

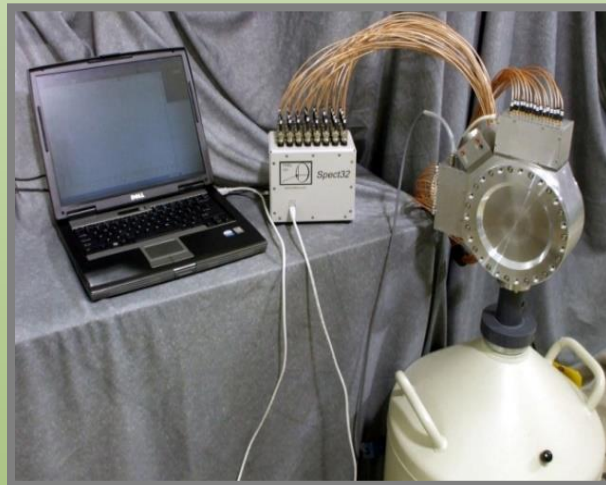
Nuclear Physics Gamma-ray Imaging System for Real-Time Rare Isotope Harvesting, Monitoring and Radiochemical Separation – NP Imager

- **PHDS Co. Introduction**
- **NP Imager Motivation**
- **NP Imager Prototype Development**
- **Radiochemical Process *Imaging***

Introduction to PHDS Co.



- Est. Fall 2004 – Nuclear and Solid-State Physics Origin
 - History: Custom Nuclear-Physics Detectors like NPX
 - Recently: Modular HPGe Systems like GeGI
- Complete Germanium Detector Manufacturing and R&D
 - Concept and Design
 - HPGe Crystal Growth
 - Detector Fabrication
 - System Integration
 - Software application
 - Sales & Service



2008 NPX (150 lbs.)



2017 GeGI-5 (15 lbs.)



Fulcrum
(7 lbs.)

GeGI[®]

Gamma-ray Imaging Spectrometer



HPGe Isotope Identification

Source Location Imaging

Source Distribution Imaging

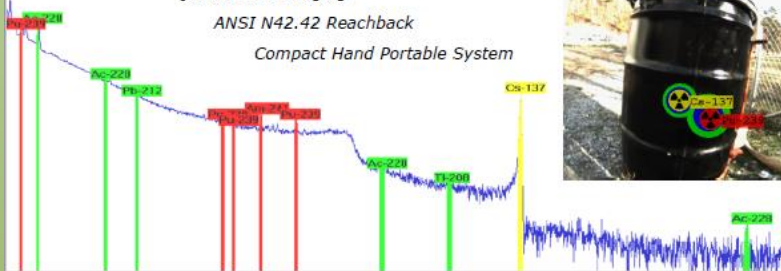
Quantitative Imaging

ANSI N42.42 Reachback

Compact Hand Portable System



Compton Int



Fulcrum[®]

Compact HPGe Gamma-ray Spectrometer



HPGe Isotope Identification

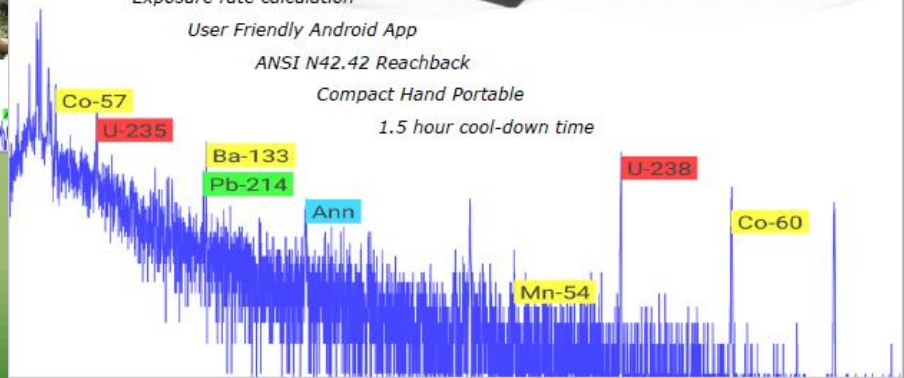
Exposure rate calculation

User Friendly Android App

ANSI N42.42 Reachback

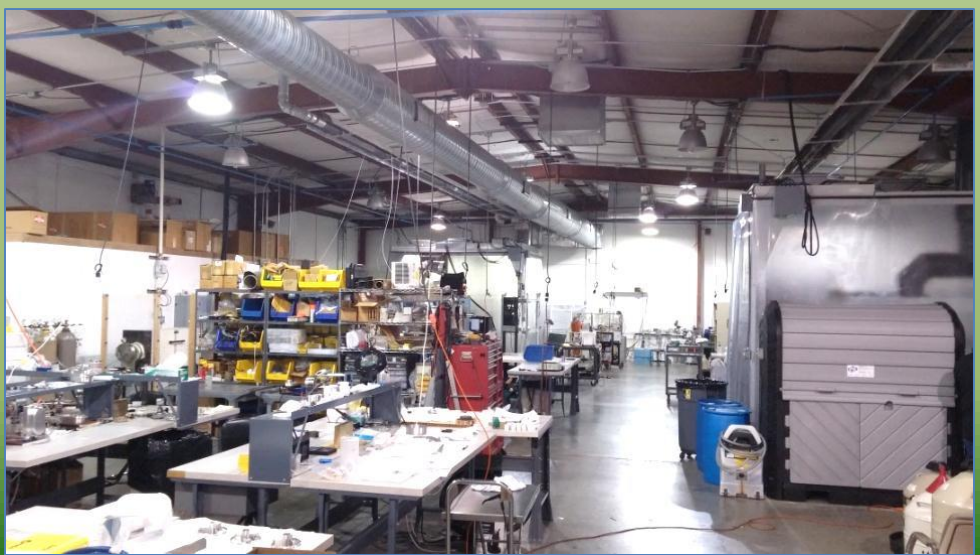
Compact Hand Portable

1.5 hour cool-down time





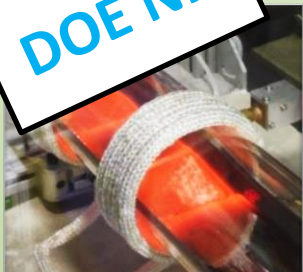
**10,000 ft² Manufacturing
and R&D Facility in
Knoxville, TN**



