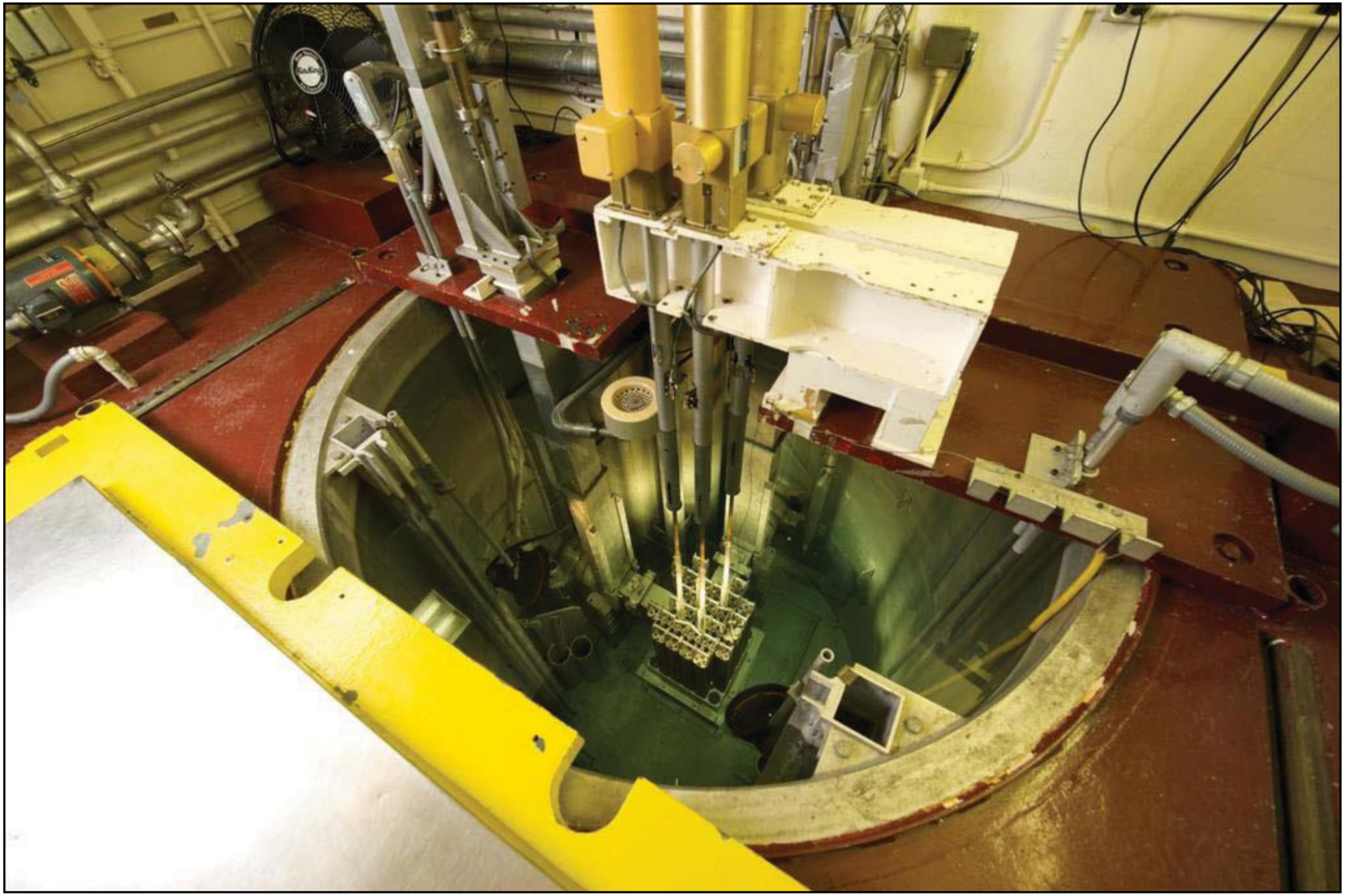

27 m × 9 m
NORTH
5-TON CAPACITY
D12772

NRAD Reactor

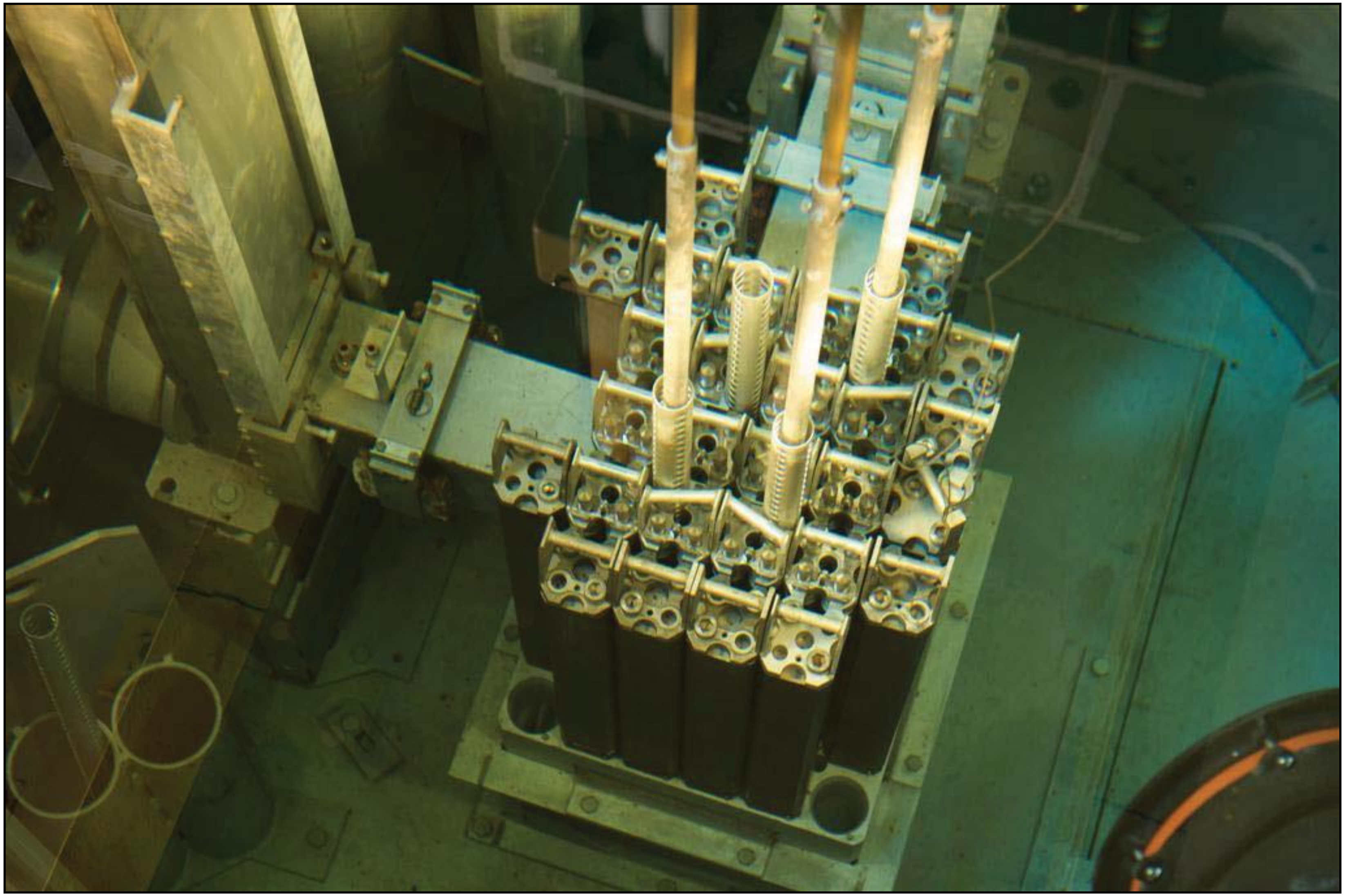
- Designed specifically for neutron radiography for PIE of fuel
- The NRAD reactor beneath the HFEF hot cell
  - 250 kW TRIGA
  - Two neutron beams
- Access to specimens in the hot cell
- A *unique* and *valuable* facility