Vertical manufacturing of GeGI Imaging Spectrometers



DOE NP



Ge Zone Refine

DOE NP



HPGe Crystal Growth

DOE NP



Analysis

DOE NP



Fabrication

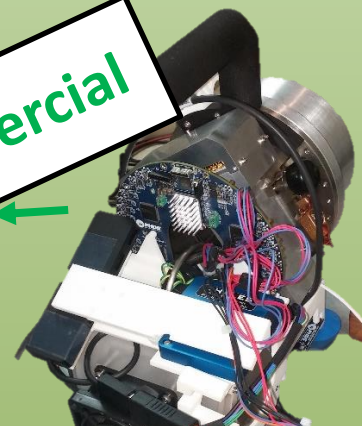
Commercial Products

Commercial

Commercial



Integration

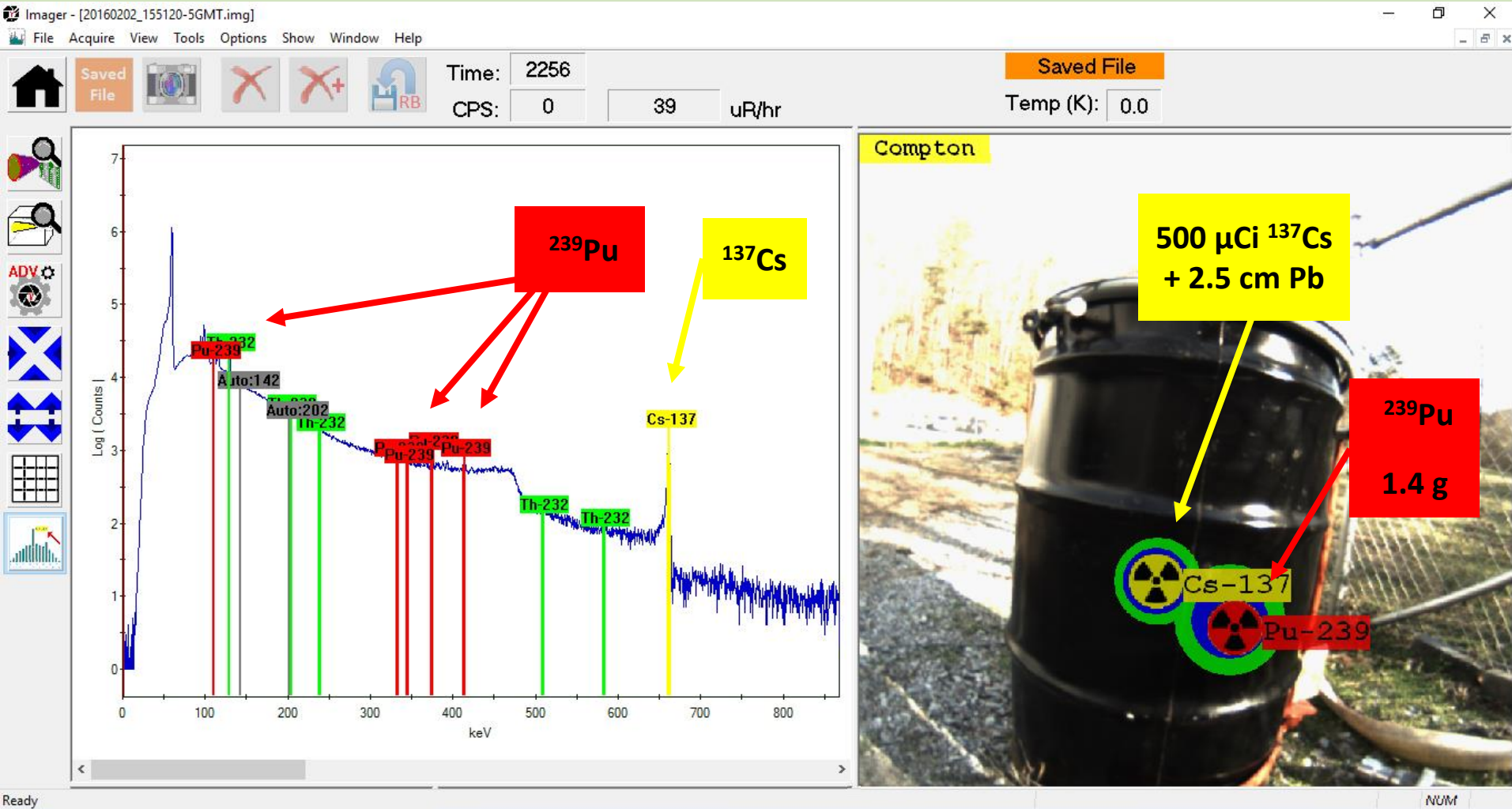


Electronics



Cryogenics

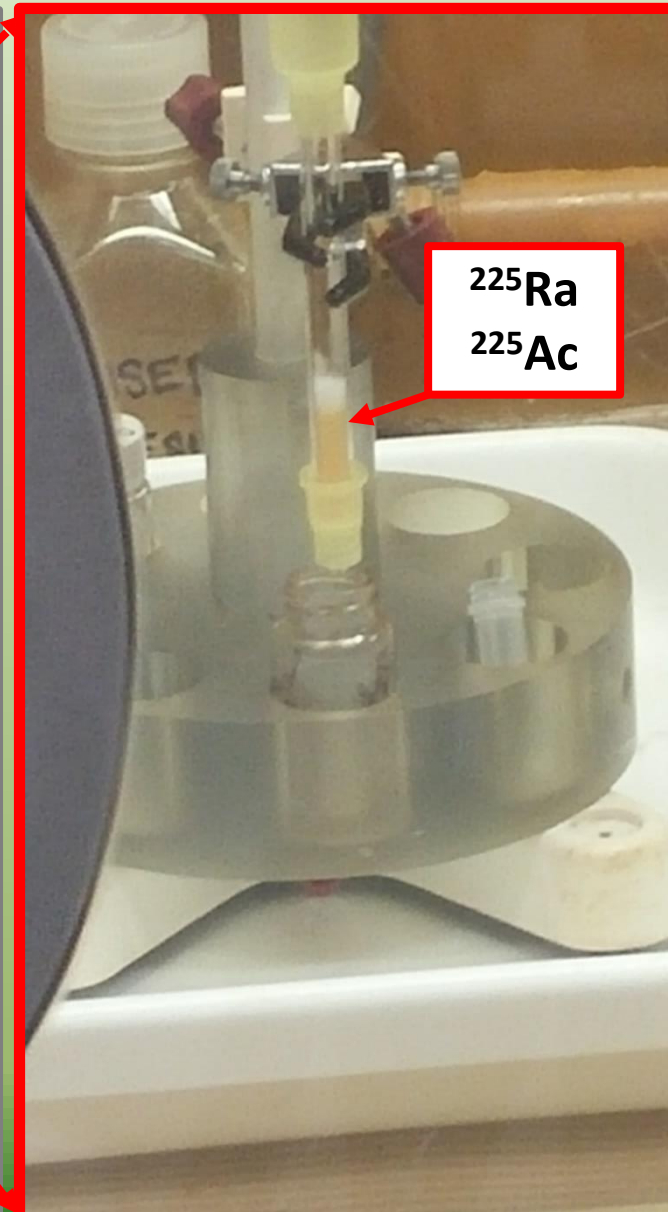




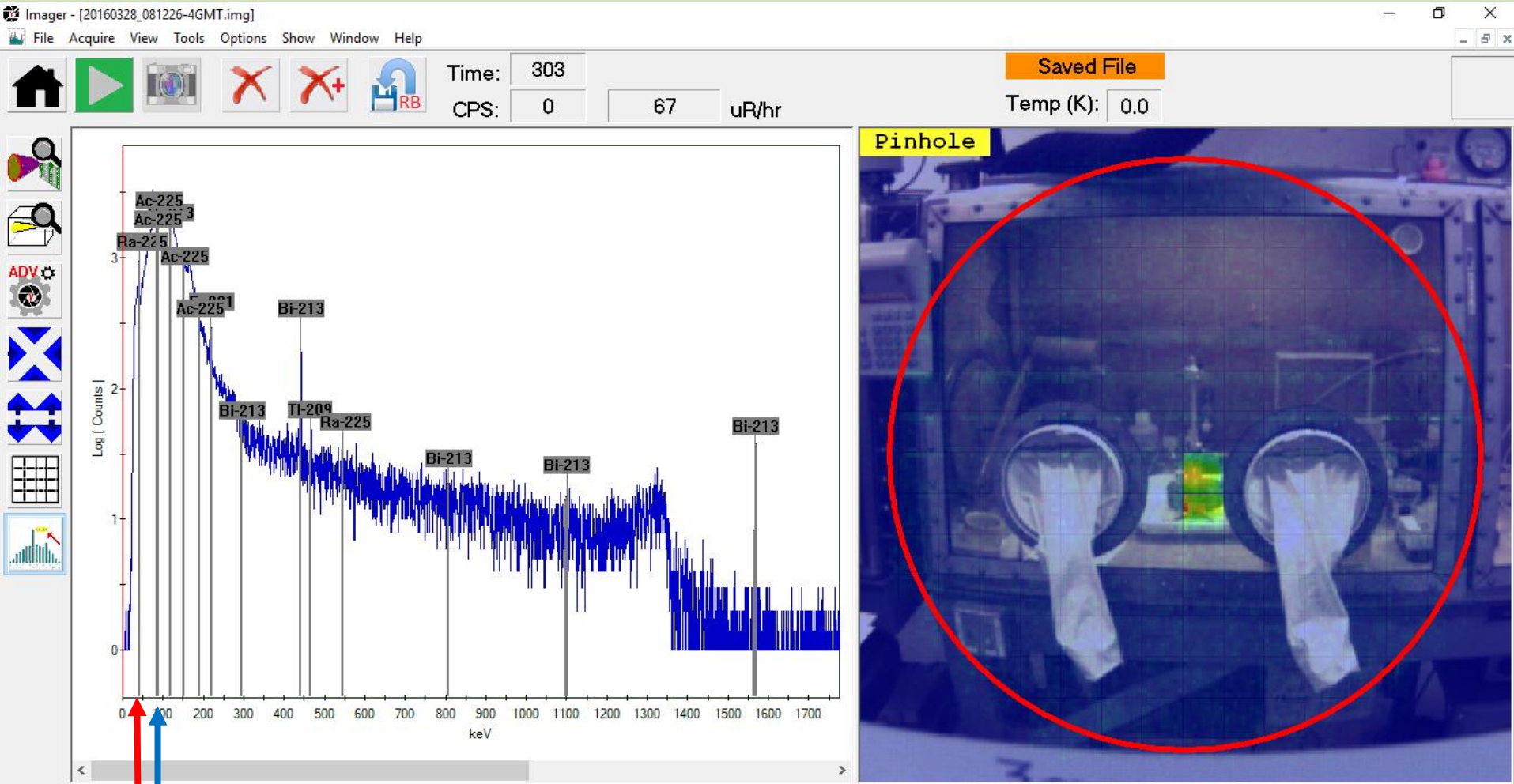
Static

Radiochemistry is Dynamic → Motivation

Radioisotope separation



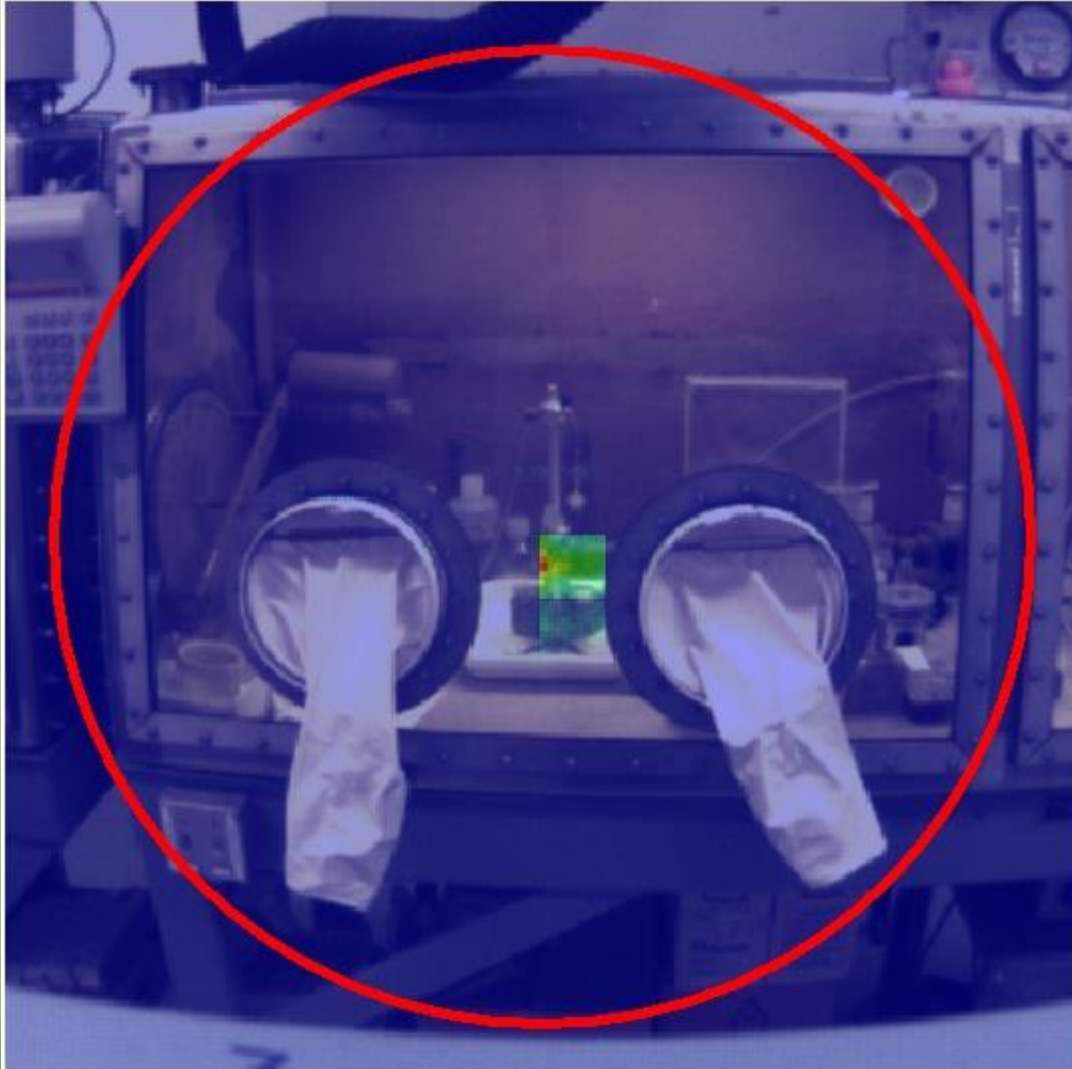
Motivation



99.8 keV ^{225}Ac

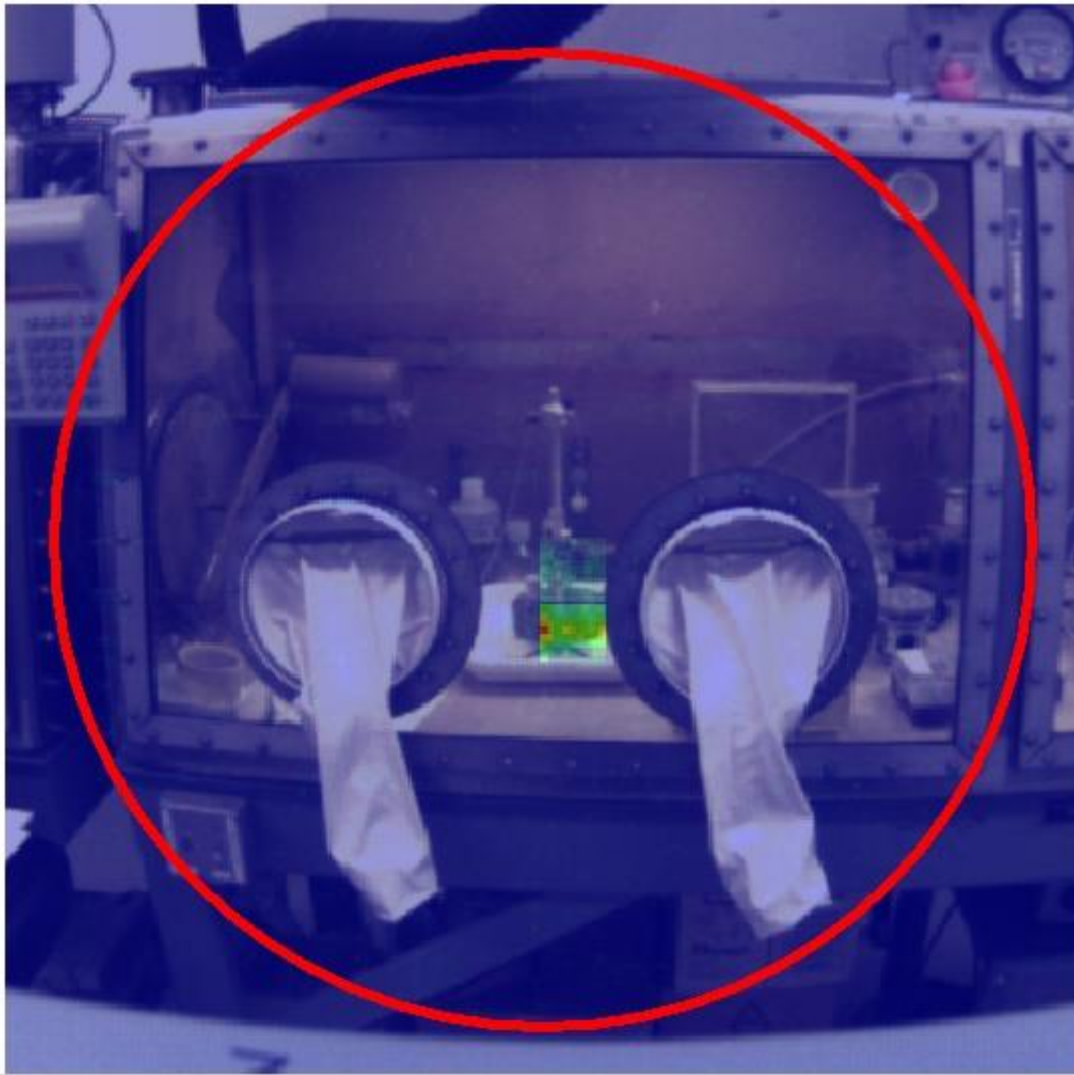
40 keV ^{225}Ra

40 keV ^{225}Ra



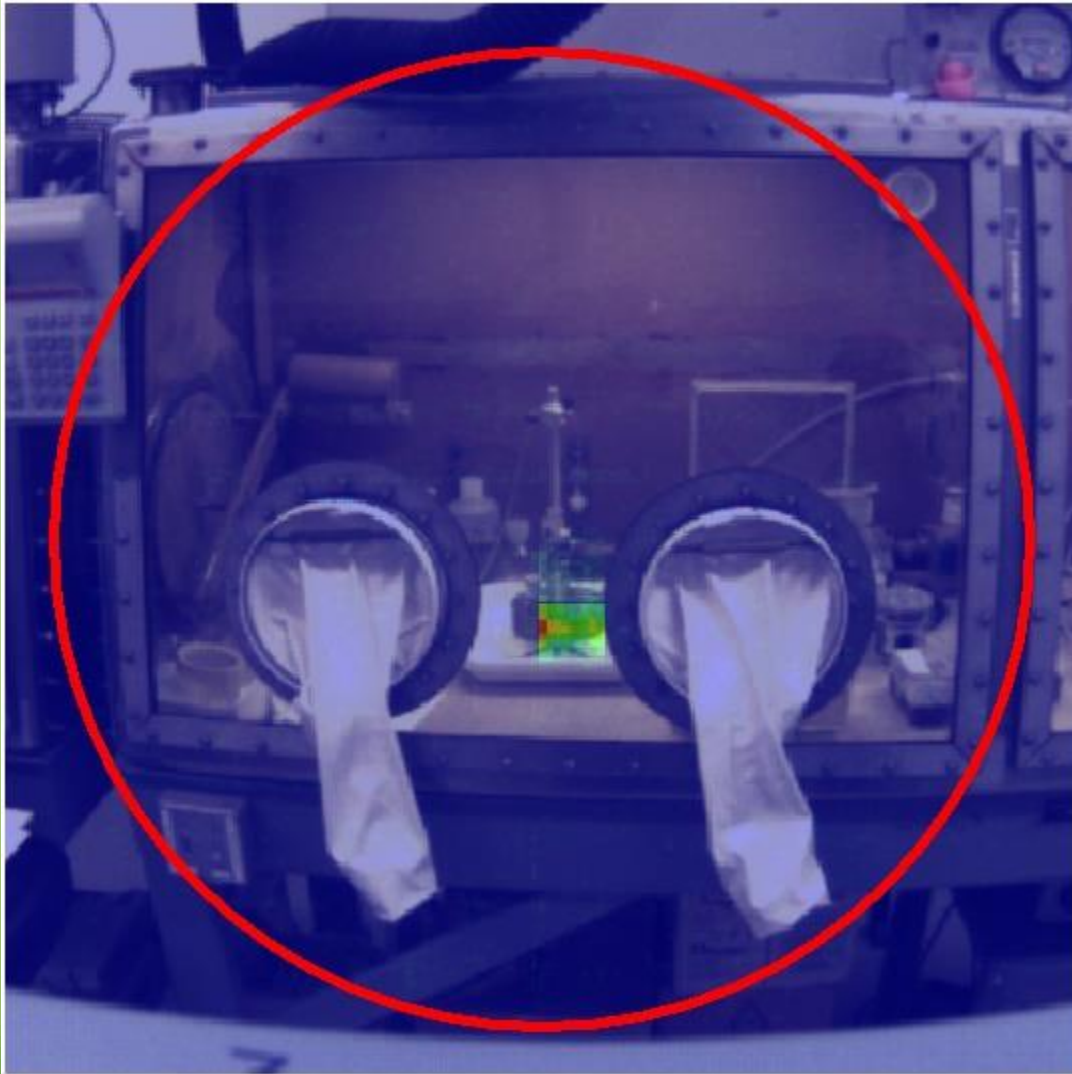
5 min

40 keV ^{225}Ra



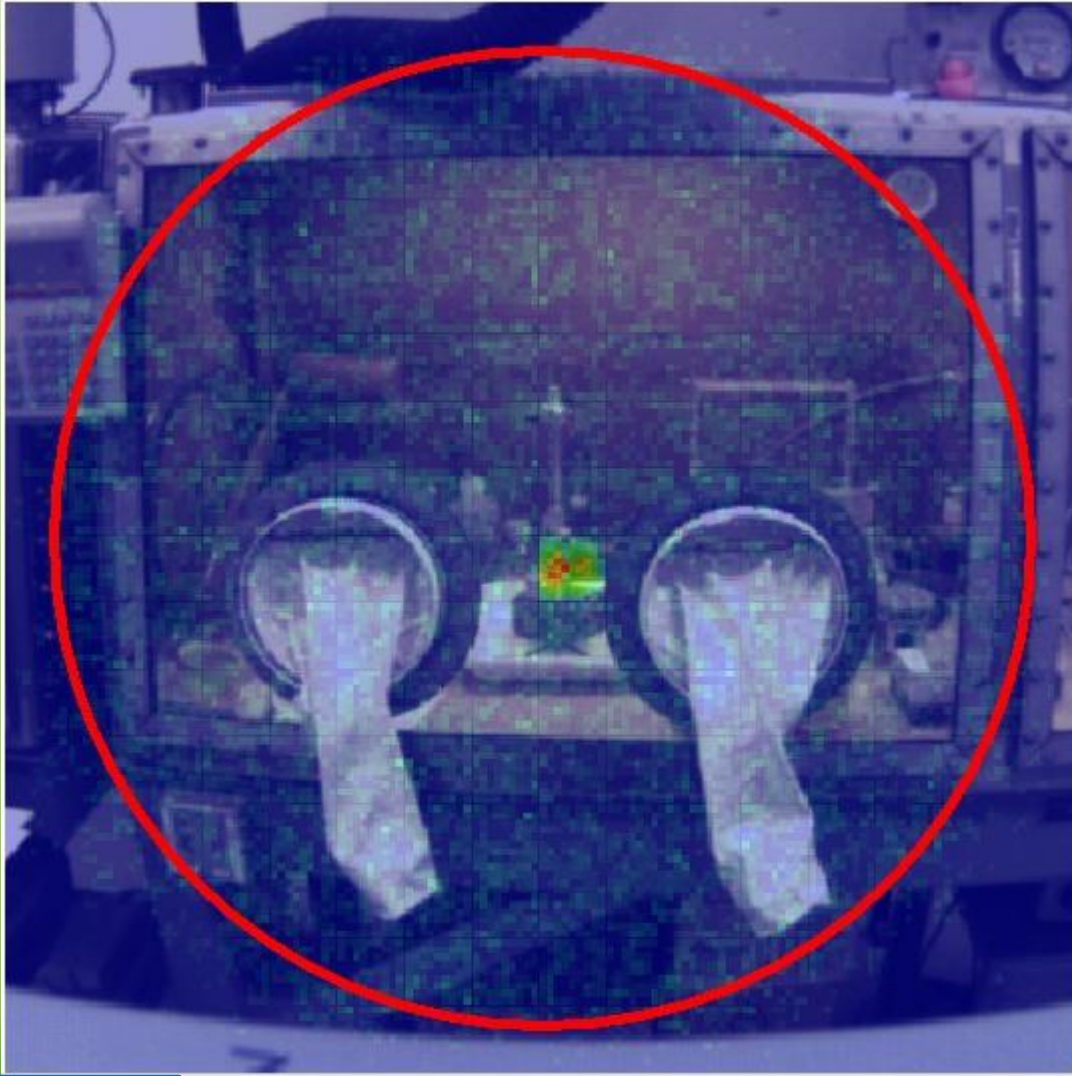
10 min

40 keV ^{225}Ra



15 min

99.8 keV ^{225}Ac



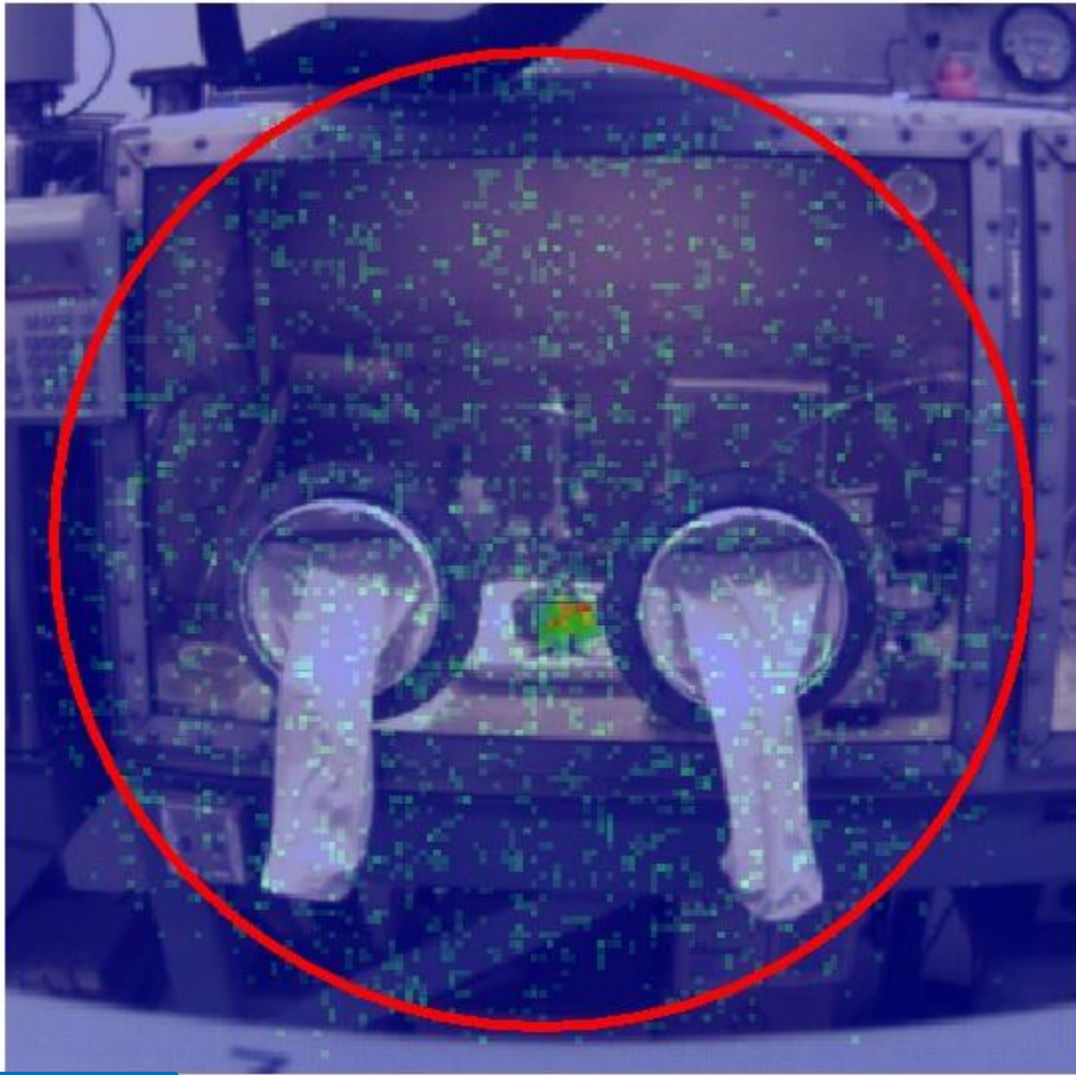
5 min

99.8 keV ^{225}Ac



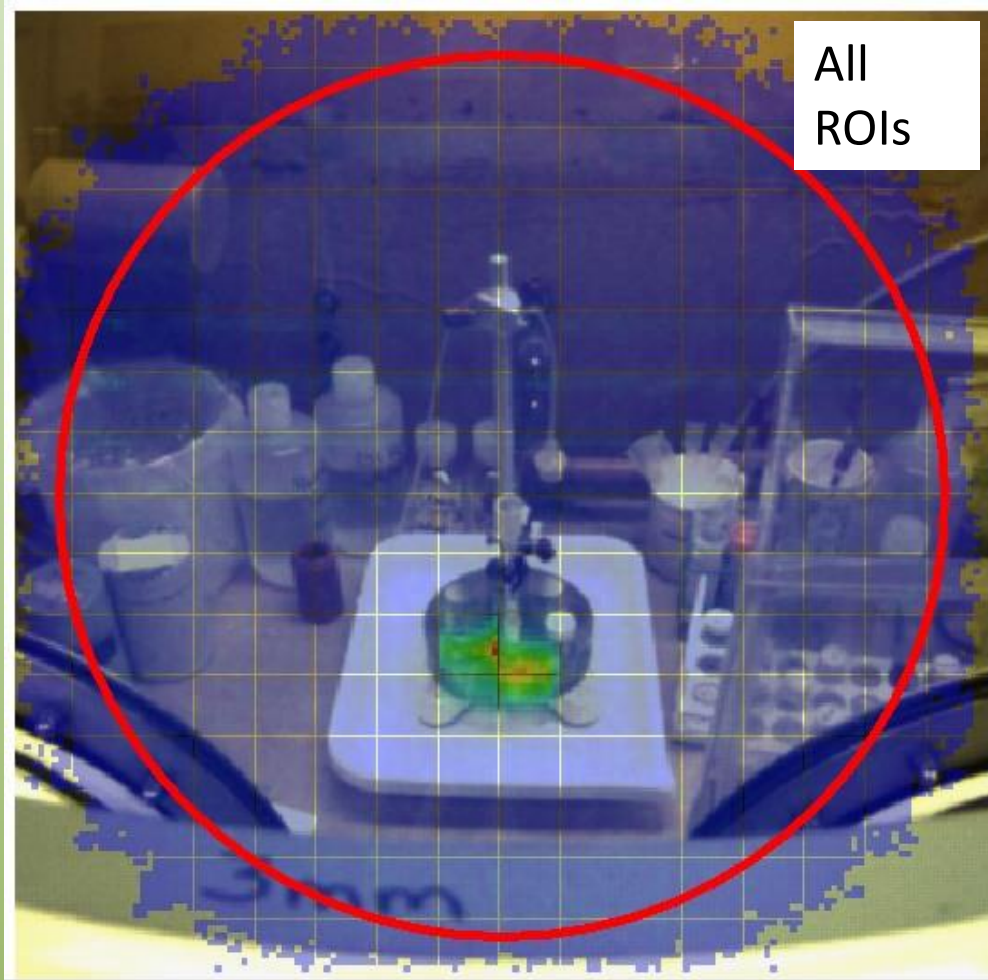
10 min

99.8 keV ^{225}Ac

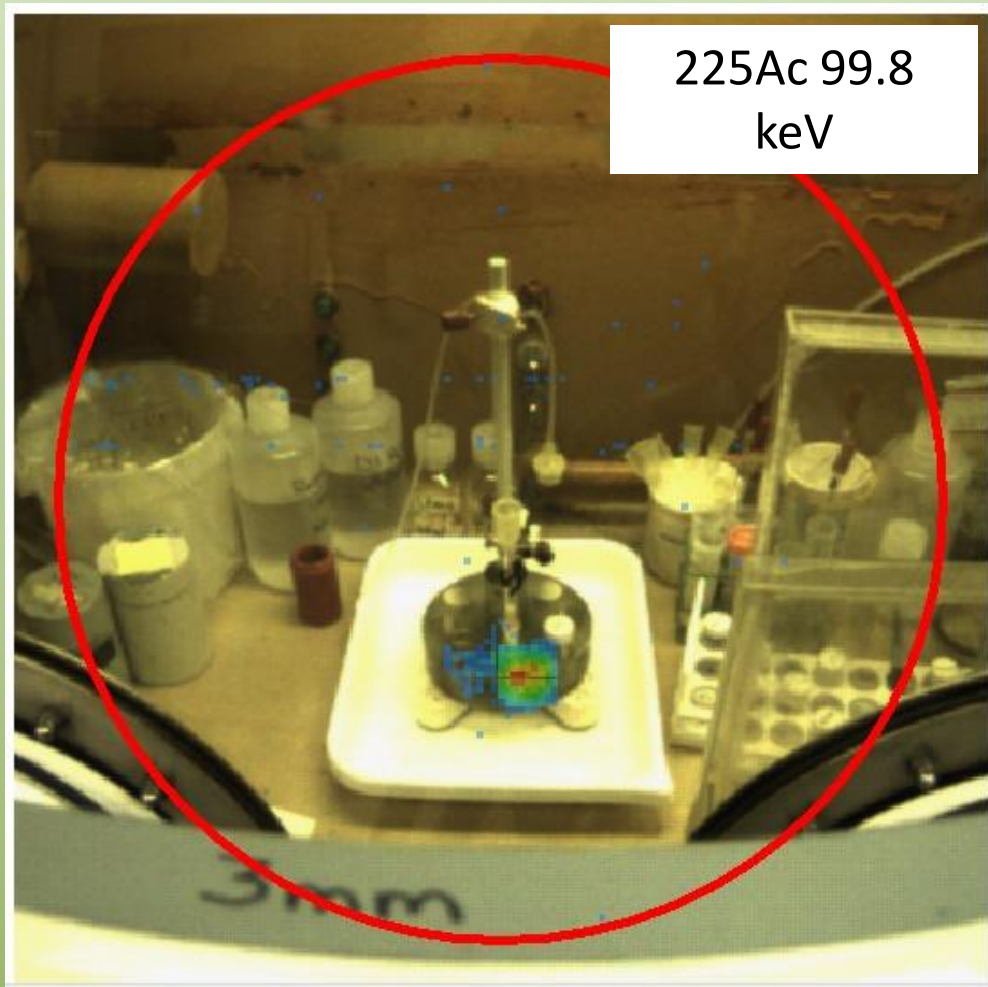


15 min

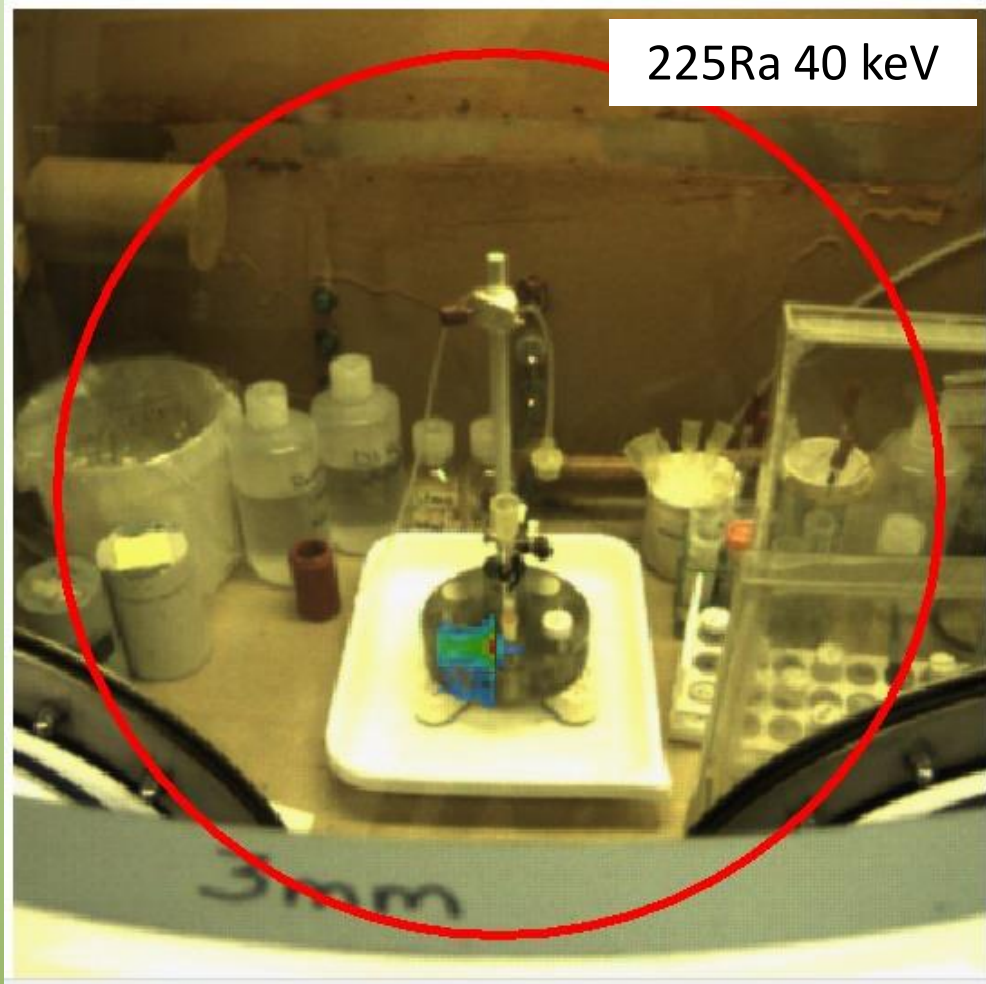
Collection Carousel



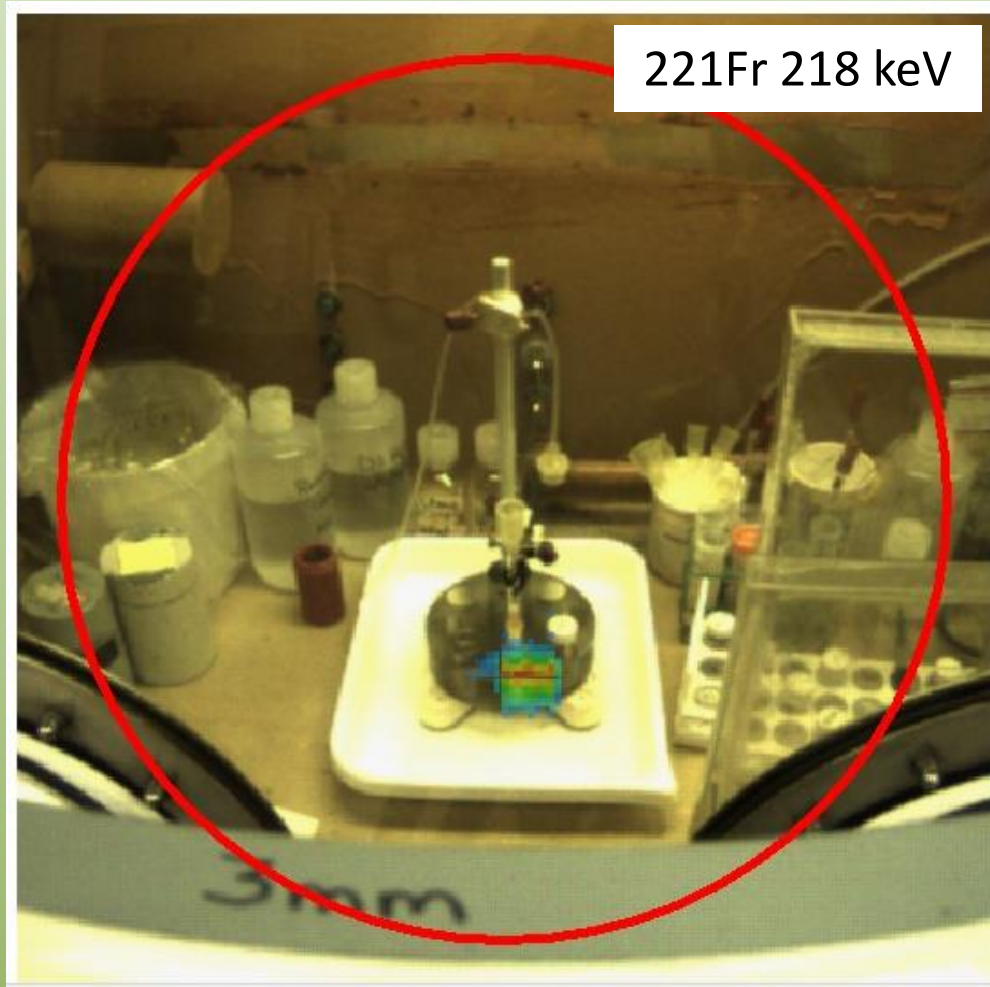
Collection Carousel



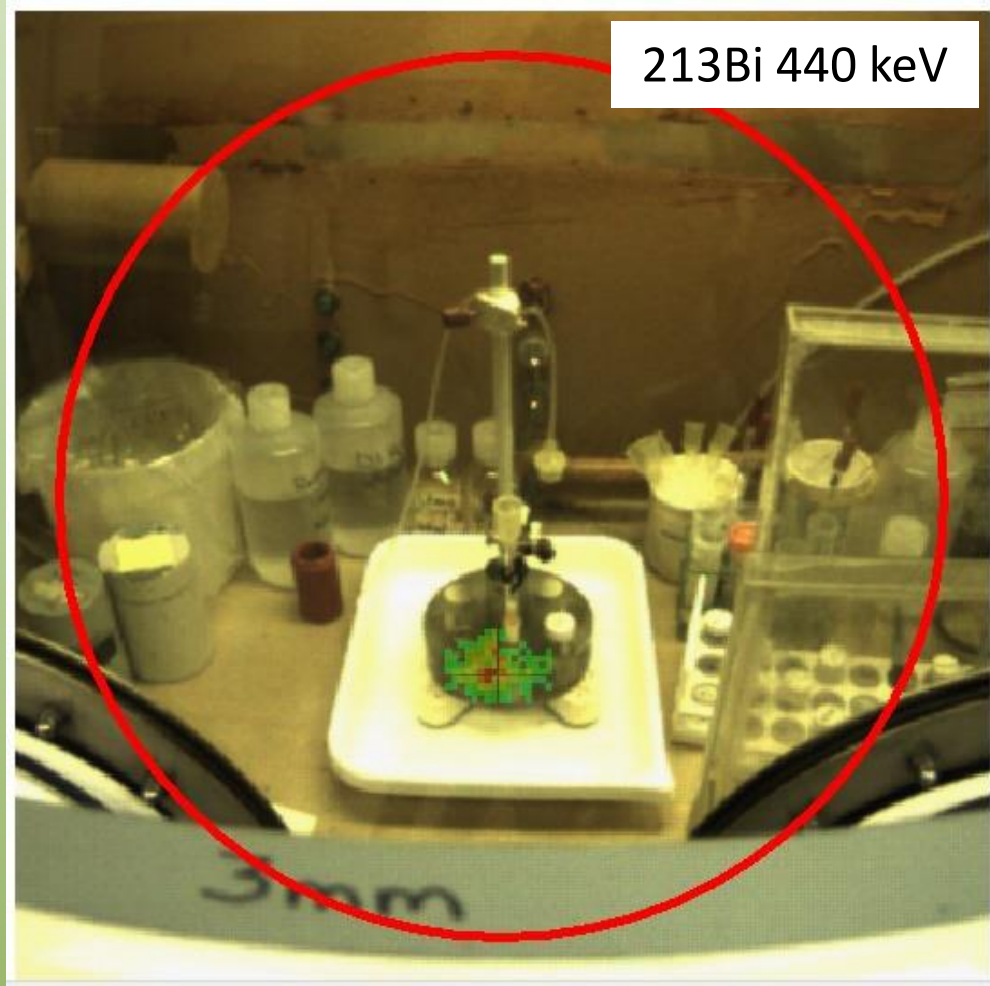
Collection Carousel

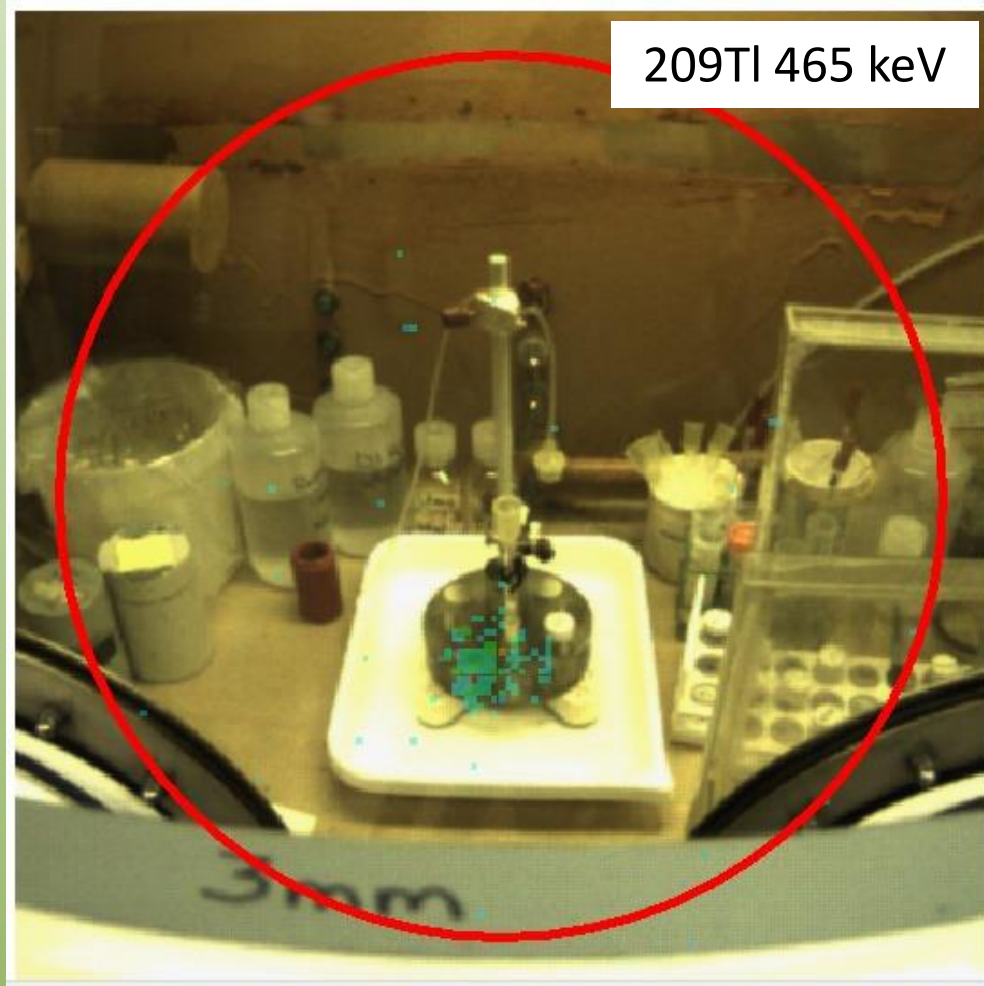


Collection Carousel

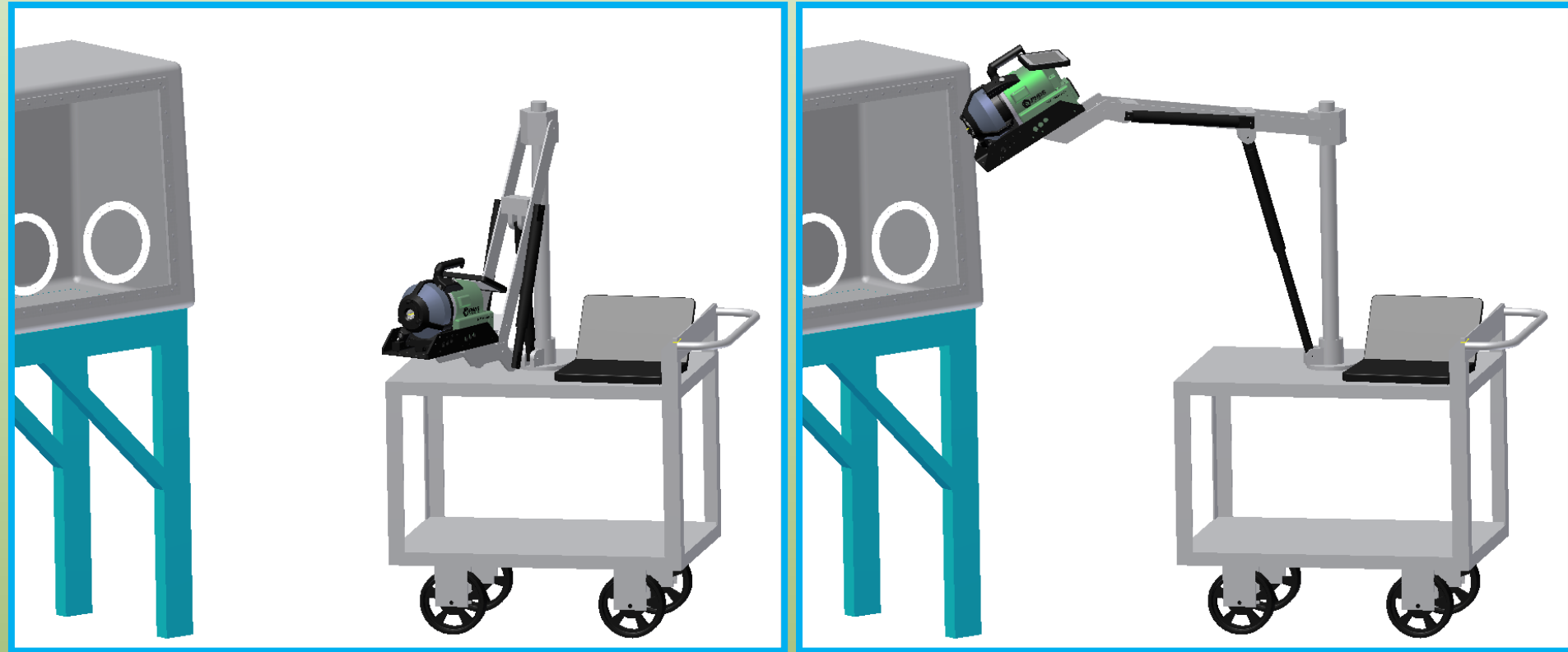


Collection Carousel

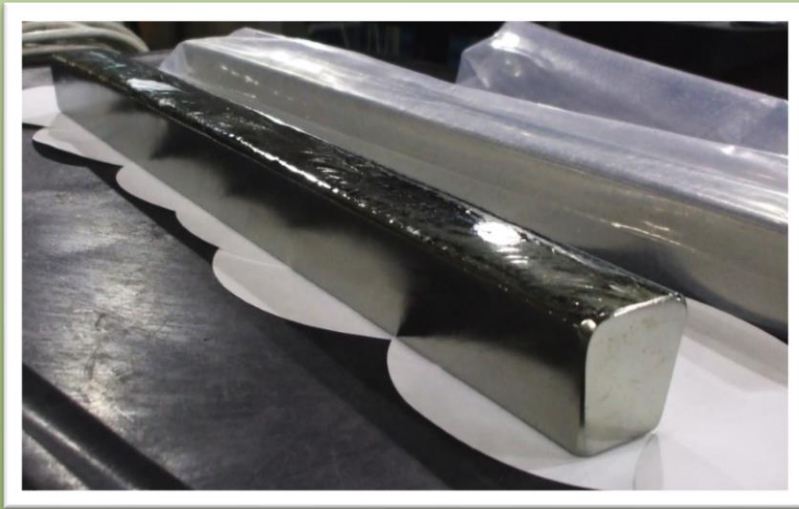




Motivation: The ability to observe the *dynamic* exchange of isotopes *in real time*, on the bench or glove box, would be a very useful tool to radiochemists and nuclear physicists.