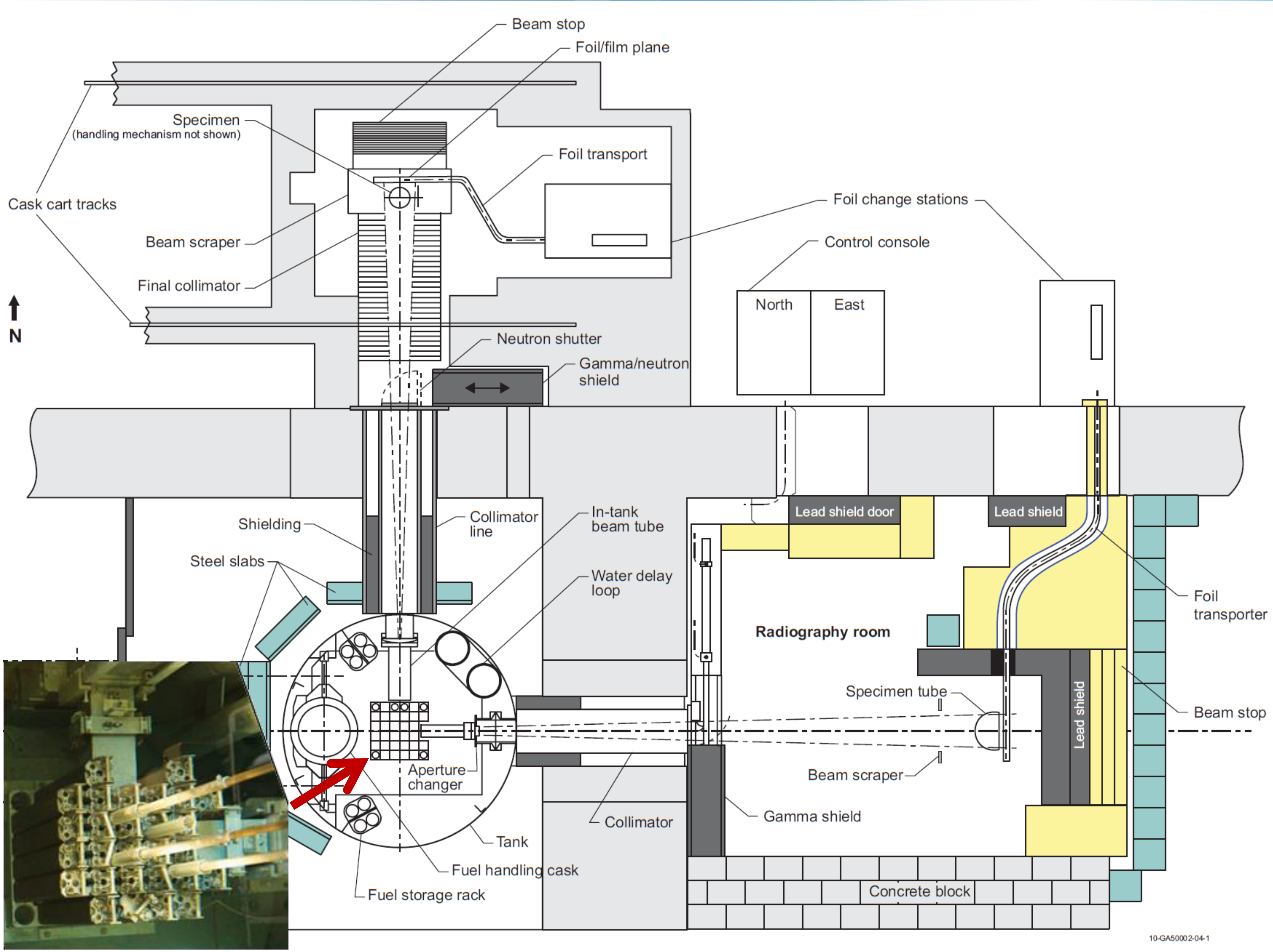


NRAD Reactor



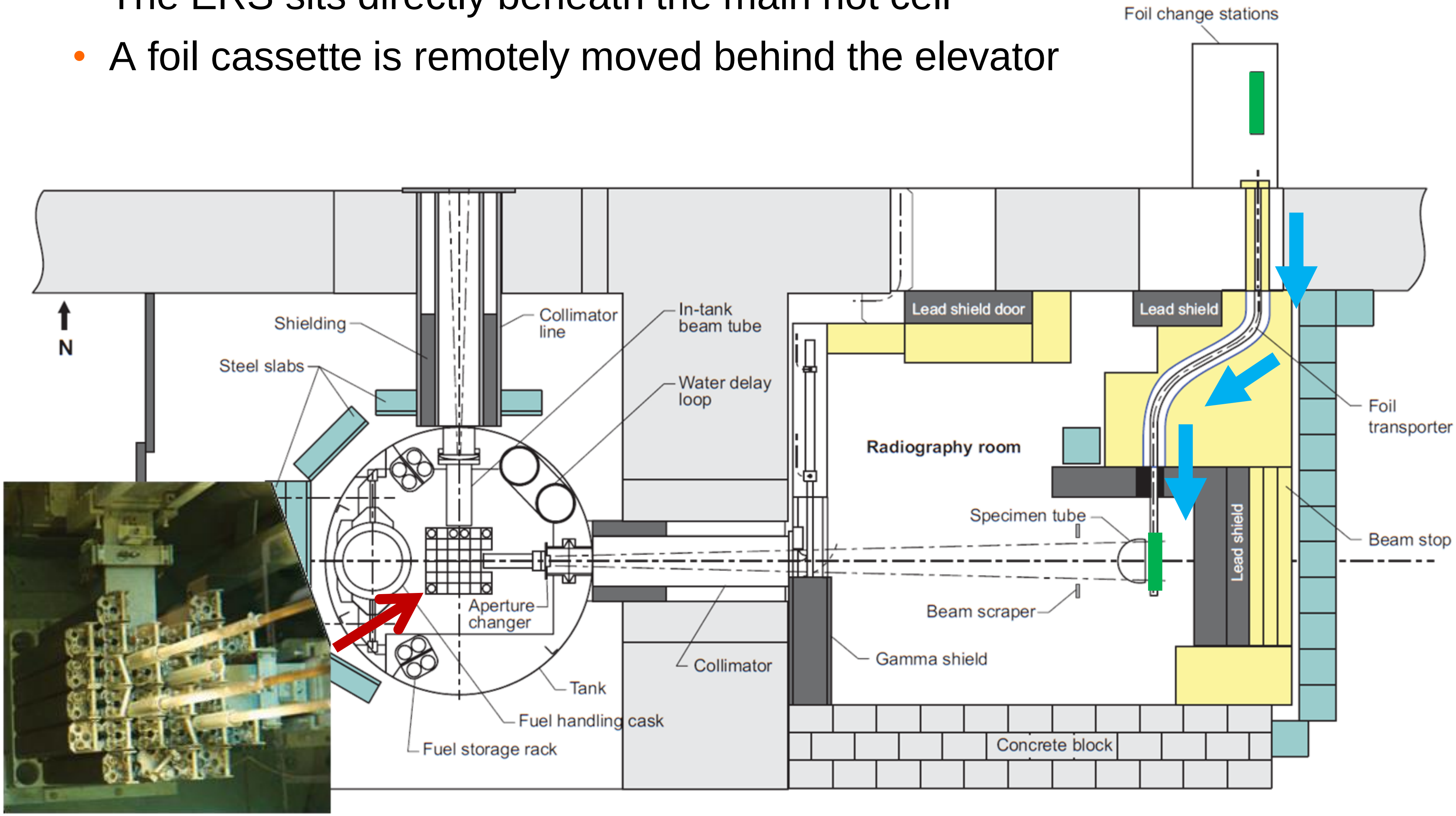
NRAD Reactor Core




Beam stop
Foil/film plane
Specimen
(handling mechanism not shown)
Foil transport
Foil change stations
Cask cart tracks
Control console
Beam scraper
Final collimator
North
East
N
Neutron shutter
Gamma/neutron shield
Lead shield door
Lead shield
Shielding
Collimator line
In-tank beam tube
Steel slabs
Water delay loop
Foil transporter
Radiography room
Specimen tube
Lead shield
Beam stop
Aperture changer
Beam scraper
Gamma shield
Collimator
Tank
Fuel handling cask
Fuel storage rack
Concrete block
10-GA50002-04-1