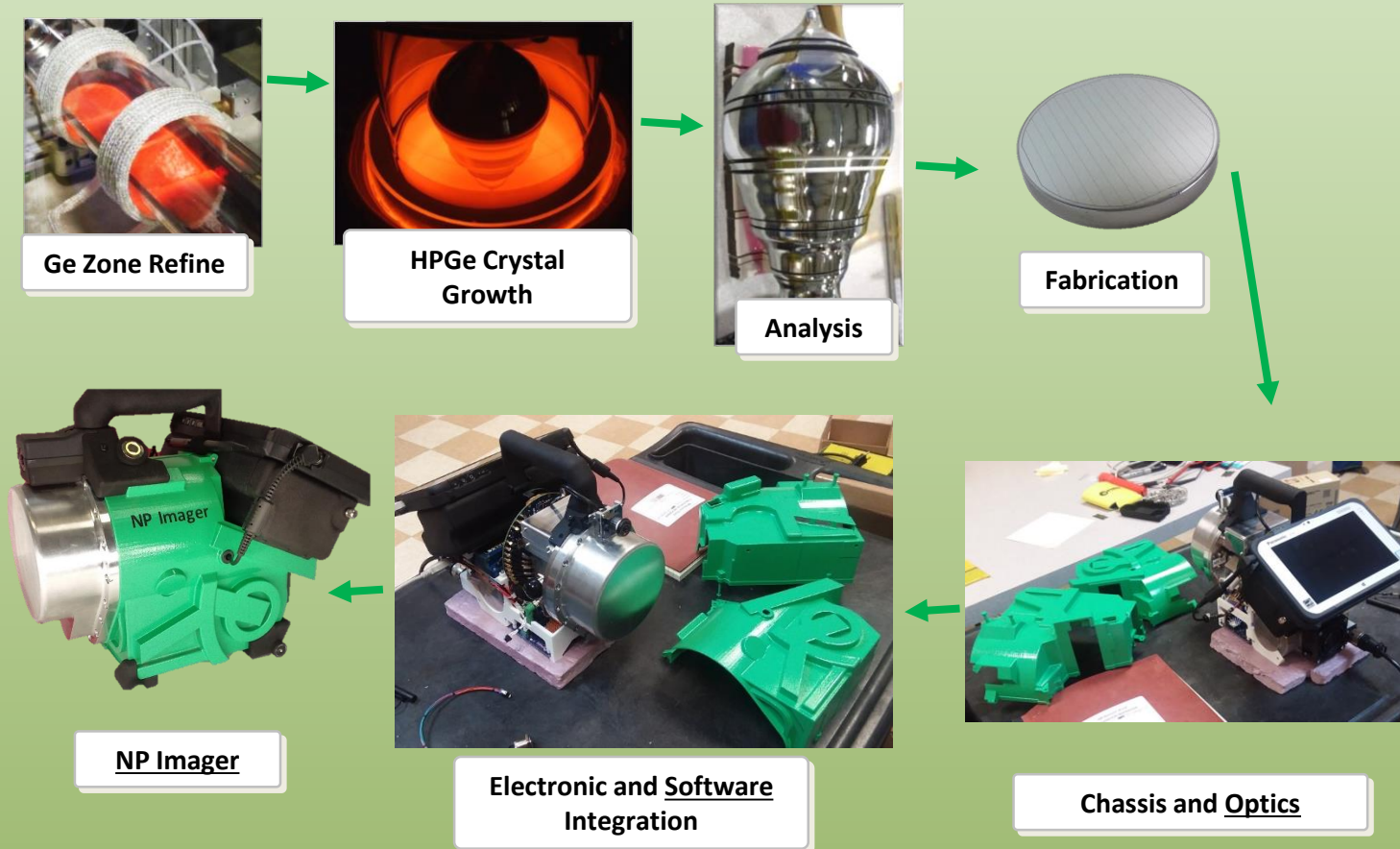


NP Imager Technical Development Phase-II Prototypes



NP Imager Technical Development Phase-II Prototypes

Adaptation of detector manufacturing to NP Imager



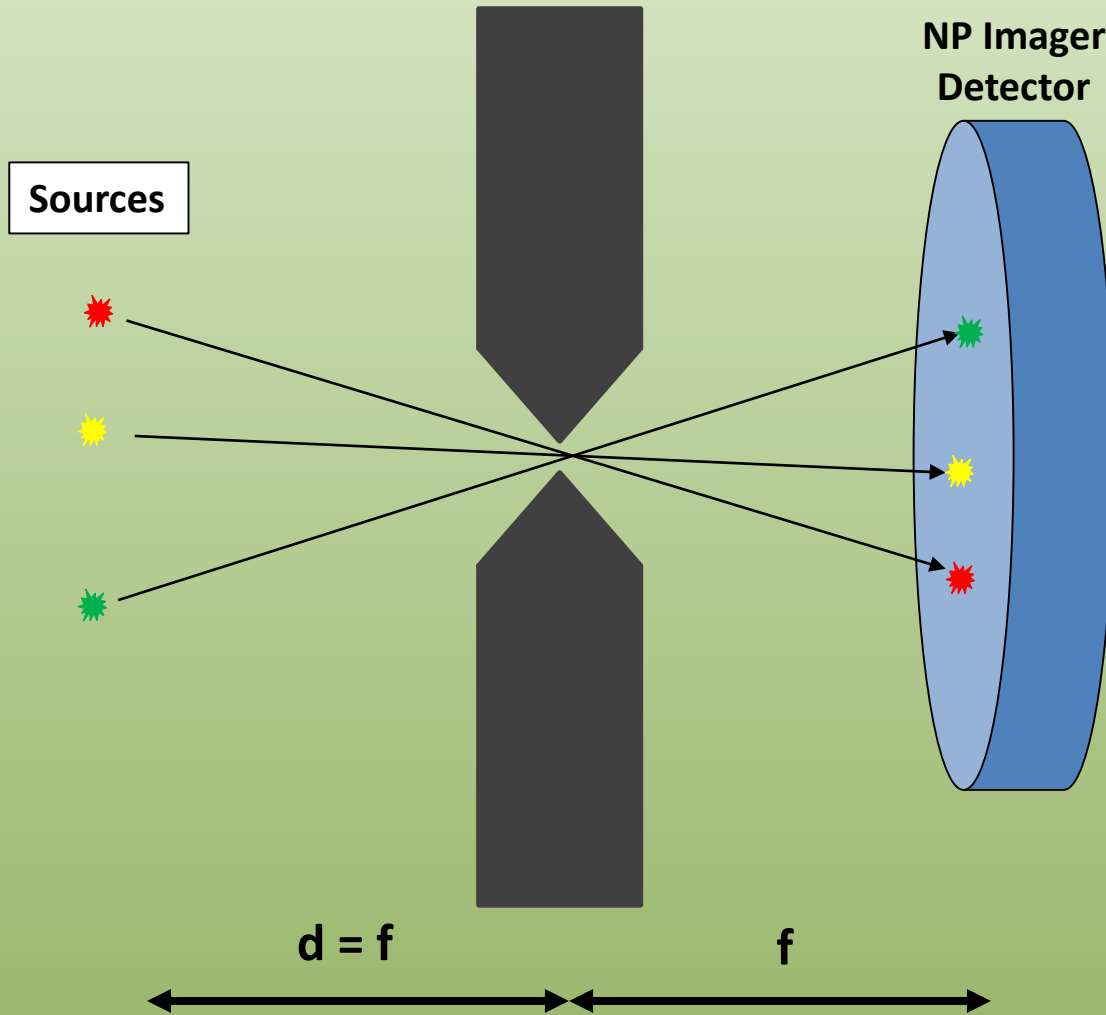
NP Imager



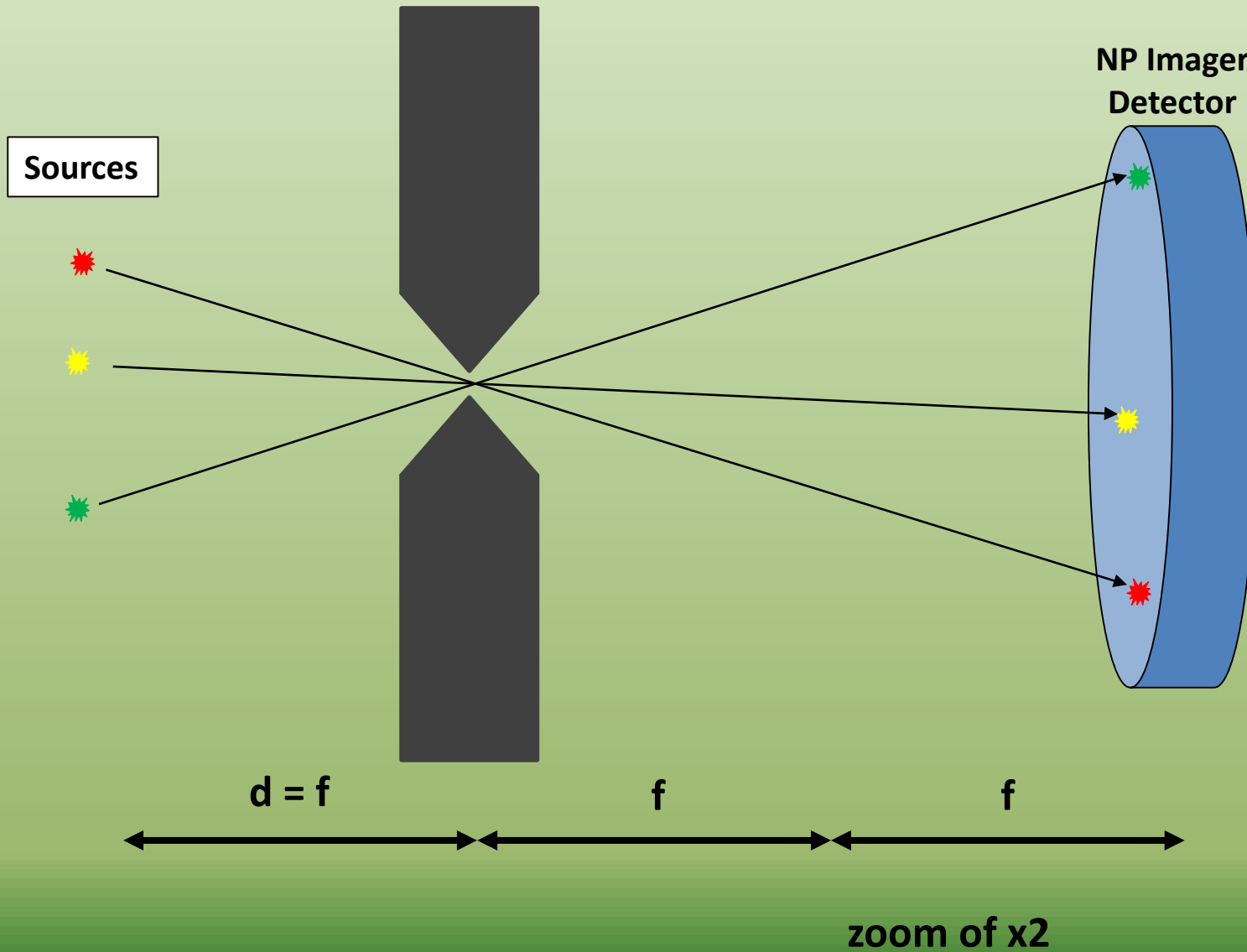
**(x, y, z)
Energy**

1. Compton Kinematic Imaging
2. **Pinhole Aperture Imaging**
 - *zoom*

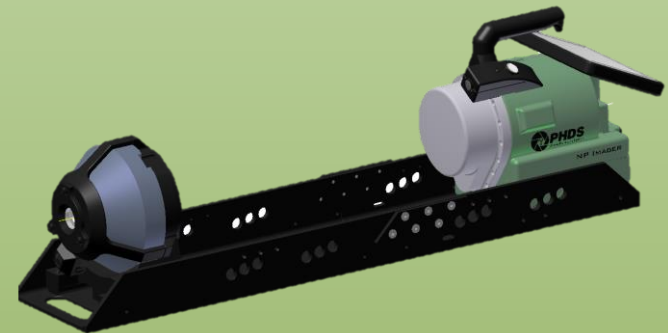
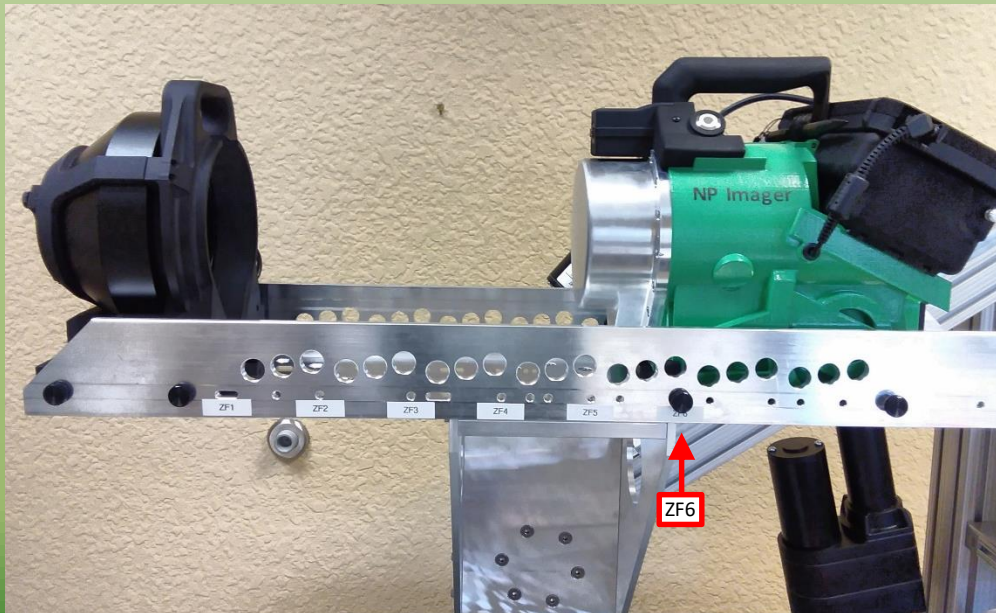
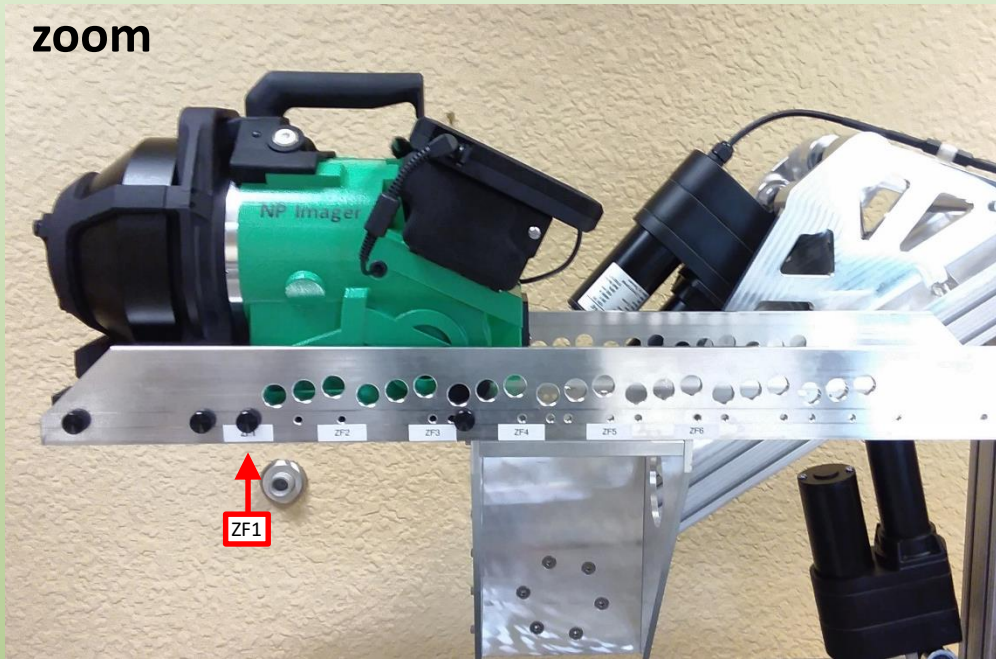
2. Pinhole Aperture Imaging



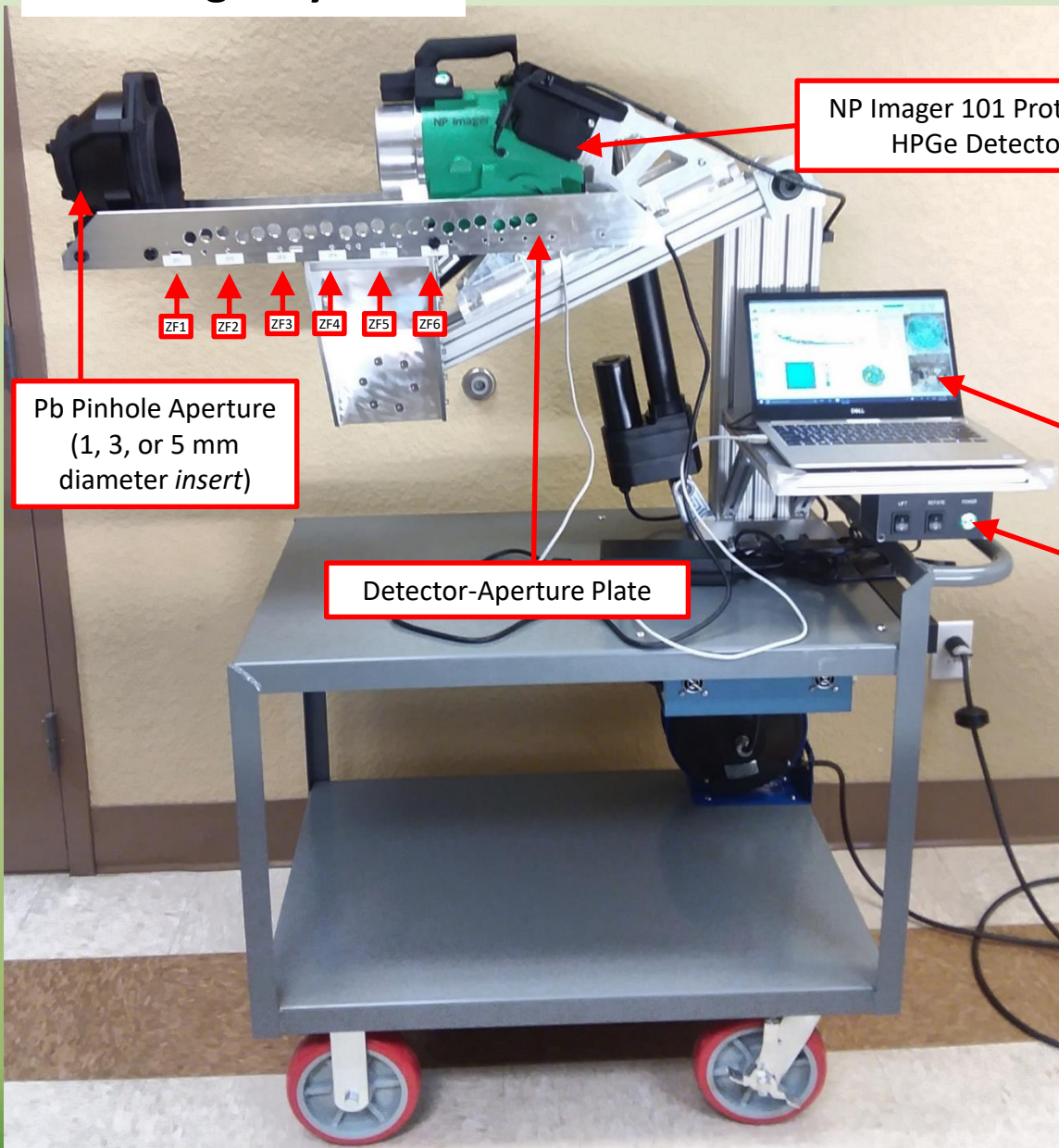
2. Pinhole Aperture Imaging



zoom



NP Imager System



NP Imager 101 Prototype
HPGe Detector

ZF1 ZF2 ZF3 ZF4 ZF5 ZF6

Pb Pinhole Aperture
(1, 3, or 5 mm
diameter insert)

Detector-Aperture Plate

Touch-
screen PC

Gantry
Controls



**NP Imager 101
Prototype**
(Ready for delivery to -
April 2019)



ADVANCED PINHOLE IMAGING



FIGURE 5. THE PINHOLE APERTURE AND THE NP IMAGER CAN BE ENGAGED ON ANY FLAT SURFACE. WITH THE PINHOLE ENGAGED FLUOR AS SHOWN HERE, THE APEX OF THE APERTURE IS 65 MM FROM THE FACE OF THE DETECTOR INSIDE THE CRYSTAL. THIS IS A ZOOMFACTOR OF 3.

Pinhole imaging is used to measure the detailed structure of radioactive material within a maximum 60-degree forward field of view (FOV). Pinhole imaging requires the Pinhole Aperture to be positioned in front of the NP Imager and engaged as shown in Figure 1. This can be done on any flat surface. It should be noted that based on the 60-degree pinhole opening, the diameter of the image plane FOV is approximately equal to the distance from the pinhole aperture to the target image plane. Also note that the distance to be entered on the Pinhole screen is the distance from the front face of the Pinhole Aperture to the parallel plane containing the source. When the Pinhole Aperture is in place, the view of the camera mounted on the NP Imager is substantially obstructed. Switching to the camera mounted in the Pinhole Aperture holder will provide an unobstructed optical overlay.



SWITCHING TO THE CAMERA MOUNTED IN THE PINHOLE APERTURE HOLDER
The order of operations below is critical for proper optical alignment of the Pinhole Image. Following the steps below will ensure the proper image alignment parameters are applied (these vary, depending on

“zoom”

ZF1

2x ^{57}Co at 38.5 cm



Imager - [ZF1-20190329_142614-4GMT.img]

File Acquire View Tools Options Show Window Help

Time: 550 Live: 1.000 Saved File

CPS: 0 8 uR/hr Temp(K): N/A

Threshold 0 Distance(m) 0.385 +/- Measure Events 847 Search Pixels Edit ROIs Switch to Polygon ROIs

Units MegaBecquerel [MBq]

ROI	Isotope	Energy	Count	Activity (Ci)	Radioactive Mass (g)	Activity Conc. (Ci/g)
There are no items to show in this view.						

Energy Windows

Isotope	Energy (keV)
<input checked="" type="checkbox"/> Co-57	122.1
<input checked="" type="checkbox"/> Co-57	136.5
<input checked="" type="checkbox"/> K-40	1460.8

Intervening Materials

Material	Density(g/cc)	Thick(cm)
There are no items to show in this view.		

ROI Materials

ROI	Material	Density(g/cc)	Thick(cm)
There are no items to show in this view.			

Ready X=37 Y=0 Rel.Count=0.00 NUM

“zoom”

ZF2

2x ⁵⁷Co at 38.5 cm

Imager - [ZF2-20190329_143726-4GMT.img]

File Acquire View Tools Options Show Window Help

Time: 410 Live: 0.984 Saved File

CPS: 0 9 uR/hr Temp(K): N/A

Threshold 0 Distance(m) 0.39 Events 886

Search Pixels Edit ROIs Switch to Polygon ROIs

Show All Energy Windows

Isotope	Energy (keV)
<input checked="" type="checkbox"/> Co-57	122.1
<input checked="" type="checkbox"/> Co-57	136.5
<input checked="" type="checkbox"/> K-40	1460.8

Intervening Materials

Material	Density(g/cc)	Thick(cm)
----------	---------------	-----------

ROI Materials


ROI	Material	Density(g/cc)	Thick(cm)
-----	----------	---------------	-----------

There are no items to show in this view.

Units: MegaBecquerel [MBq]

ROI	Isotope	Energy	Count	Activity (Ci)	Radioactive Mass (g)	Activity Conc. (Ci/g)
-----	---------	--------	-------	---------------	----------------------	-----------------------

There are no items to show in this view.



Ready

NUM

“zoom”

ZF3

2x ⁵⁷Co at 38.5 cm

Imager - [ZF3-20190329_145114-4GMT.img]

File Acquire View Tools Options Show Window Help

Time: 725 Live: 0.985 Saved File

CPS: 0 6 uR/hr Temp(K): N/A

Threshold 0 Distance(m) 0.385 +/- Measure Events 1826 Search Pixels Edit ROIs Switch to Polygon ROIs

Show All Energy Windows

Isotope	Energy (keV)
<input checked="" type="checkbox"/> Co-57	122.1
<input checked="" type="checkbox"/> Co-57	136.5
<input checked="" type="checkbox"/> K-40	1460.8
<input checked="" type="checkbox"/> Auto:2609	2609.2

Intervening Materials

Material	Density(g/cc)	Thick(cm)
----------	---------------	-----------

ROI Materials

ROI	Material	Density(g/cc)	Thick(cm)
-----	----------	---------------	-----------

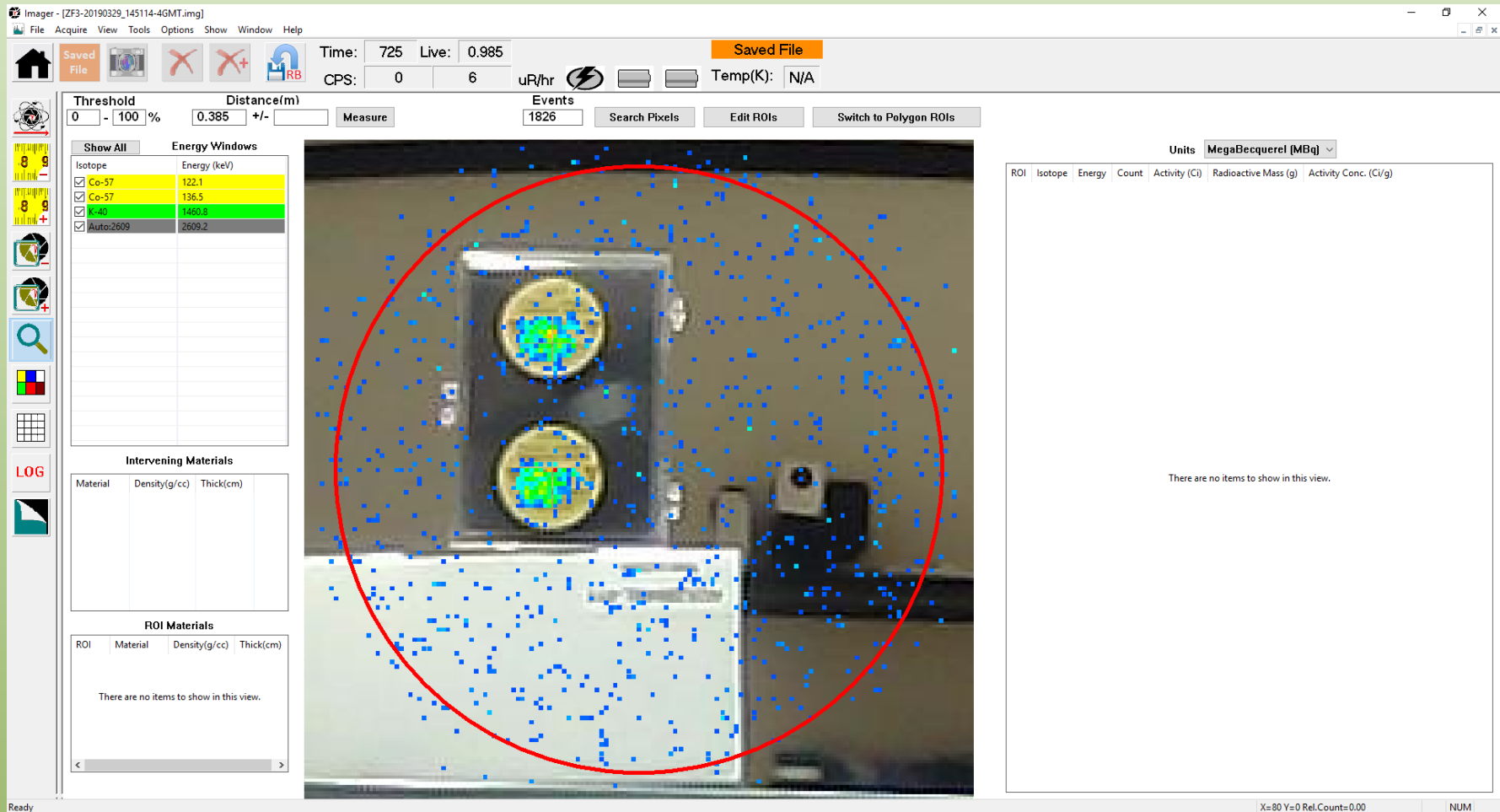
There are no items to show in this view.

Units: MegaBecquerel [MBq]

ROI	Isotope	Energy	Count	Activity (Ci)	Radioactive Mass (g)	Activity Conc. (Ci/g)
-----	---------	--------	-------	---------------	----------------------	-----------------------

There are no items to show in this view.

Ready X=80 Y=0 Rel.Count=0.00 NUM



“zoom”

ZF4

2x ^{57}Co at 38.5 cm

Imager - [ZF4-20190329_150901-4GMT.img]

File Acquire View Tools Options Show Window Help

Time: 906 Live: 0.987 Saved File

CPS: 0 10 uR/hr Temp(K): N/A

Threshold 0 Distance(m) 0.385 +/- Measure Events 2723 Search Pixels Edit ROIs Switch to Polygon ROIs

Units: MegaBecquerel [MBq]

ROI	Isotope	Energy	Count	Activity (Ci)	Radioactive Mass (g)	Activity Conc. (Ci/g)
There are no items to show in this view.						

Energy Windows

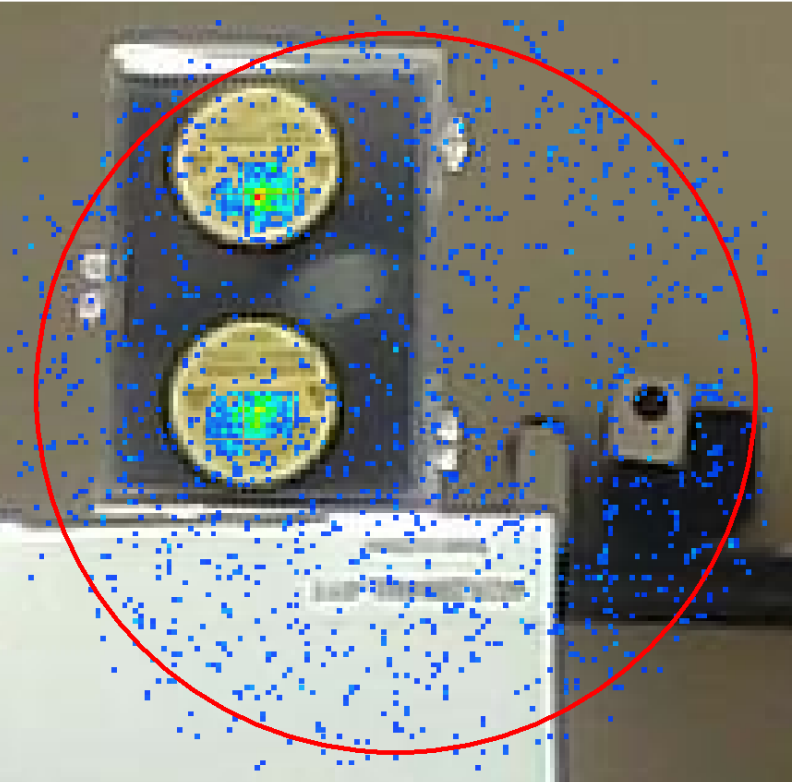
Isotope	Energy (keV)
<input checked="" type="checkbox"/> Co-57	122.1
<input checked="" type="checkbox"/> Co-57	136.5
<input checked="" type="checkbox"/> K-40	1460.8
<input checked="" type="checkbox"/> Bi-214	609.3
<input checked="" type="checkbox"/> Th-232	238.6
<input checked="" type="checkbox"/> Th-232	2614.5

Intervening Materials

Material	Density(g/cc)	Thick(cm)
There are no items to show in this view.		

ROI Materials

ROI	Material	Density(g/cc)	Thick(cm)
There are no items to show in this view.			



Ready X=43 Y=0 Rel.Count=0.00 NUM

“zoom”

ZF5

2x ^{57}Co at 38.5 cm

Imager - [ZF5-20190329_152442-4GMT.img]

File Acquire View Tools Options Show Window Help

Time: 822 Live: 0.986 Saved File

CPS: 0 10 uR/hr Temp(K): N/A

Threshold: 0 Distance(m): 0.385 +/- Measure Events: 2409 Search Pixels Edit ROIs Switch to Polygon ROIs

Units: MegaBecquerel [MBq]

ROI	Isotope	Energy	Count	Activity (Ci)	Radioactive Mass (g)	Activity Conc. (Ci/g)
There are no items to show in this view.						

Energy Windows

Isotope	Energy (keV)
<input checked="" type="checkbox"/> Co-57	122.1
<input checked="" type="checkbox"/> Co-57	136.5
<input checked="" type="checkbox"/> K-40	1460.8
<input checked="" type="checkbox"/> Bi-214	609.3
<input checked="" type="checkbox"/> Th-232	238.6
<input checked="" type="checkbox"/> Th-232	2614.5

Intervening Materials

Material	Density(g/cc)	Thick(cm)
There are no items to show in this view.		

ROI Materials

ROI	Material	Density(g/cc)	Thick(cm)
There are no items to show in this view.			

Ready X=32 Y=2 Rel.Count=0.00 NUM

“zoom”

ZF6

2x ^{57}Co at 38.5 cm

Imager - [ZF6-20190329_154132-4GMT.img]

File Acquire View Tools Options Show Window Help

Time: 949 Live: 1.000 Saved File

CPS: 0 10 uR/hr Temp(K): N/A

Threshold 0 - 100% Distance(m) 0.385 +/- Measure Events 3883 Search Pixels Edit ROIs Switch to Polygon ROIs

Units: MegaBecquerel [MBq]

ROI	Isotope	Energy	Count	Activity (Ci)	Radioactive Mass (g)	Activity Conc. (Ci/g)
There are no items to show in this view.						

Energy Windows

Isotope	Energy (keV)
<input checked="" type="checkbox"/> Co-57	122.1
<input checked="" type="checkbox"/> Co-57	136.5
<input checked="" type="checkbox"/> K-40	1460.8
<input checked="" type="checkbox"/> Bi-214	609.3
<input checked="" type="checkbox"/> Th-232	238.6
<input checked="" type="checkbox"/> Th-232	2614.5
<input checked="" type="checkbox"/> Auto:117	116.7
<input checked="" type="checkbox"/> Auto:351	351.0

Intervening Materials

Material	Density(g/cc)	Thick(cm)
----------	---------------	-----------

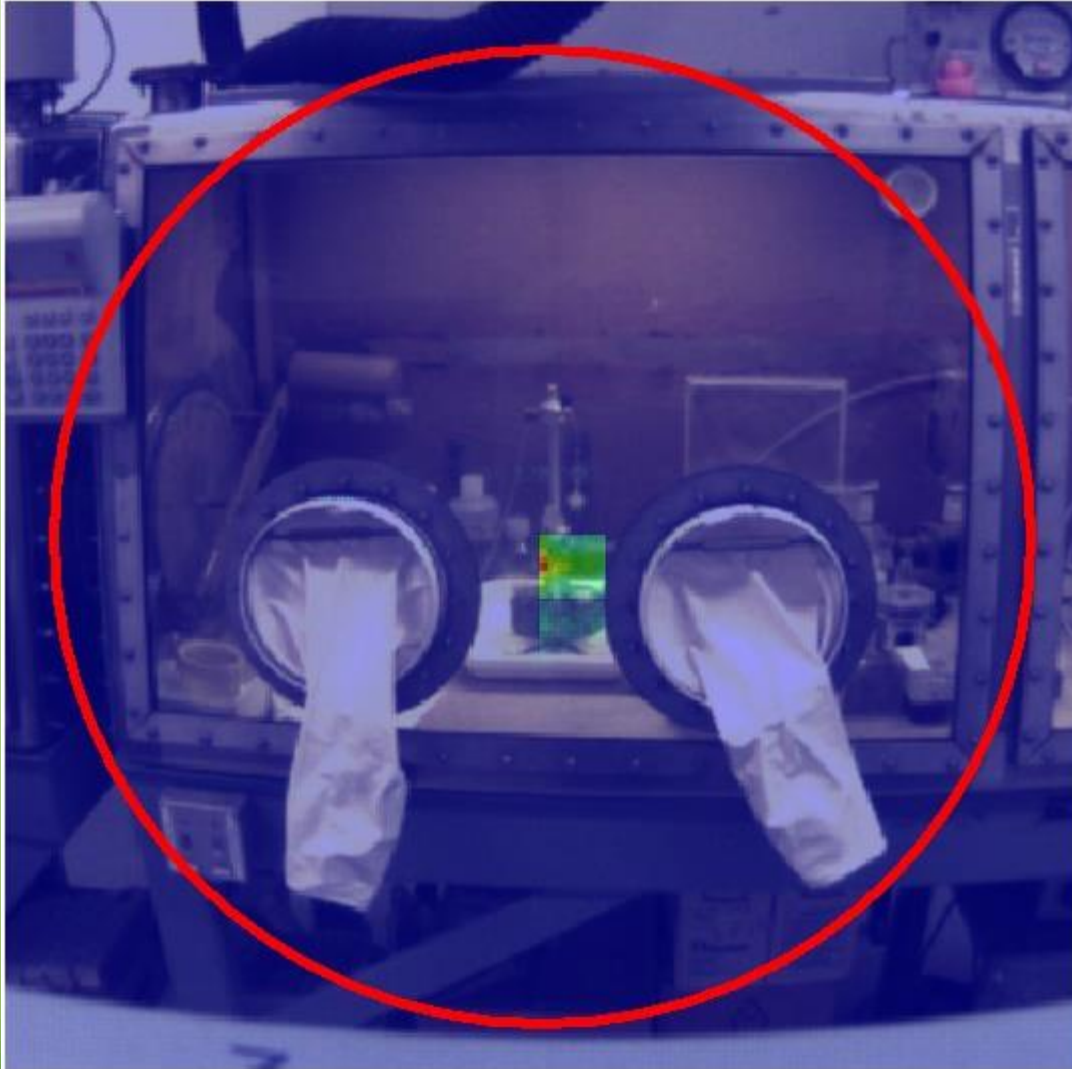
ROI Materials

ROI	Material	Density(g/cc)	Thick(cm)
-----	----------	---------------	-----------

There are no items to show in this view.

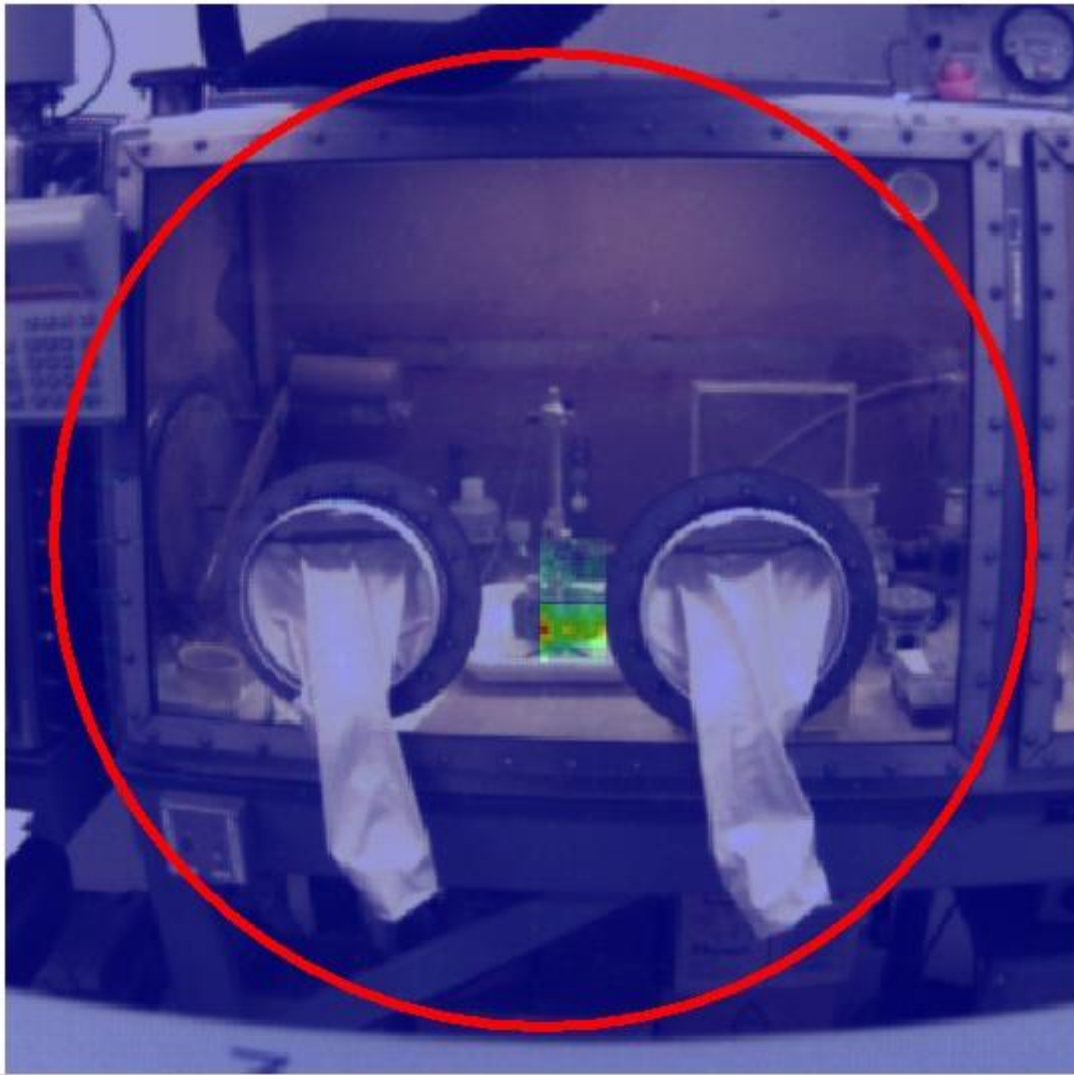
Ready NUM

40 keV ^{225}Ra



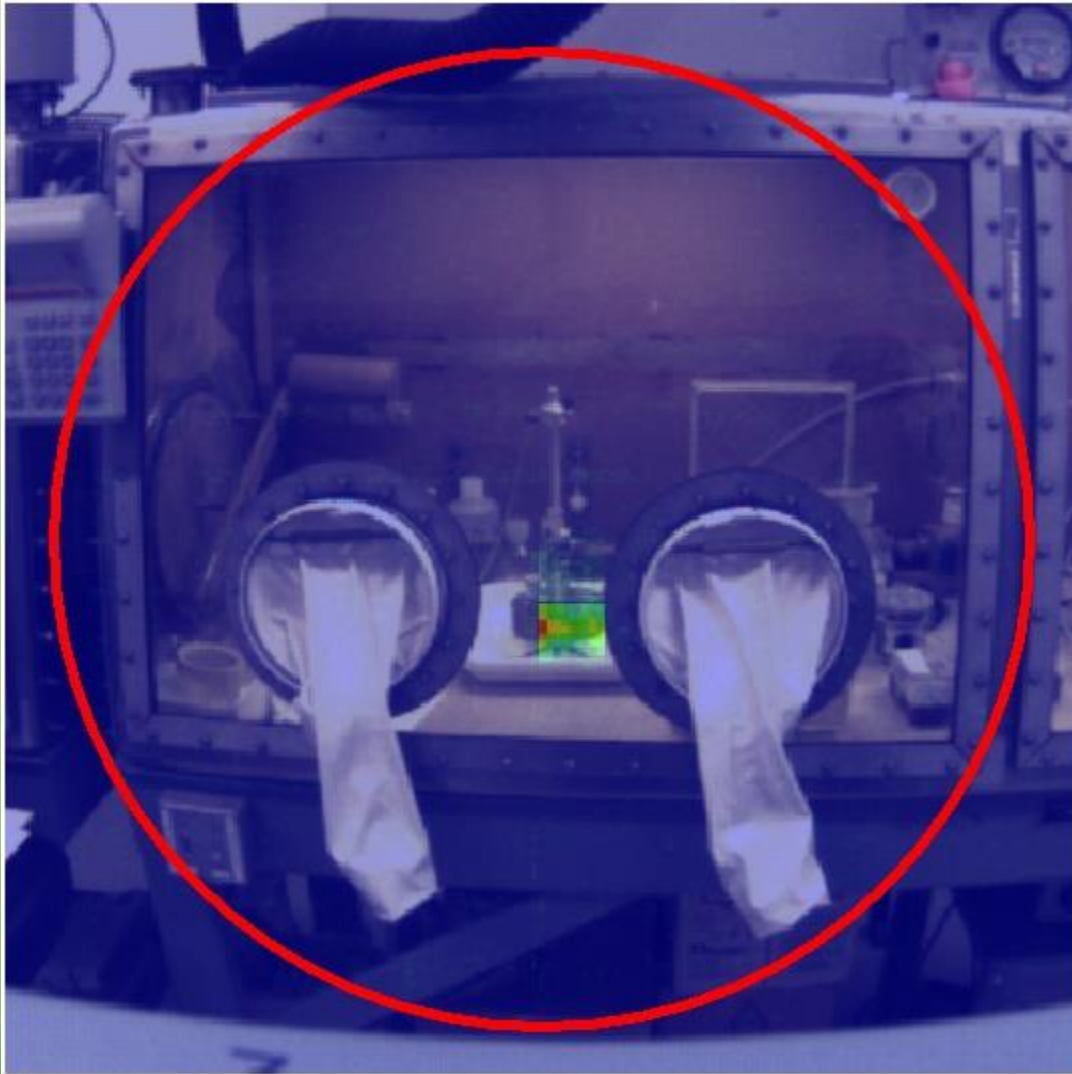
5 min

40 keV ^{225}Ra



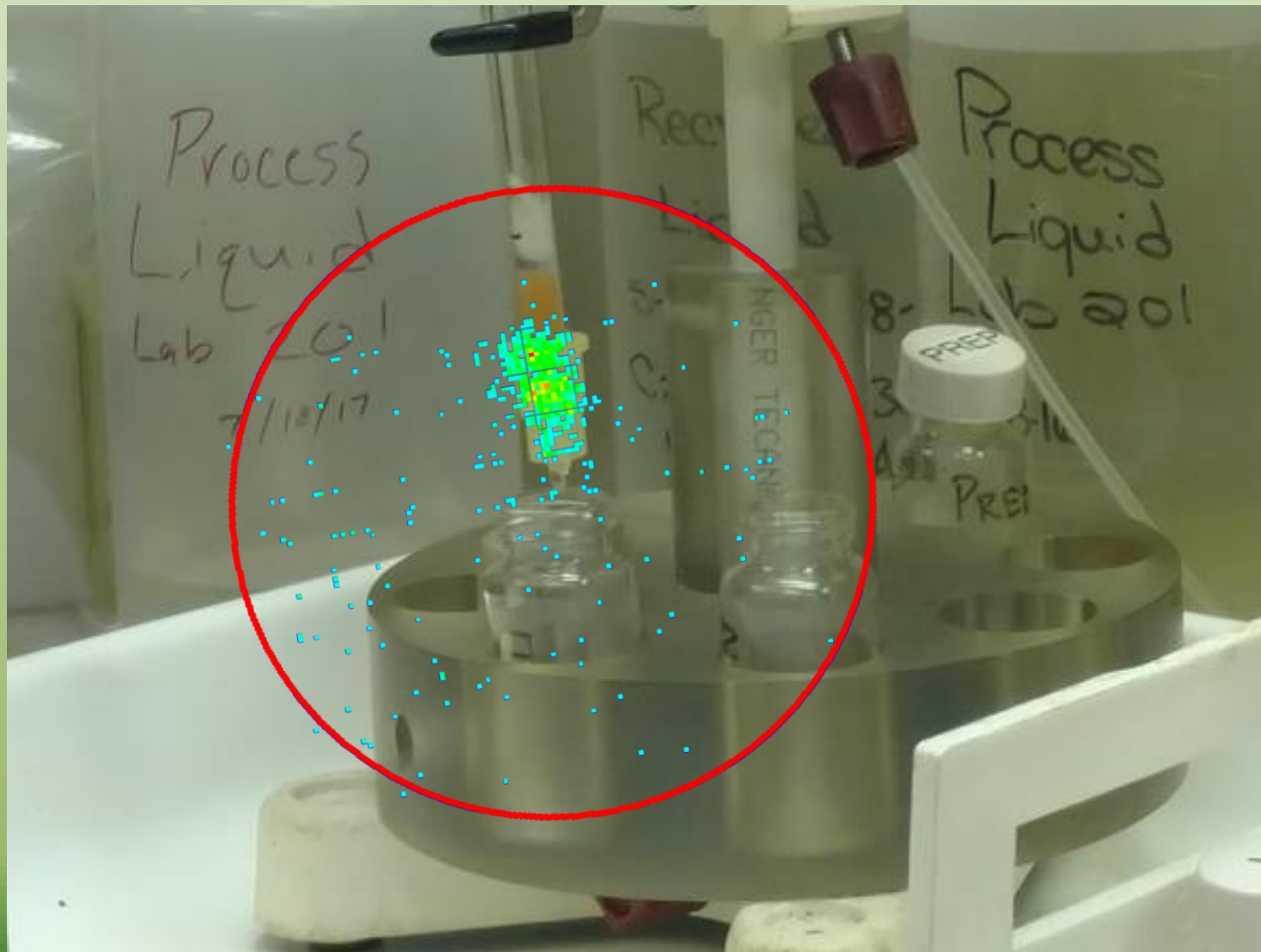
10 min

40 keV ^{225}Ra



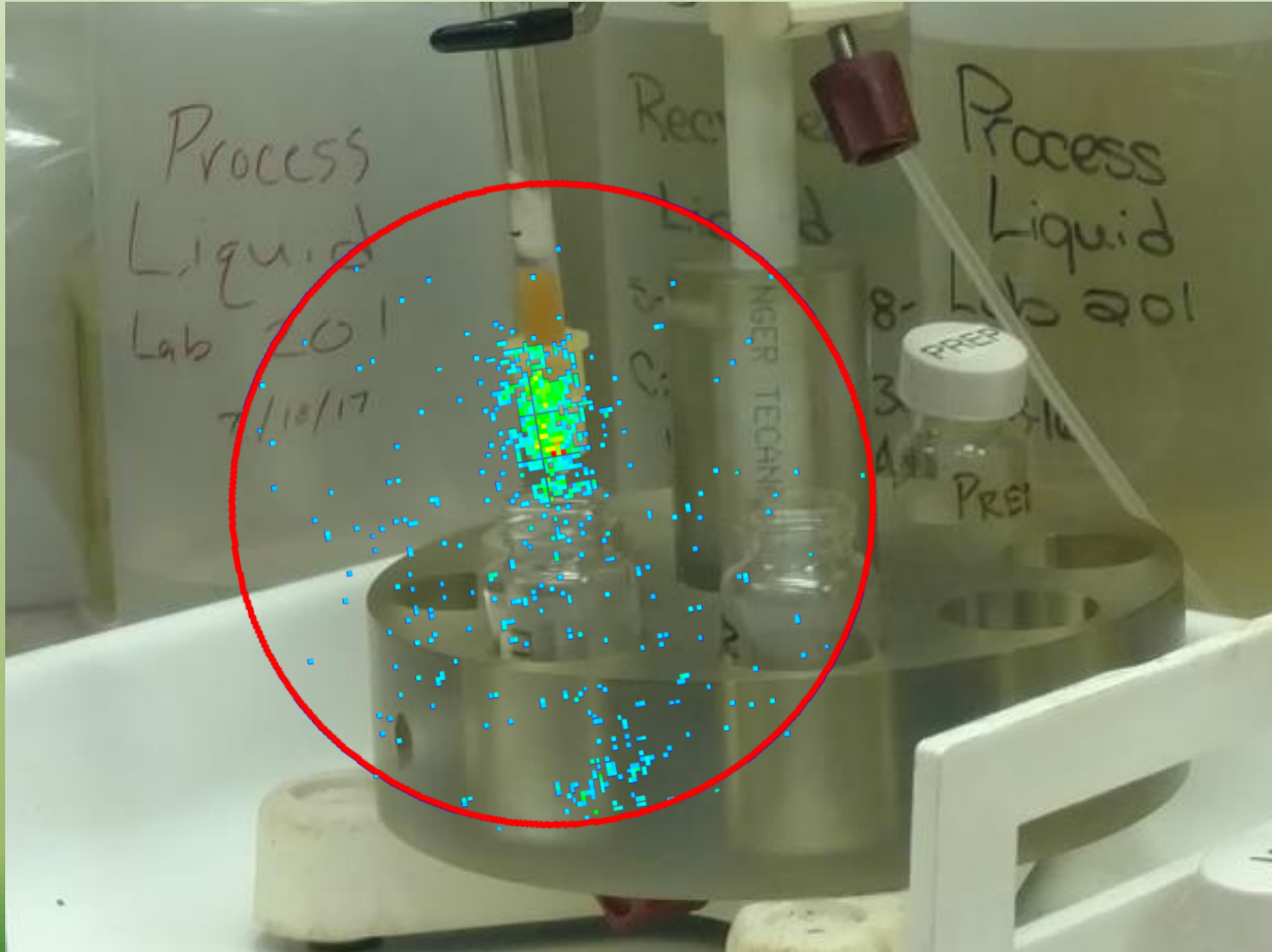
15 min

^{225}Ra Wash (0 min)



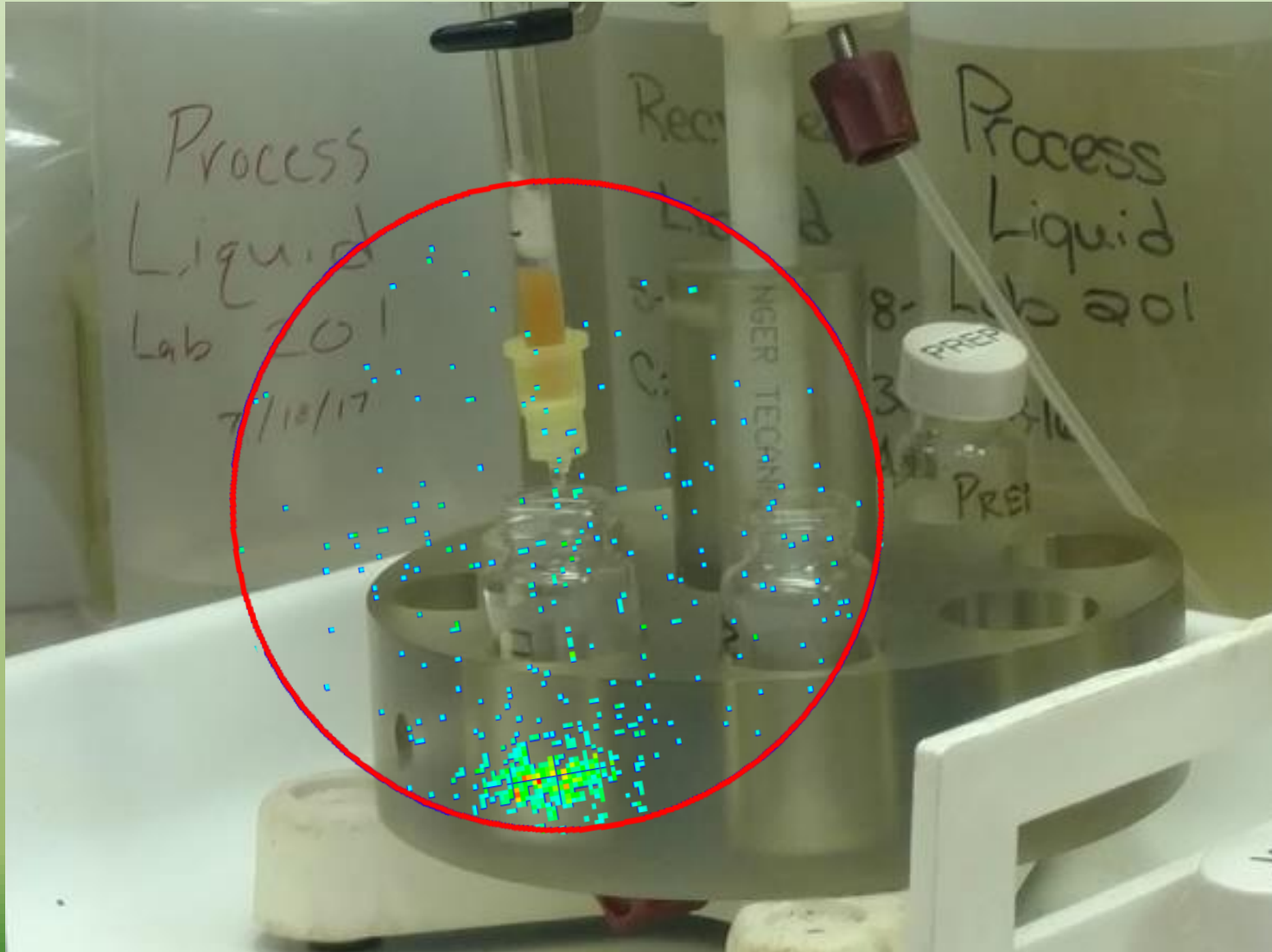
8x
Larger
than
before

^{225}Ra Wash (5 min)