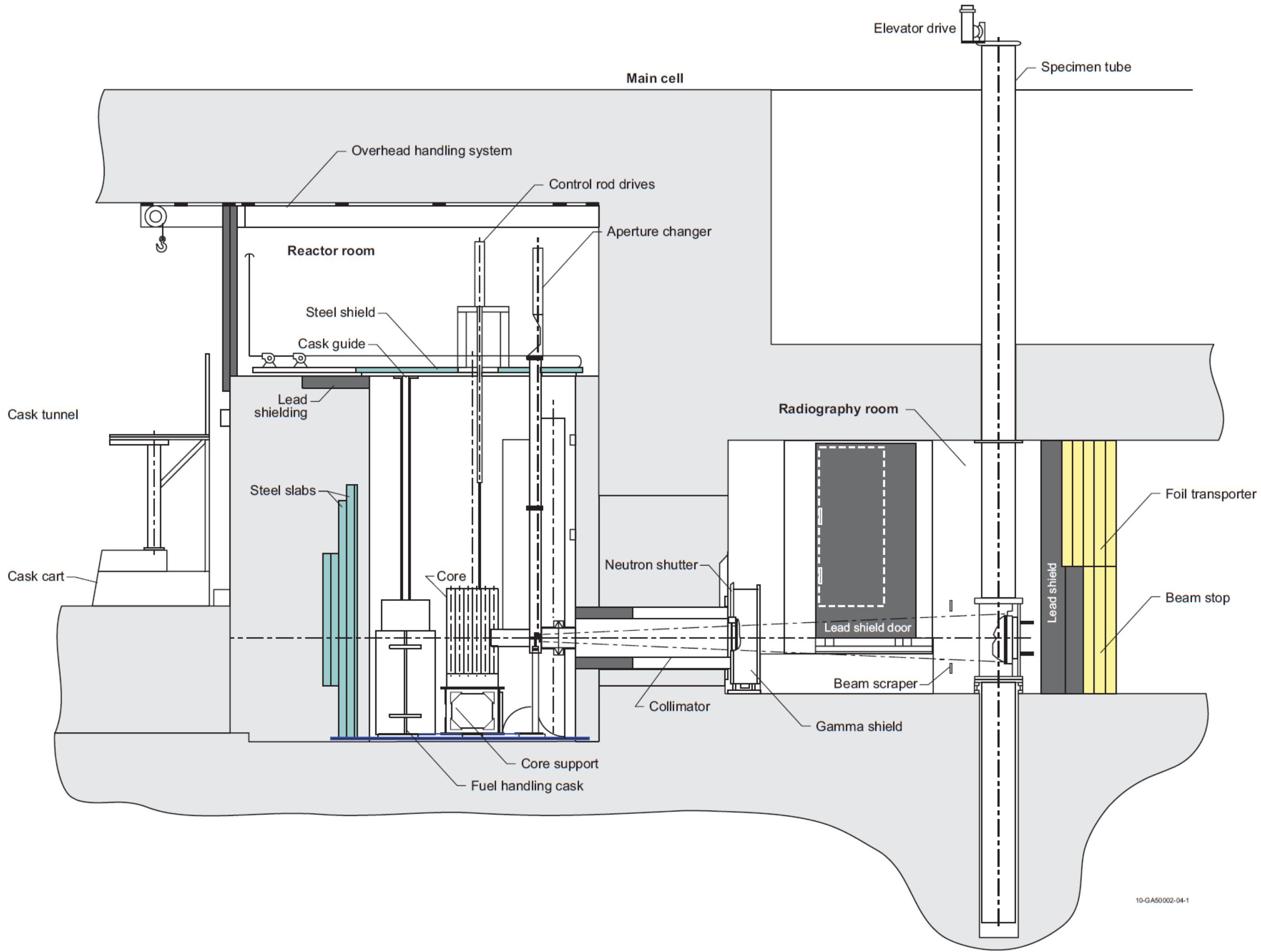
East Radiography Station (ERS)

- The ERS sits directly beneath the main hot cell
- A foil cassette is remotely moved behind the elevator



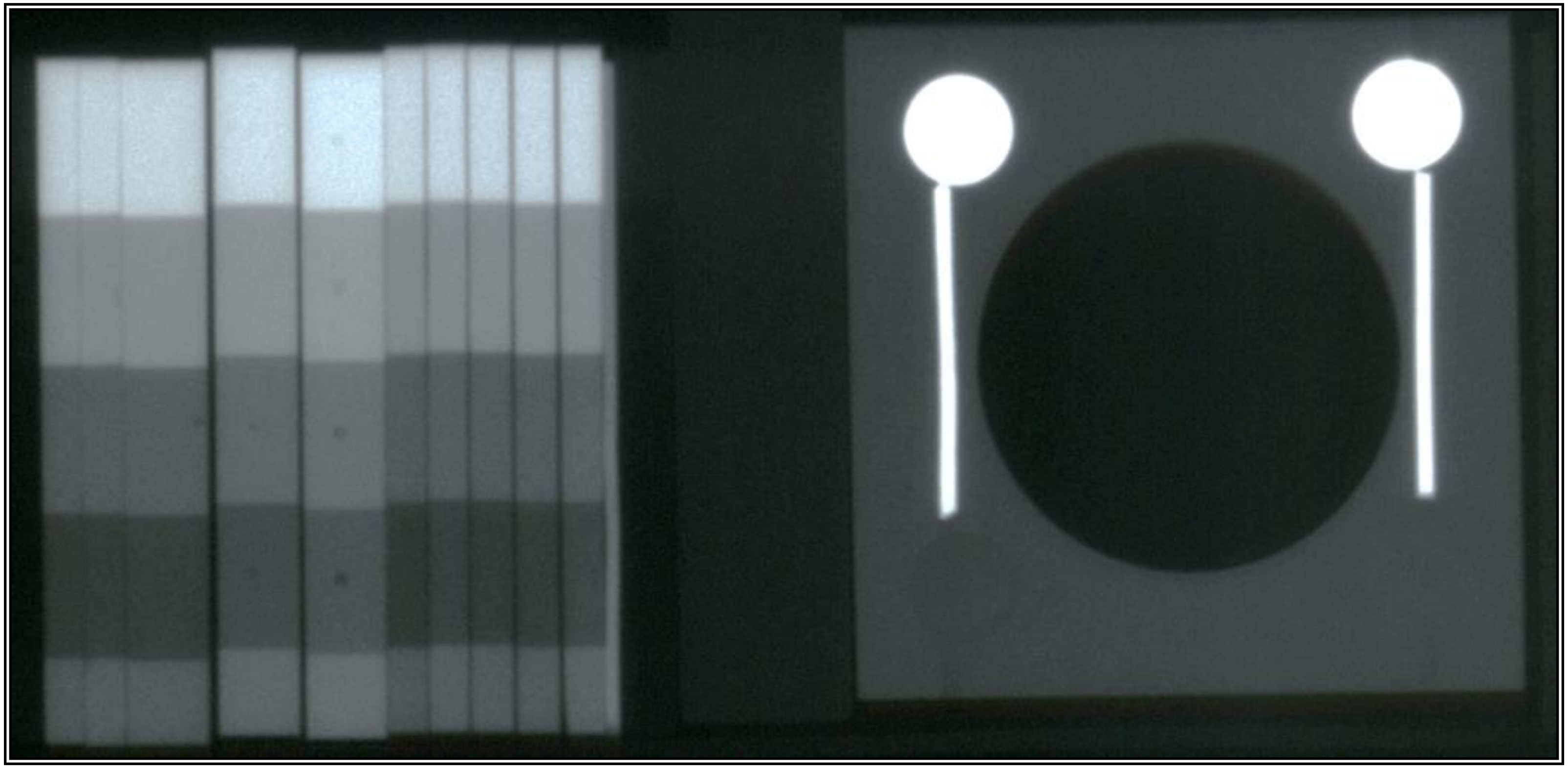
East Radiography Station (ERS)

- Elevator positions specimens into the ERS cell

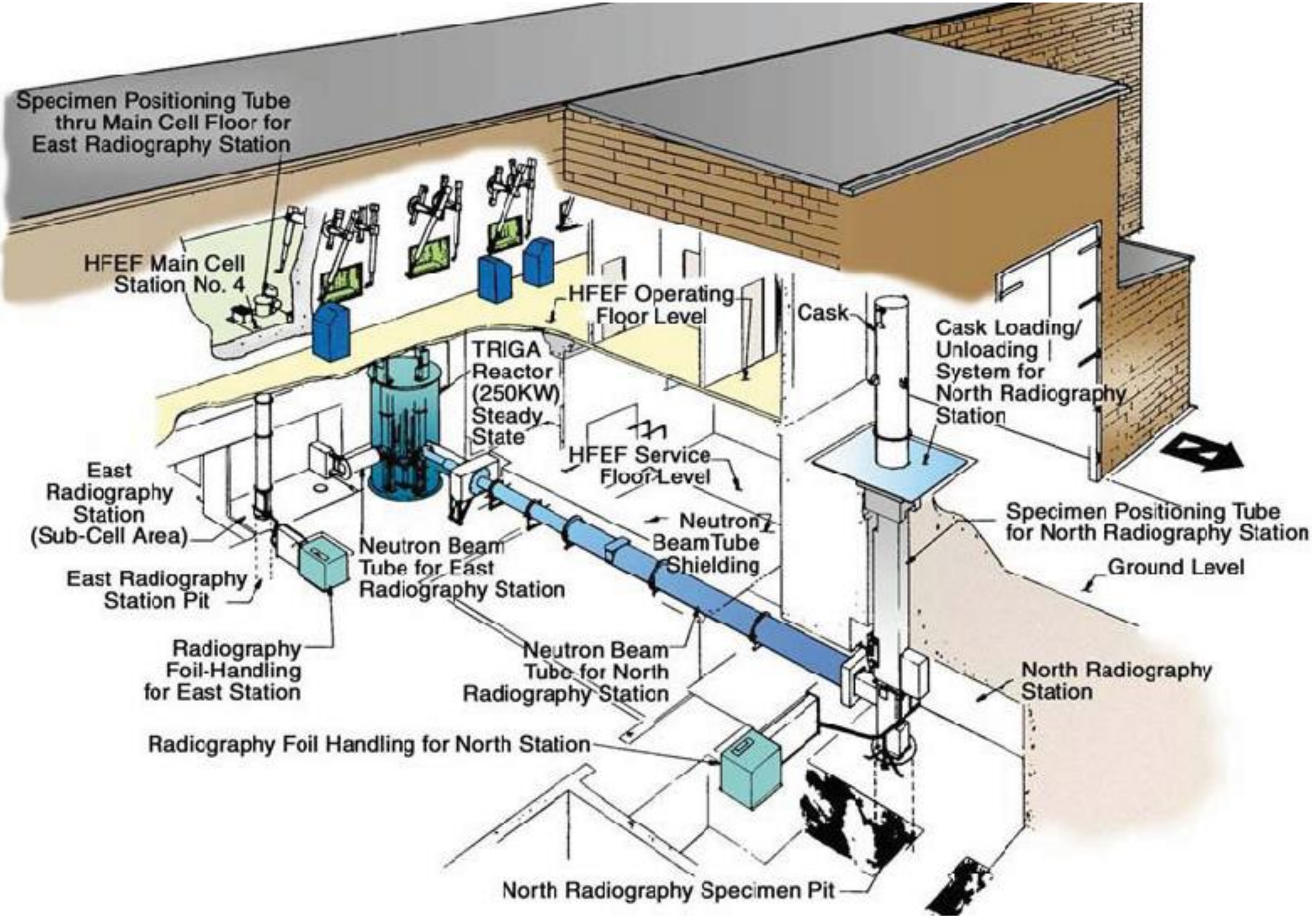


East Radiography Station (ERS)