8x
Larger
than
before

^{225}Ra Wash (10 min)



8x
Larger
than
before

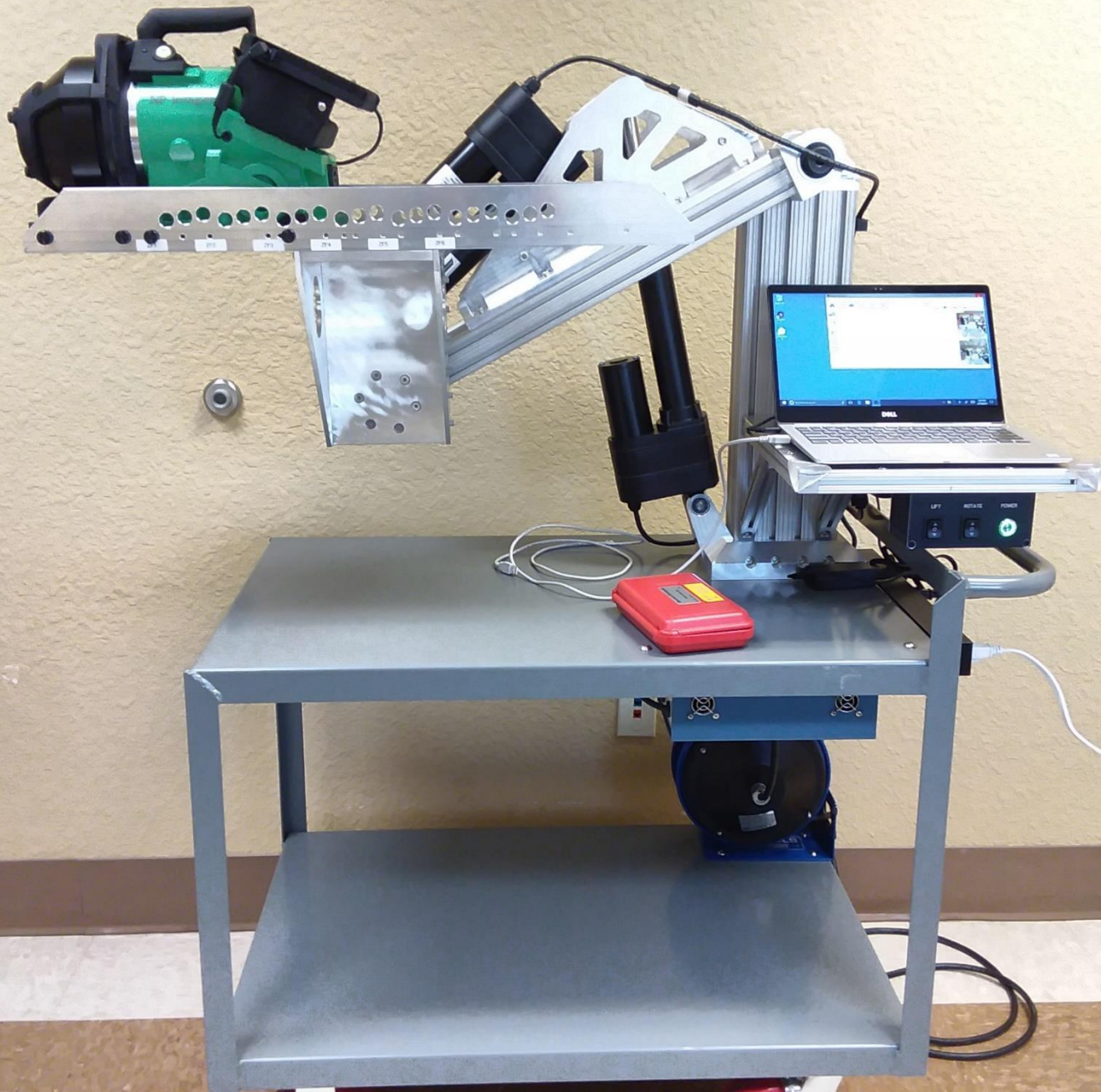
^{225}Ra Wash (15 min)

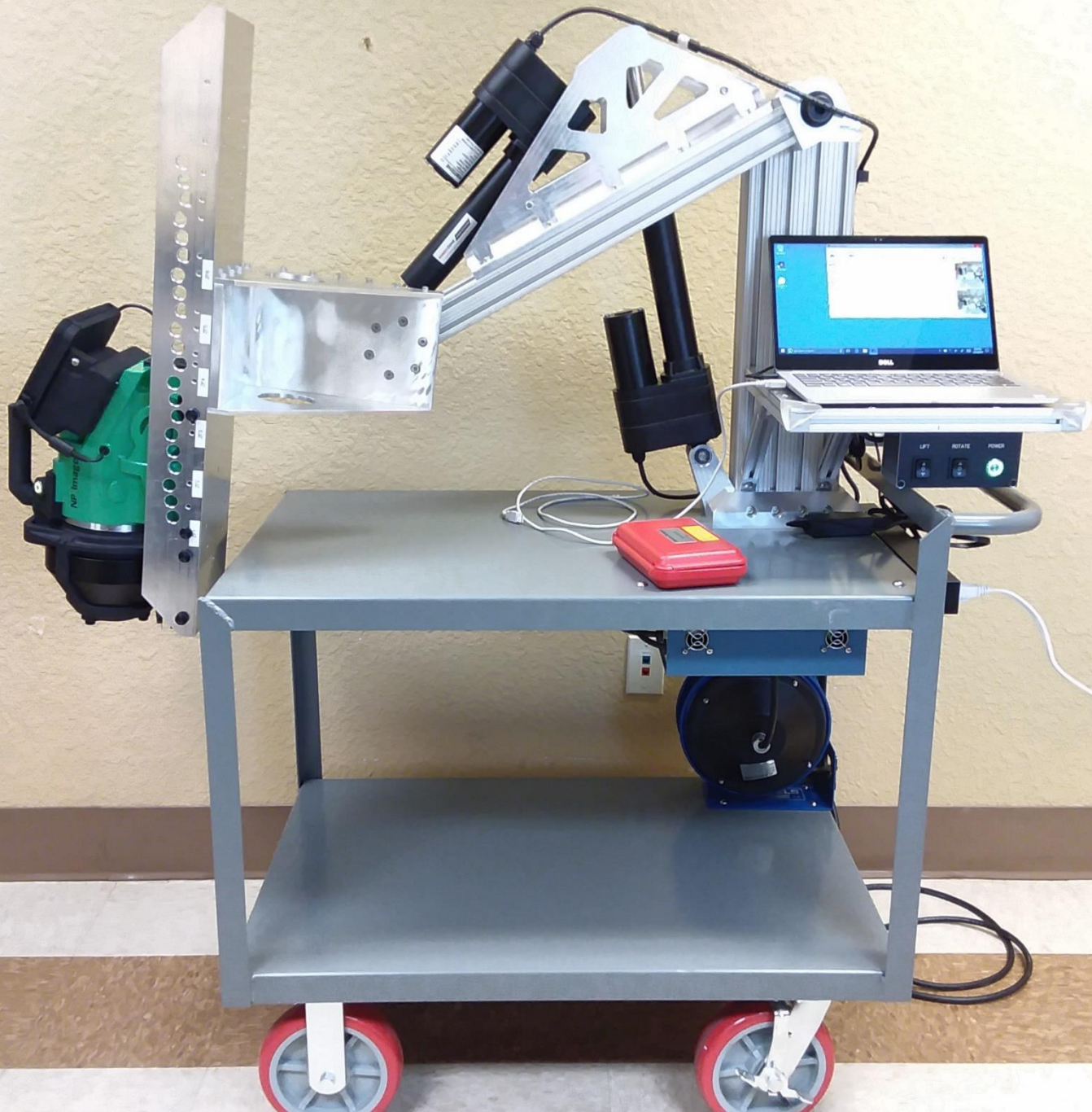


8x
Larger
than
before

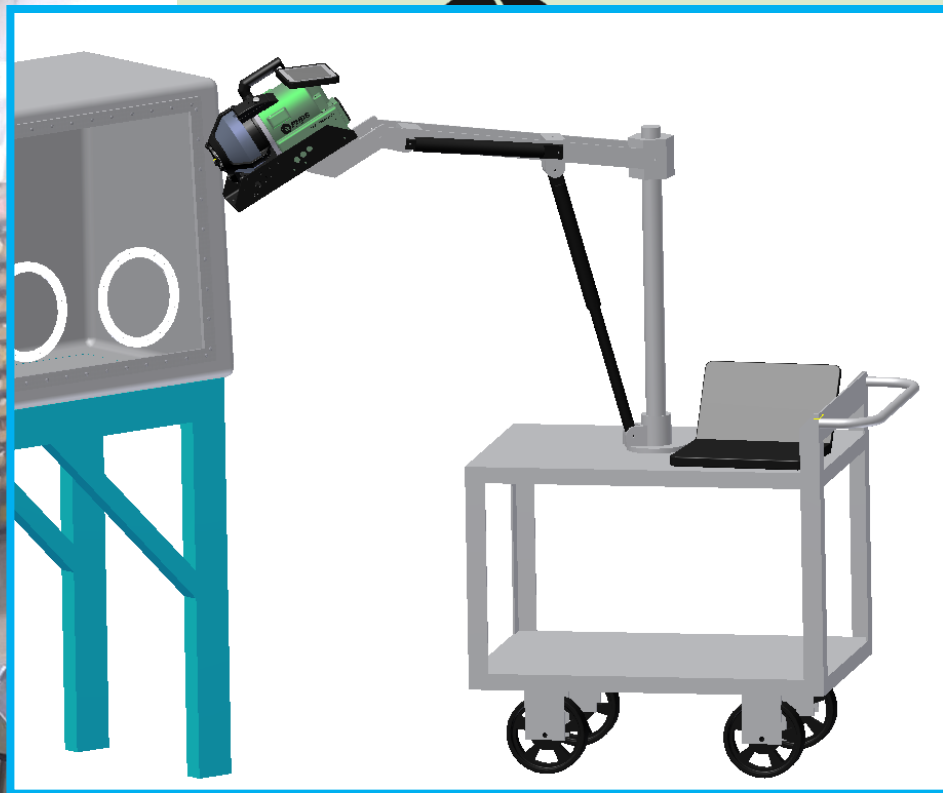










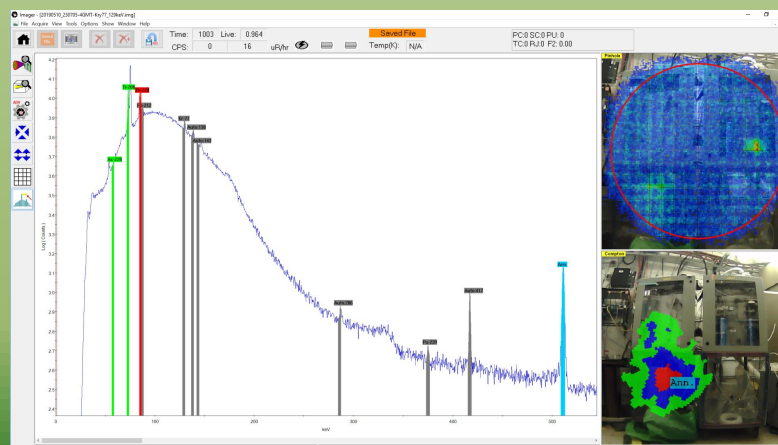
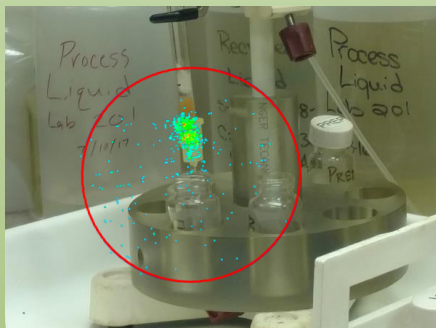






PHDS
Gamma Ray Imaging Detectors

Radiochemistry Imaging Examples

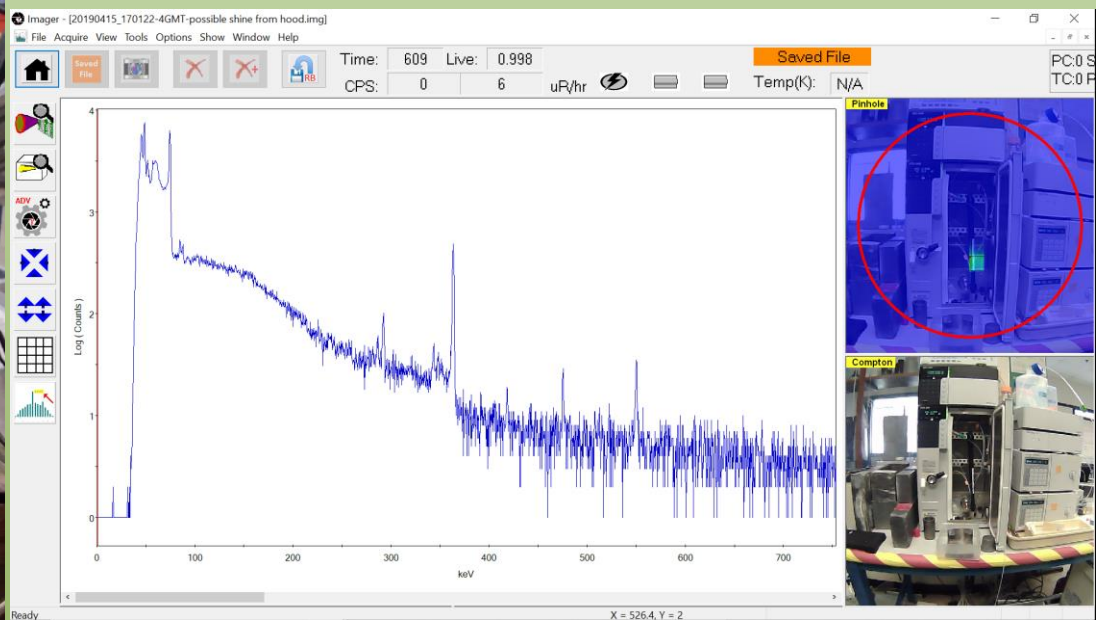




PHDS

Gamma Ray Imaging Detectors

- HPLC separation of ^{159}Gd and ^{161}Tb (High pressure liquid chromatography)

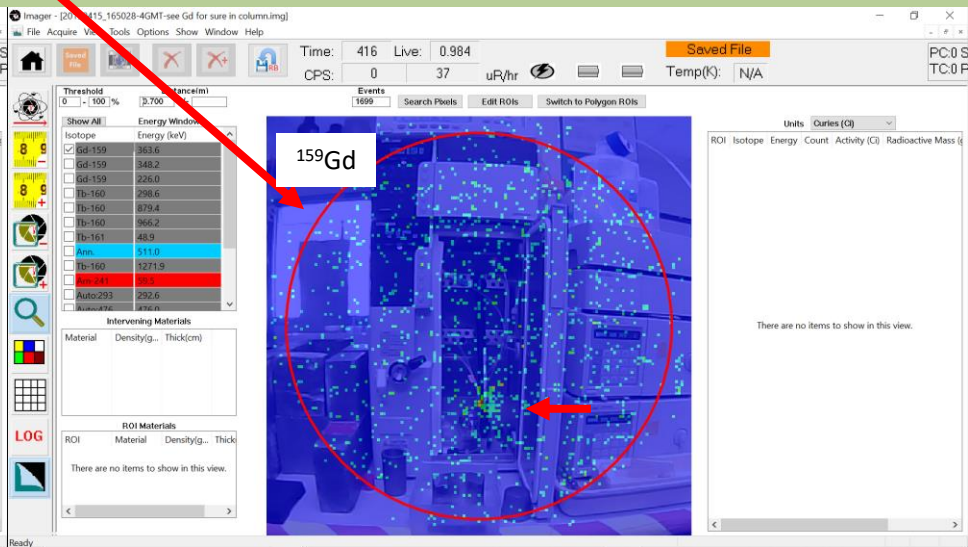
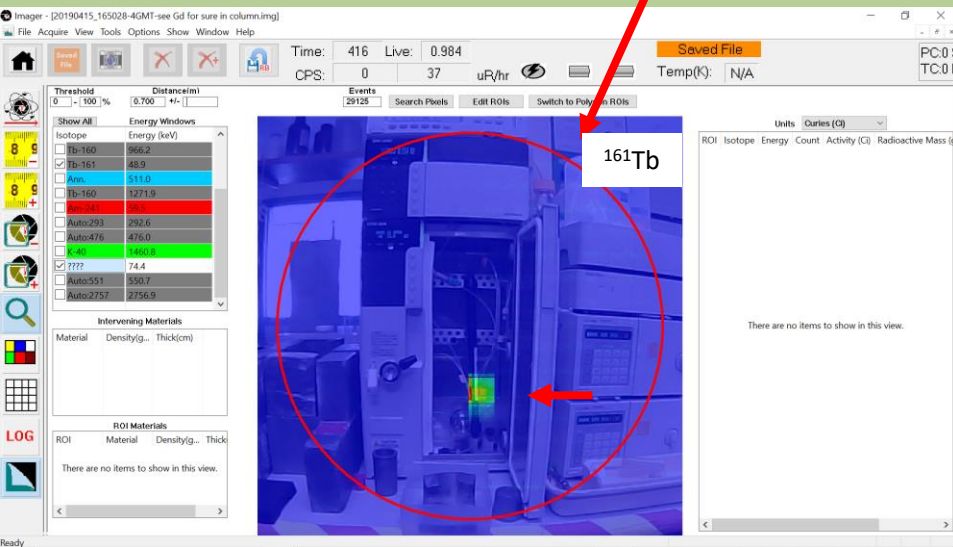
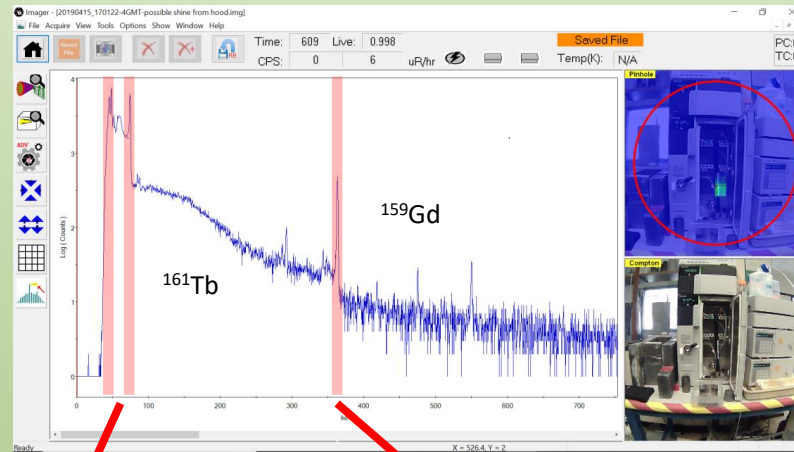


49 keV

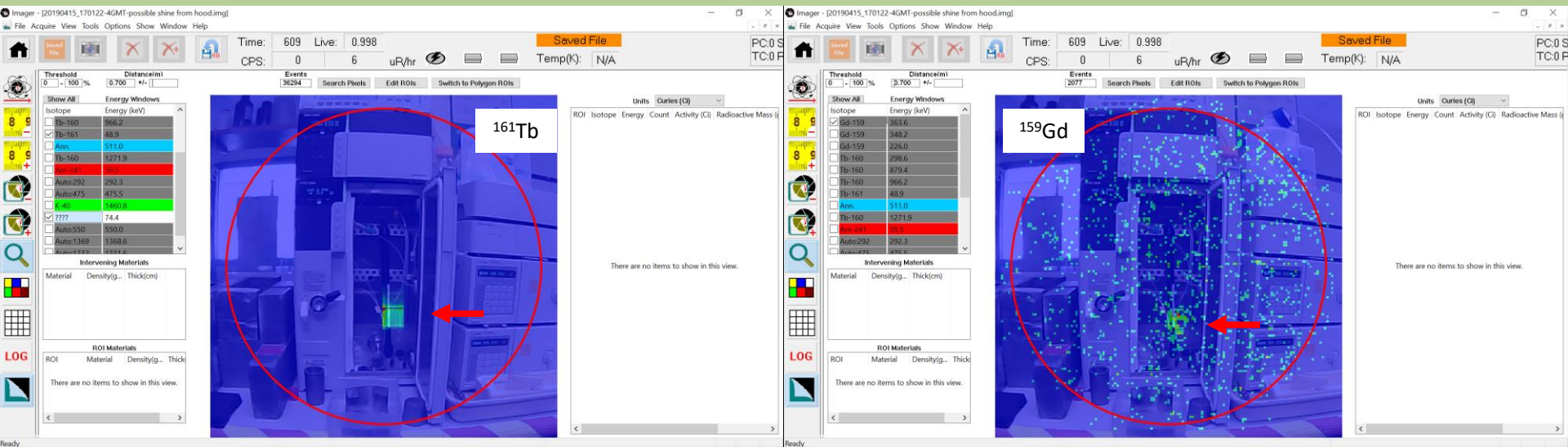
74 keV

363 keV

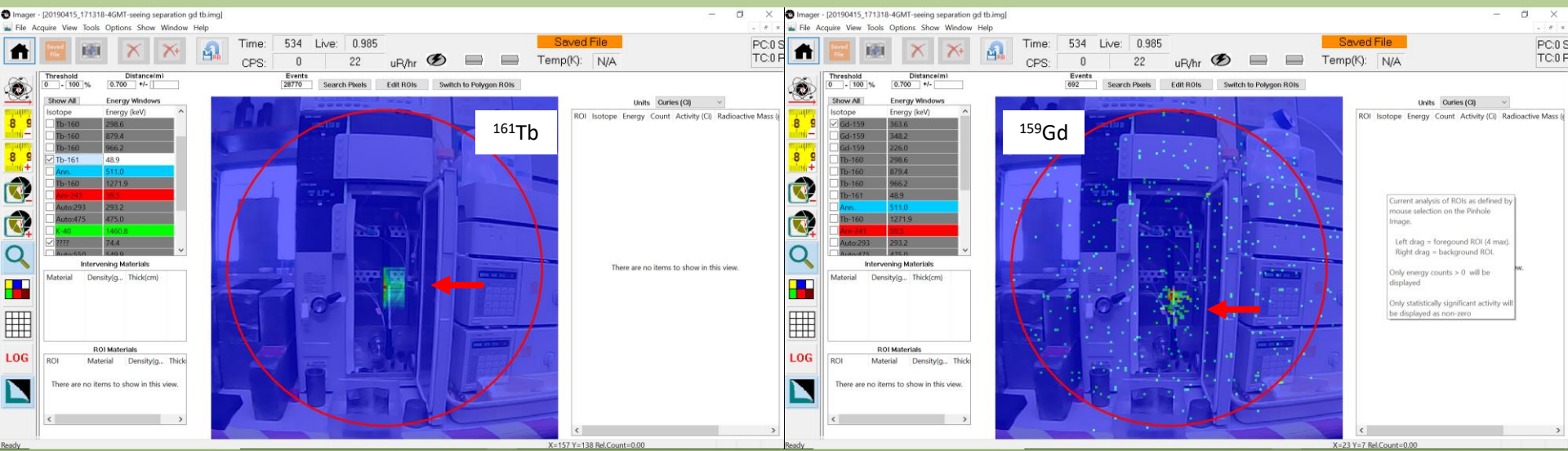
7 min



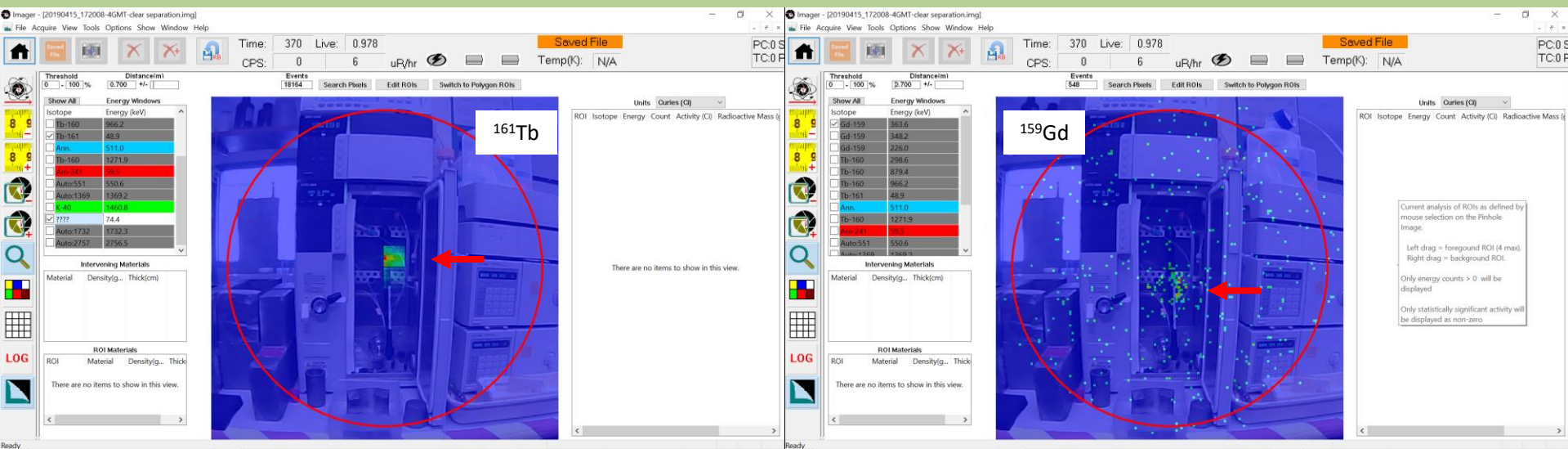
18 min



30 min



37 min



The image displays two side-by-side screenshots of the PHDS software interface, showing the results of a gamma ray imaging experiment. Both screenshots show a 3D visualization of a detector setup with a red circle highlighting a specific region of interest (ROI) and a red arrow pointing to it.