- Category-I radiography facility according to ASTM standards
- Image area: 17.8 cm ×43.2 cm (7”×17”)
- Neutron flux: ~9.5×10^{6} n/cm^{2}-s
- L/D ratio: 50, 125, 300 (L = 4.45 m)

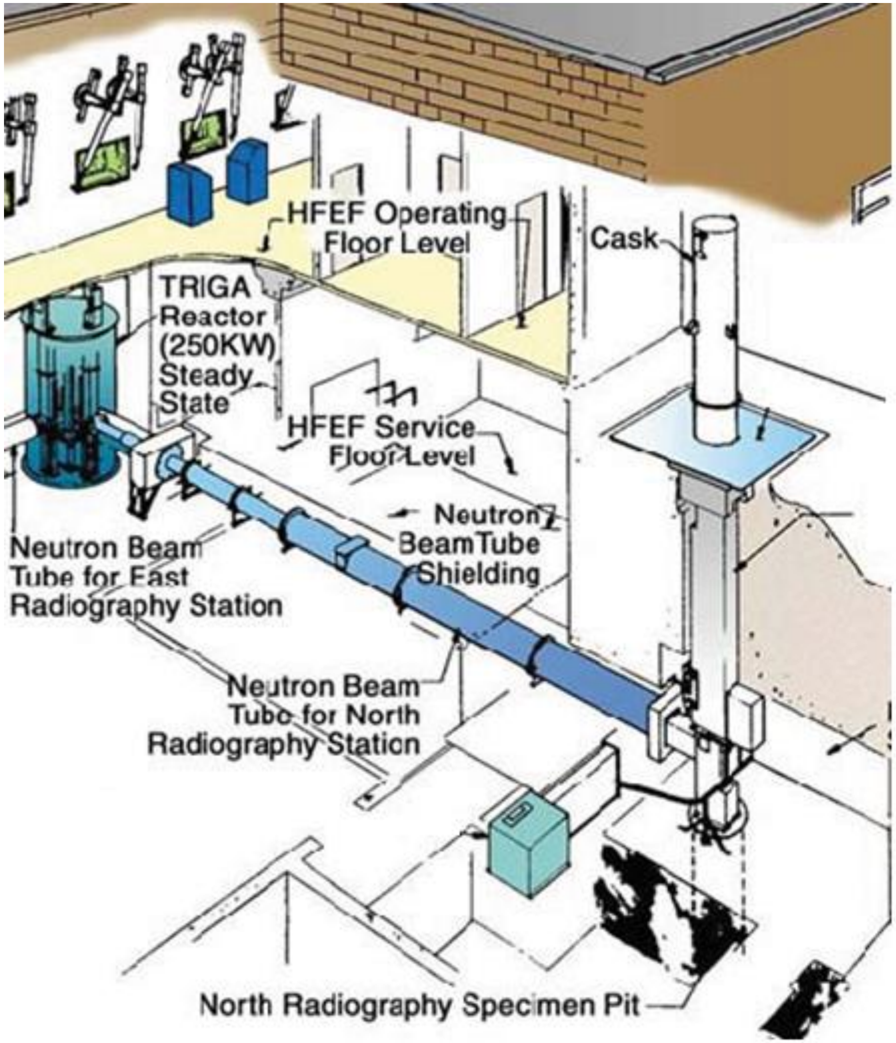


North Radiography Station (NRS)



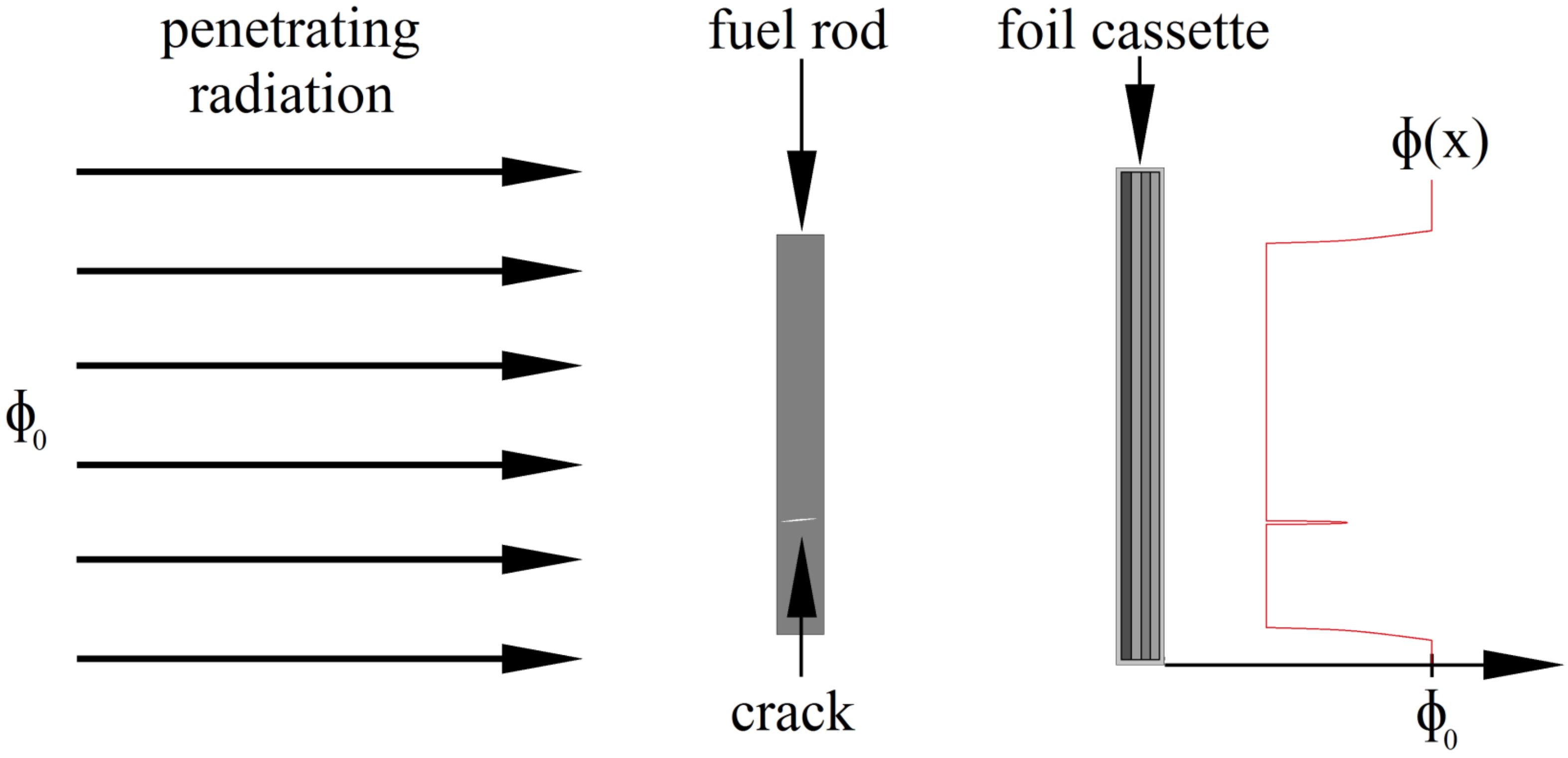
North Radiography Station (NRS)