Left Screenshot (161Tb):

- Isotope List:**

Isotope	Energy (keV)
Tb-160	966.2
Tb-161	48.9
Am	511.0
Tb-160	1271.9
Auto141	96.0
Auto551	550.6
Auto1369	1369.2
K-40	1460.8
???	74.4
Auto1732	1732.3
Auto2757	2756.5
- ROI List:**

ROI	Material	Density(g./cm)	Thick
There are no items to show in this view.			

Right Screenshot (159Gd):

- Isotope List:**

Isotope	Energy (keV)
Gd-159	363.6
Gd-159	348.2
Gd-159	226.0
Tb-160	298.6
Tb-160	879.4
Tb-160	966.2
Tb-161	48.9
Am	511.0
Tb-160	1271.9
Auto141	96.0
Auto551	550.6
Auto1369	1369.2
- ROI List:**

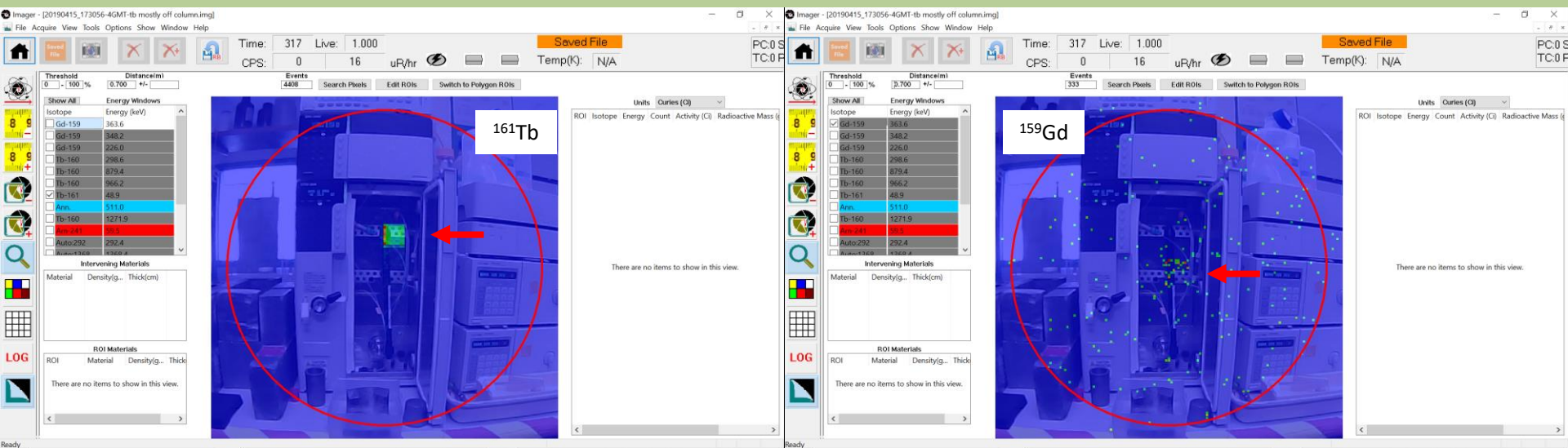
ROI	Material	Density(g./cm)	Thick
There are no items to show in this view.			

Right Screenshot Text Box:

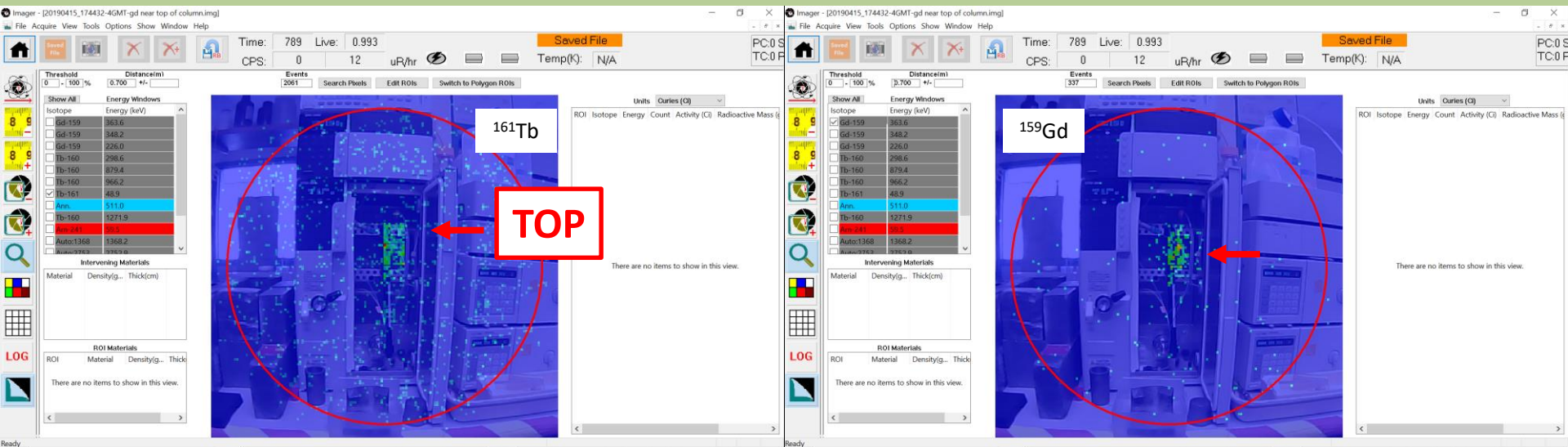
Current analysis of ROIs as defined by mouse selection on the Pinhole Image.

- Left drag = foreground ROI (4 max).
- Right drag = background ROI.
- Only energy counts > 0 will be displayed.
- Only statistically significant activity will be displayed as non-zero.

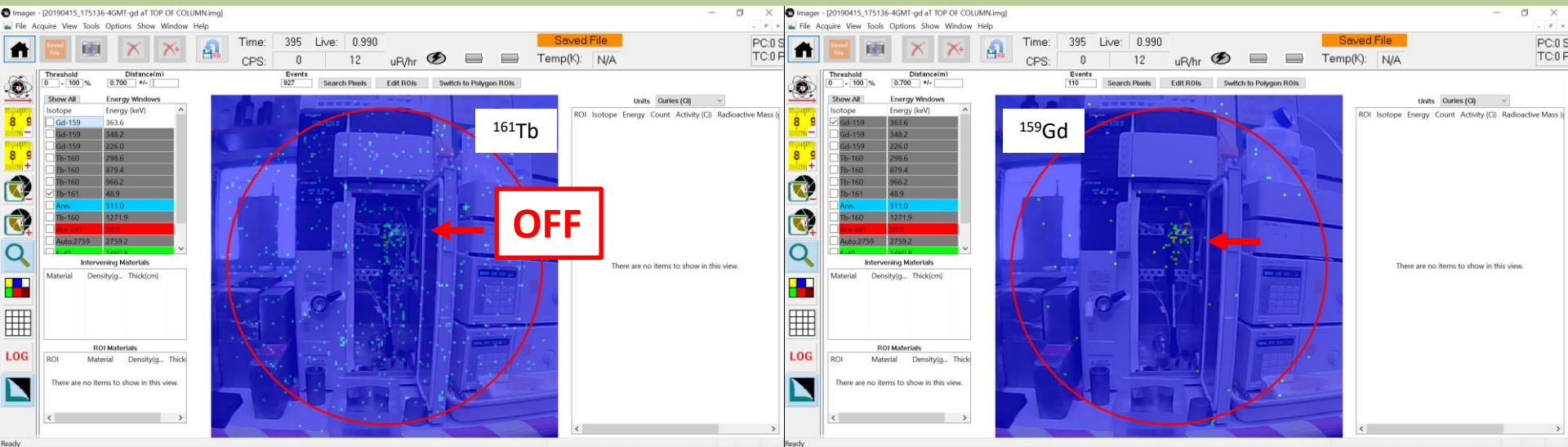
47 min



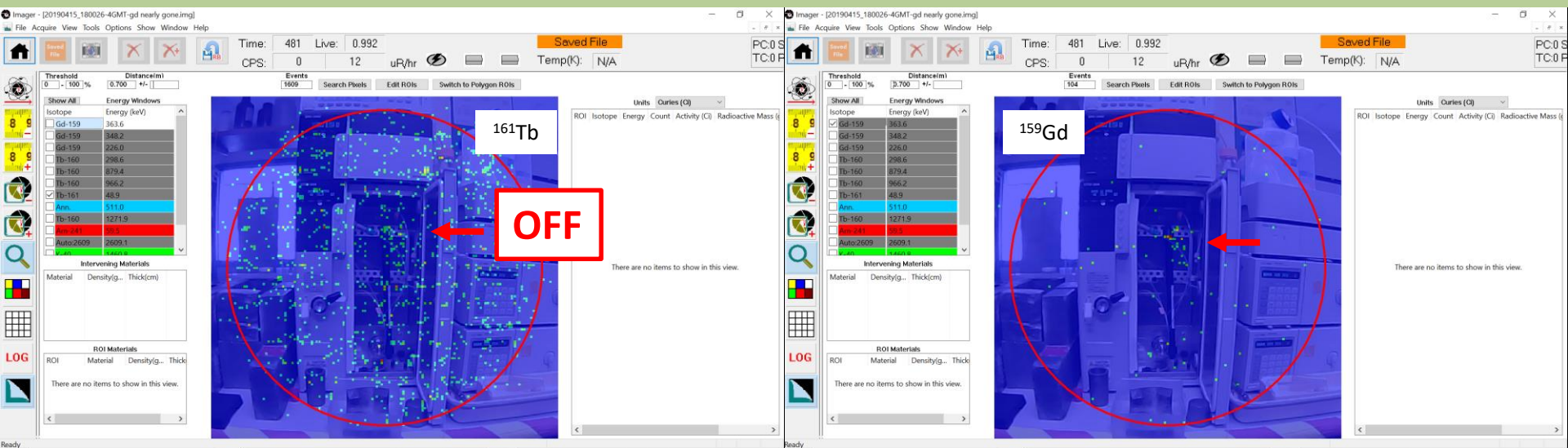
61 min



68 min

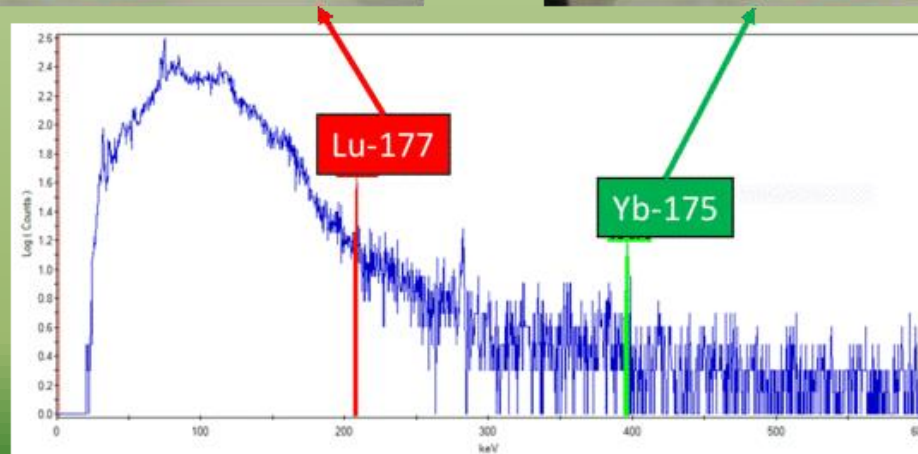


77 min



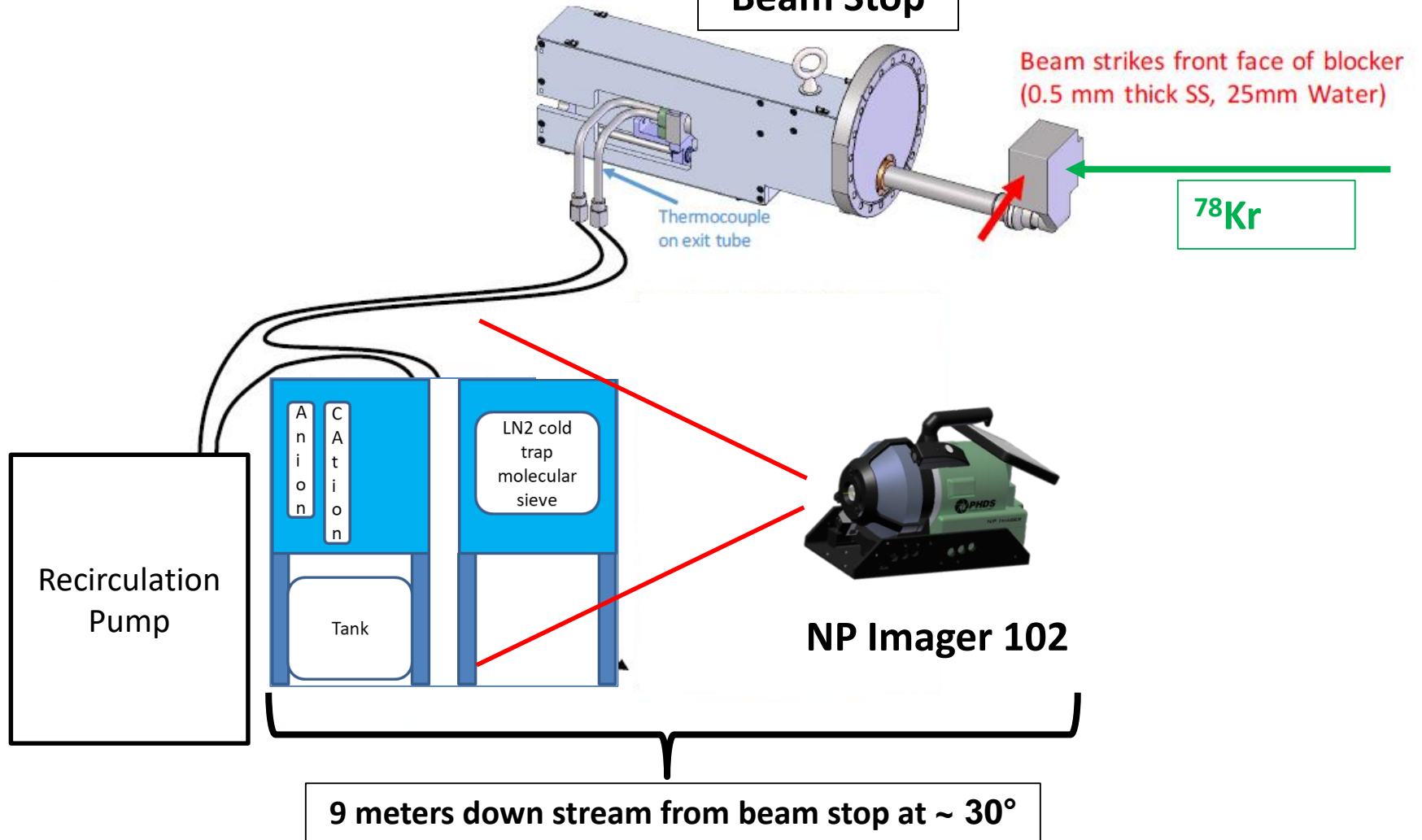
$^{177}\text{Lu}/^{175}\text{Yb}$ Column Separation

t = 0 - 10 minutes



May 10, 2019

Beam Stop



View from NP Imager

Distance = 1.7 meters



Imager - [20190510_230705-4GMT-Kry77_129keV.img]

File Acquire View Tools Options Show Window Help

Time: 1003 Live: 0.964 Saved File PC:0 SC:0 PU: 0
CPS: 0 16 uR/hr Temp(K): N/A TC:0 RJ:0 F2: 0.00

Threshold 0 - 100 % Distance(m) 1.700 +/-

Events 4164 Search Pixels Edit ROIs Switch to Polygon ROIs

Show All Energy Windows

Isotope	Energy (keV)
<input type="checkbox"/> Th-232	57.8
<input type="checkbox"/> Th-232	72.8
<input type="checkbox"/> Auto:87	87.3
<input type="checkbox"/> Ann.	511.0
<input type="checkbox"/> U-232	129.1
<input type="checkbox"/> U-232	85.4
<input type="checkbox"/> Auto:138	137.8
<input type="checkbox"/> NEU:847	845.9
<input type="checkbox"/> Auto:143	143.3
<input type="checkbox"/> Auto:286	286.0
<input type="checkbox"/> Auto:375	375.1
<input type="checkbox"/> Auto:417	417.1
<input type="checkbox"/> Auto:635	635.1
<input type="checkbox"/> Th-232	911.2
<input type="checkbox"/> Auto:820	819.7
<input type="checkbox"/> Auto:900	900.4
<input type="checkbox"/> Th-232	1501.6
<input type="checkbox"/> Auto:1041	1041.1
<input type="checkbox"/> Auto:1098	1097.7
<input type="checkbox"/> Auto:1294	1294.4

Intervening Materials

Material	Density(g... Thick(cm)
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ROI Materials

ROI	Material	Density(g... Thick
-----	----------	--------------------

There are no items to show in this view.

Units Curies (Ci)

ROI	Isotope	Energy	Count	Activity (Ci)	Radioactive Mass (g)	Activity Conc. (Ci/g)
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There are no items to show in this view.

NP Imager 102



20190510 1925 78Kr BOT – 2-4 particle nA – 20% dead time 20 kcps
Nothing imaged with BOT – too much background, same cave as the beam stop.