- NRS is <u>not</u> beneath the hot cell
- Equipment and specimens can be placed in the NRS cell by hand
- Easier access to NRS
- FOV up to 50 cm
- L/D ratio: 185, 300, 700
- Neutron flux: ~4.5×10^6 *n*/cm^2-s
- NRS is ideal for:
  - Detector development
  - Unirradiated objects
- Recovery of NRS is underway
  - Was used for other experiments



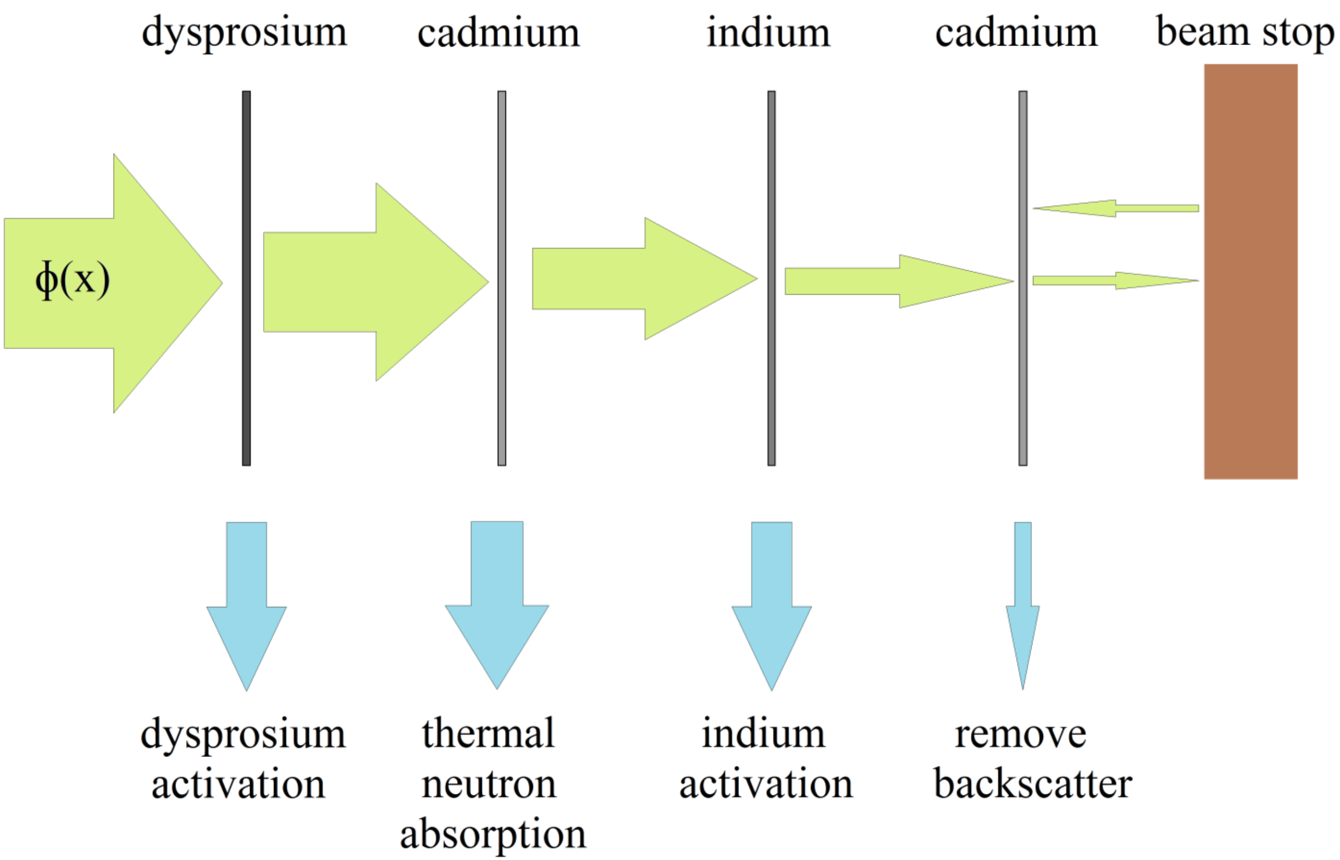
Radiography at the NRAD

- Transfer method radiography is currently employed at the NRAD
  1. Neutron beam passes through the specimen and activates the foils in the cassette



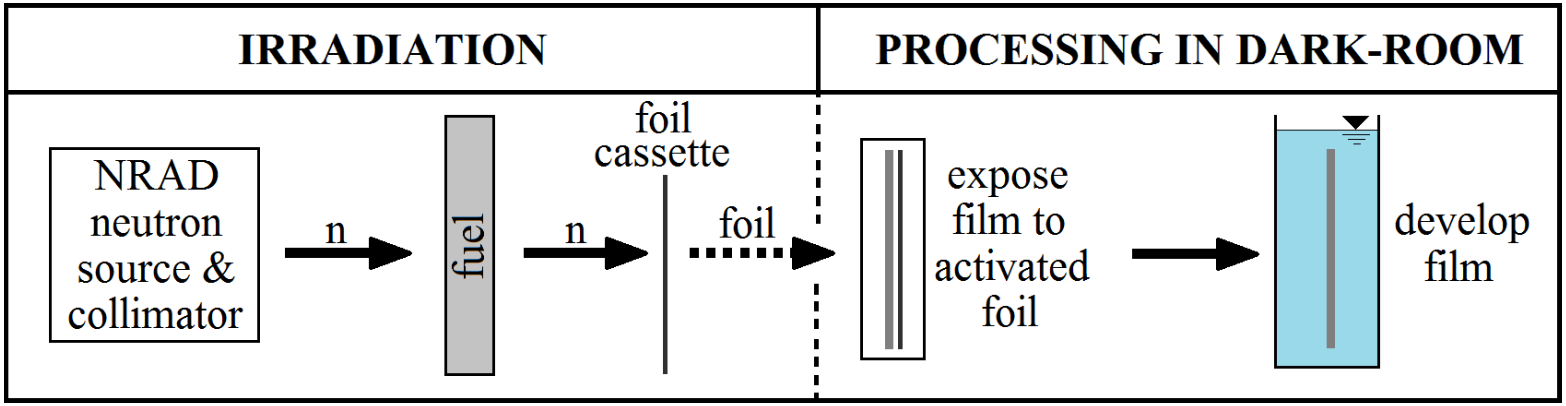
Radiography at the NRAD, cont.

- Transfer method radiography is currently employed at the NRAD
    1. Neutron beam passes through the specimen and activates the foils in the cassette



Radiography at the NRAD, cont.

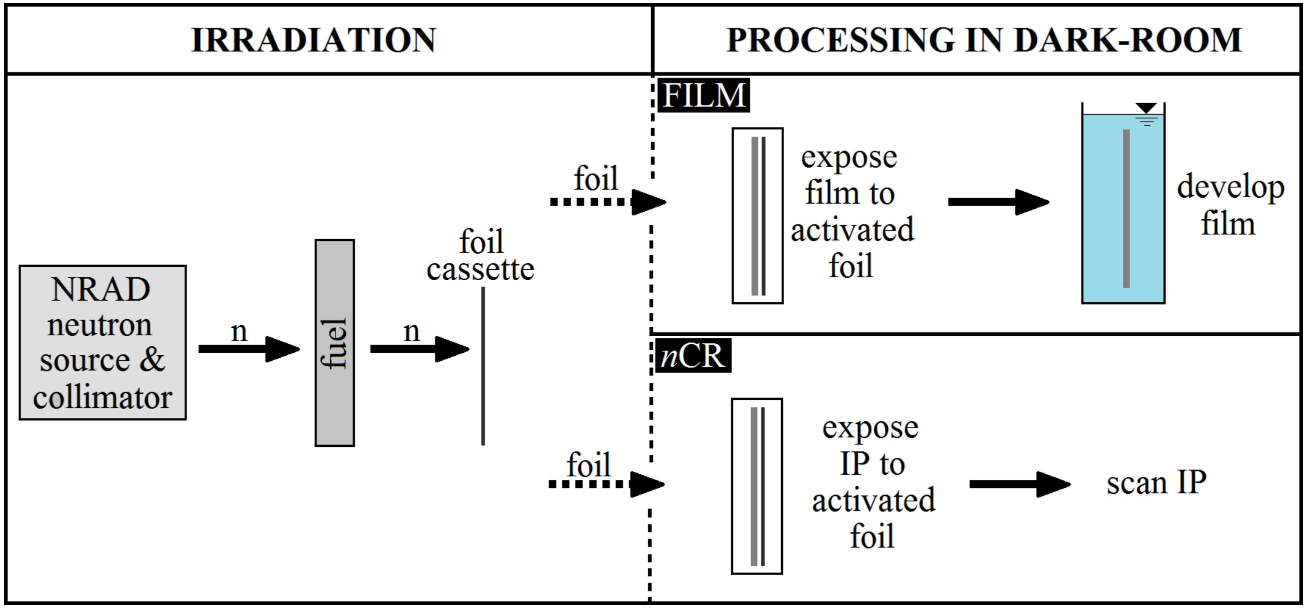
- Transfer method radiography is currently employed at the NRAD
   2. Foils are removed from the cell and taken to a nearby dark room
   3. X-ray film placed into contact with the activated foils
   4. Decay radiation from foils exposes the film (over night)
   5. Film is developed and scanned



- This is *typically* the only radiography technique used for nuclear fuel
   – For highly radioactive objects, transfer method radiography is <u>still</u> the state of the art

Neutron Computed Radiography

- Developing a new capability that uses image plates (IP) for neutron computed radiography (*n*CR)
- Same transfer method as film



- Removes film development and scanning (↓ time, ↓ cost)
- IPs are reusable, but consumable