Imager - [20190510_223235-4GMT-4pNAto2pNA.img]

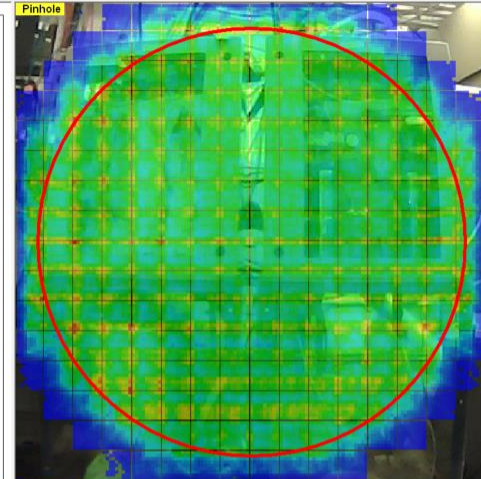
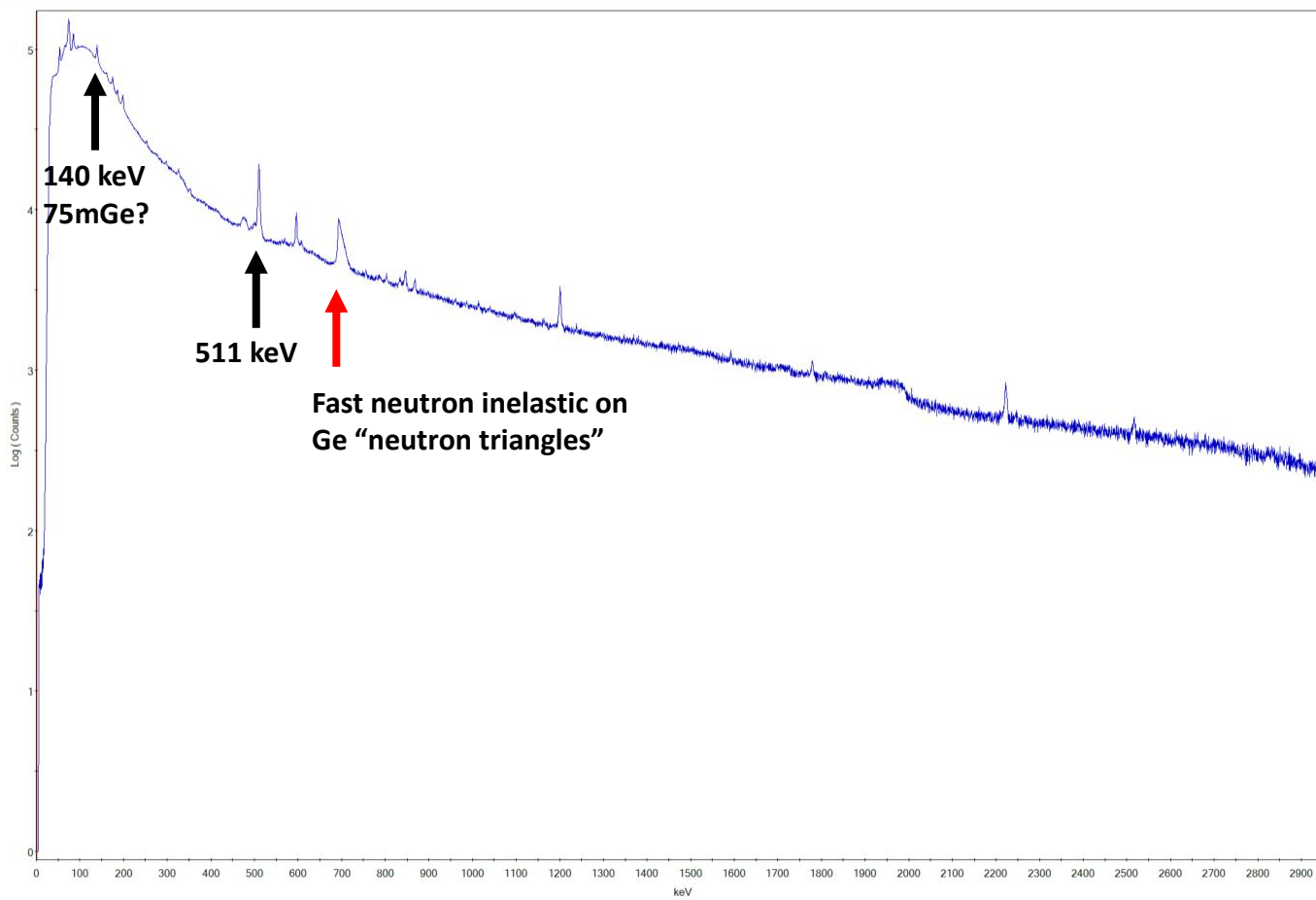
File Acquire View Tools Options Show Window Help

Time: 2480 Live: 0.801

Saved File

PC:0 SC:0 PU: 0
TC:0 RJ:0 F2: 0.00

CPS: 0 9 uR/hr Temp(K): 1.2



Ready

20190510 2307 Beam off – look at column array – see 77Kr (129 keV) and 511s

Imager - [20190510_230705-4GMT-Kry77_129keV.img]

File Acquire View Tools Options Show Window Help

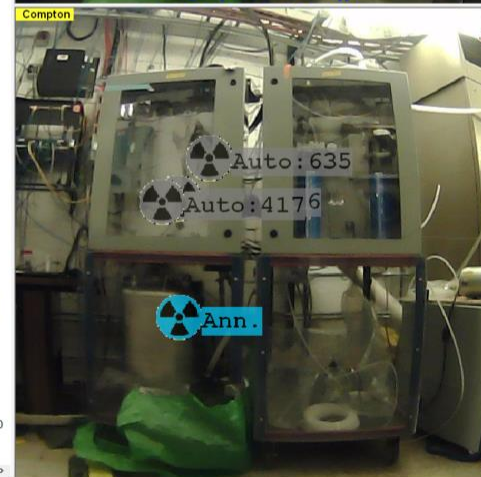
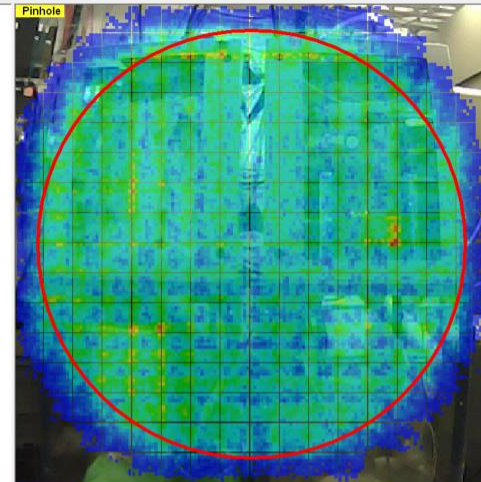
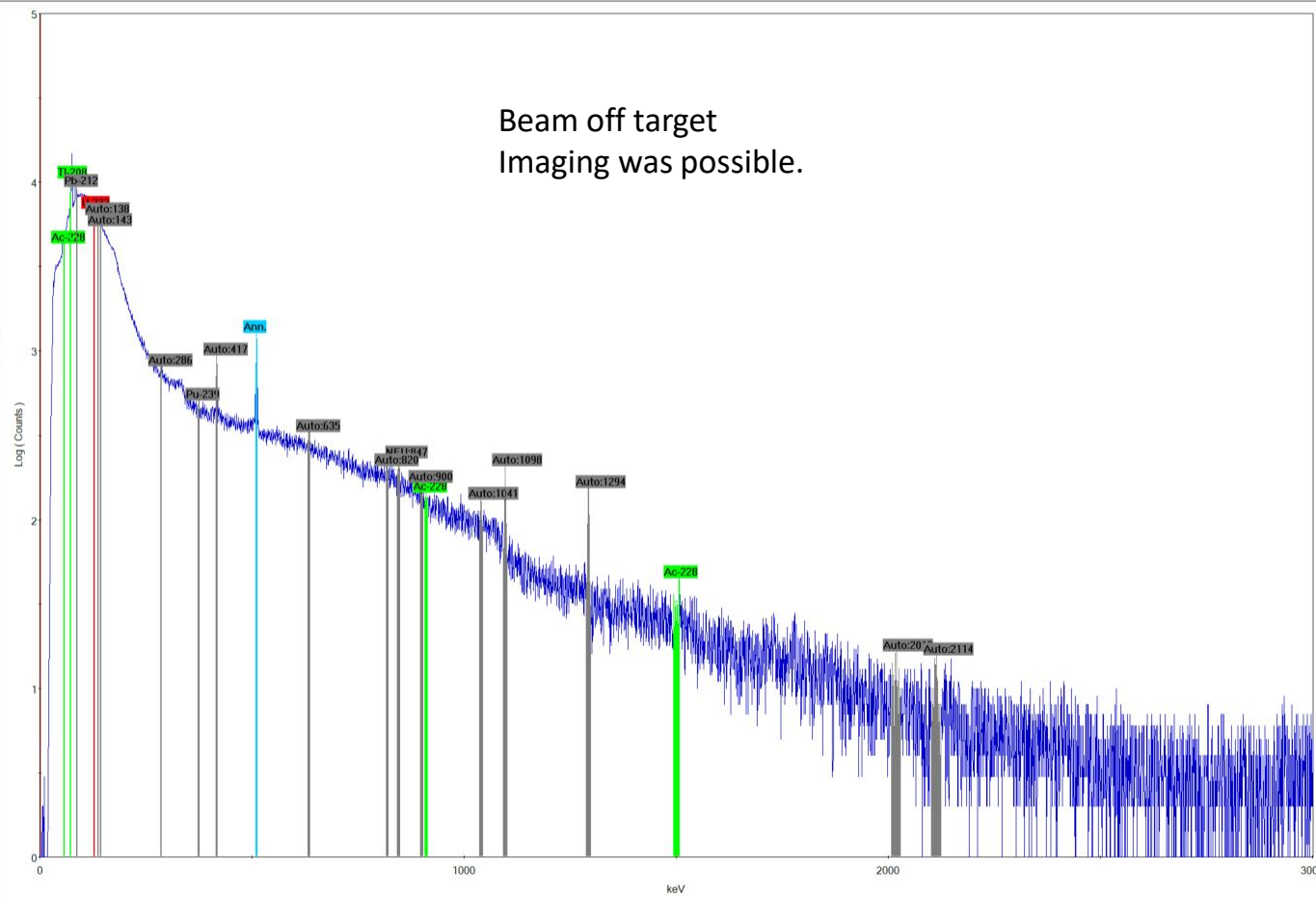


Time: 1003 Live: 0.964

Saved File

PC:0 SC:0 PU:0
TC:0 RJ:0 F2: 0.00

CPS: 0 16 uR/hr Temp(K): N/A



Ready

Imager - [20190510_230705-4GMT-Kry77_129keV.img]

File Acquire View Tools Options Show Window Help

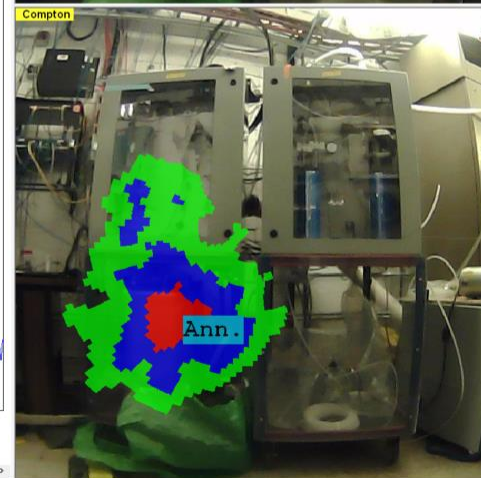
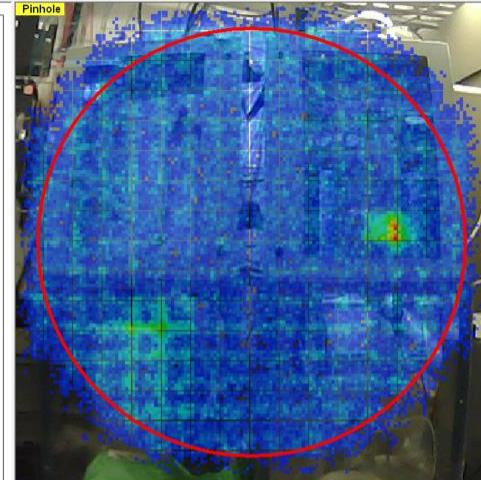
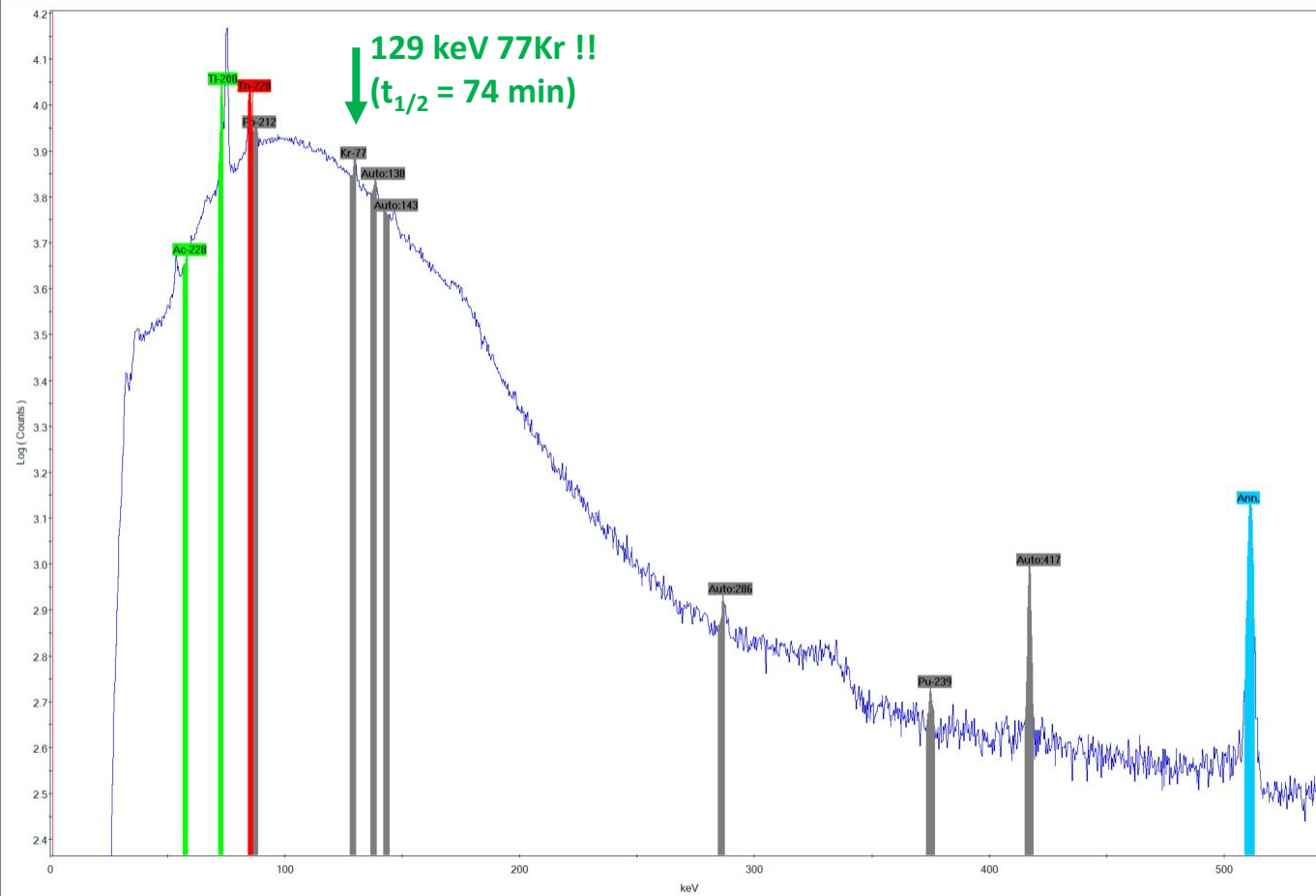


Time: 1003 Live: 0.964

Saved File

PC:0 SC:0 PU:0
TC:0 RJ:0 F2:0.00

CPS: 0 16 uR/hr Temp(K): N/A



Ready

Imager - [20190510_230705-4GMT-Kry77_129keV.img]

File Acquire View Tools Options Show Window Help

Time: 1003 Live: 0.964

Saved File

PC:0 SC:0 PU: 0
TC:0 RJ:0 F2: 0.00

CPS: 0 16 uR/hr

Temp(K): N/A

Threshold 0 - 100 % Distance(m) 1.700 +/-

Events

48080

Search Pixels

Edit ROIs

Switch to Polygon ROIs

Show All Energy Windows

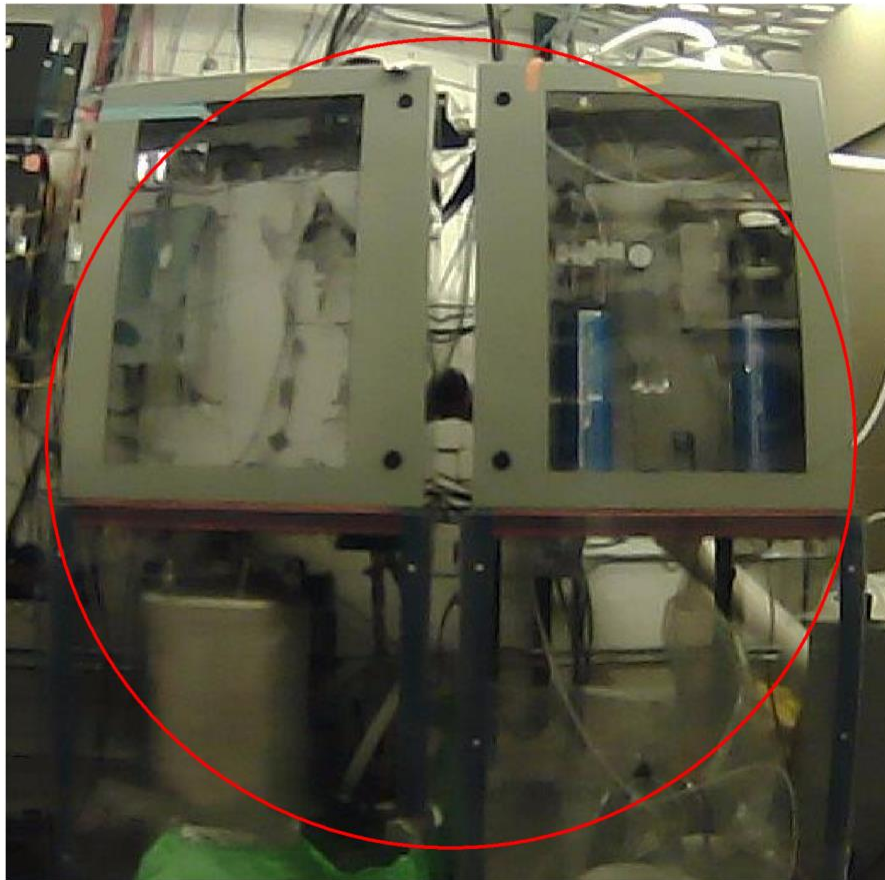
Isotope	Energy (keV)
<input type="checkbox"/> Th-232	57.8
<input type="checkbox"/> Th-232	72.8
<input type="checkbox"/> Auto:87	87.3
<input type="checkbox"/> Ann.	511.0
<input checked="" type="checkbox"/> U-232	129.1
<input checked="" type="checkbox"/> U-232	35.4
<input type="checkbox"/> Auto:138	137.8
<input type="checkbox"/> NEU:847	845.9
<input type="checkbox"/> Auto:143	143.3
<input type="checkbox"/> Auto:286	286.0
<input type="checkbox"/> Auto:375	375.1
<input type="checkbox"/> Auto:417	417.1
<input type="checkbox"/> Auto:635	635.1
<input type="checkbox"/> Th-232	911.2
<input type="checkbox"/> Auto:820	819.7
<input type="checkbox"/> Auto:900	900.4
<input type="checkbox"/> Th-232	1501.6
<input type="checkbox"/> Auto:1041	1041.1
<input type="checkbox"/> Auto:1098	1097.7
<input type="checkbox"/> Auto:1294	1294.4

Intervening Materials

Material	Density(g... Thick(cm)
There are no items to show in this view.	

ROI Materials

ROI	Material	Density(g... Thick
There are no items to show in this view.		



Units Curies (Ci)

ROI Isotope Energy Count Activity (Ci) Radioactive Mass (g) Activity Conc. (Ci/g)

There are no items to show in this view.

Time: 1003 Live: 0.964

Saved File

PC:0 SC:0 PU:0
TC:0 RJ:0 F2:0.00

CPS: 0 16

uR/hr

Temp(K): N/A

Threshold 0 - 100 % Distance(m) 1.700 +/- 0.000

Events 46747

Search Pixels

Edit ROIs

Switch to Polygon ROIs

Show All Energy Windows

Isotope Energy (keV)

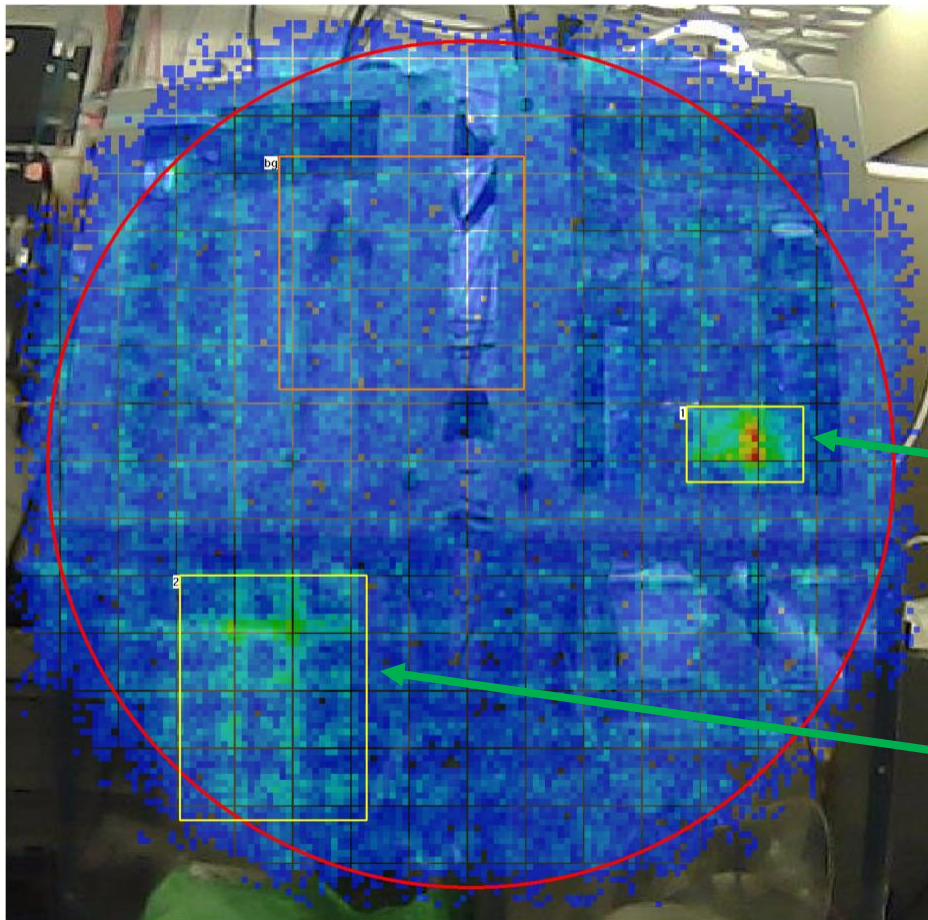
- Th-232 57.8
- Th-232 72.8
- Auto:87 87.3
- Amm 511.0
- Kr-77 129.1
- U-232 85.4
- Auto:138 137.8
- NEU:847 845.9
- Auto:143 143.3
- Auto:286 286.0
- Auto:375 375.1
- Auto:417 417.1
- Auto:635 635.1
- Th-232 911.2
- Auto:820 819.7
- Auto:900 900.4
- Th-232 1501.6
- Auto:1041 1041.1
- Auto:1098 1097.7
- Auto:1294 1294.4
- Auto:2019 2018.8

Intervening Materials

Material	Density(g... Thick(cm)

ROI Materials

ROI	Material	Density(g... Thick
1		0.0000 20.72
2		0.0000 45.95



Units: Curies (Ci)						
ROI	Isotope	Energy	Count	Activity (Ci)	Radioactive Mass (g)	Activity Conc. (Ci/g)
1	Kr-77	129.1	1908	3.92e-03 +/- 9.24e-05	1.83e-04 +/- 4.32e-06	N/A
2	Kr-77	129.1	4718	8.74e-03 +/- 1.67e-04	4.09e-04 +/- 7.82e-06	N/A
BG	Kr-77	129.1	3088			

129 keV 77Kr 3.9 mCi

129 keV 77Kr 8.7 mCi

Time: 1003 Live: 0.964

Saved File

 PC:0 SC:0 PU: 0
 TC:0 RJ:0 F2: 0.00

CPS: 0 16 uR/hr Temp(K): N/A

Threshold 0 - 100 % Distance(m) 1.700 +/- 0.000

Events

11456

Search Pixels

Edit ROIs

Switch to Polygon ROIs

Show All Energy Windows

Isotope Energy (keV)

 Th-232 57.8

 Th-232 72.8

 Auto:87 87.3

 Am-241 511.0

 Kr-77 129.1

 U-232 85.4

 Auto:138 137.8

 NEU:847 845.9

 Auto:143 143.3

 Auto:286 286.0

 Auto:375 375.1

 Auto:417 417.1

 Auto:635 635.1

 Th-232 911.2

 Auto:820 819.7

 Auto:900 900.4

 Th-232 1501.6

 Auto:1041 1041.1

 Auto:1098 1097.7

 Auto:1294 1294.4

 Auto:2019 2018.8

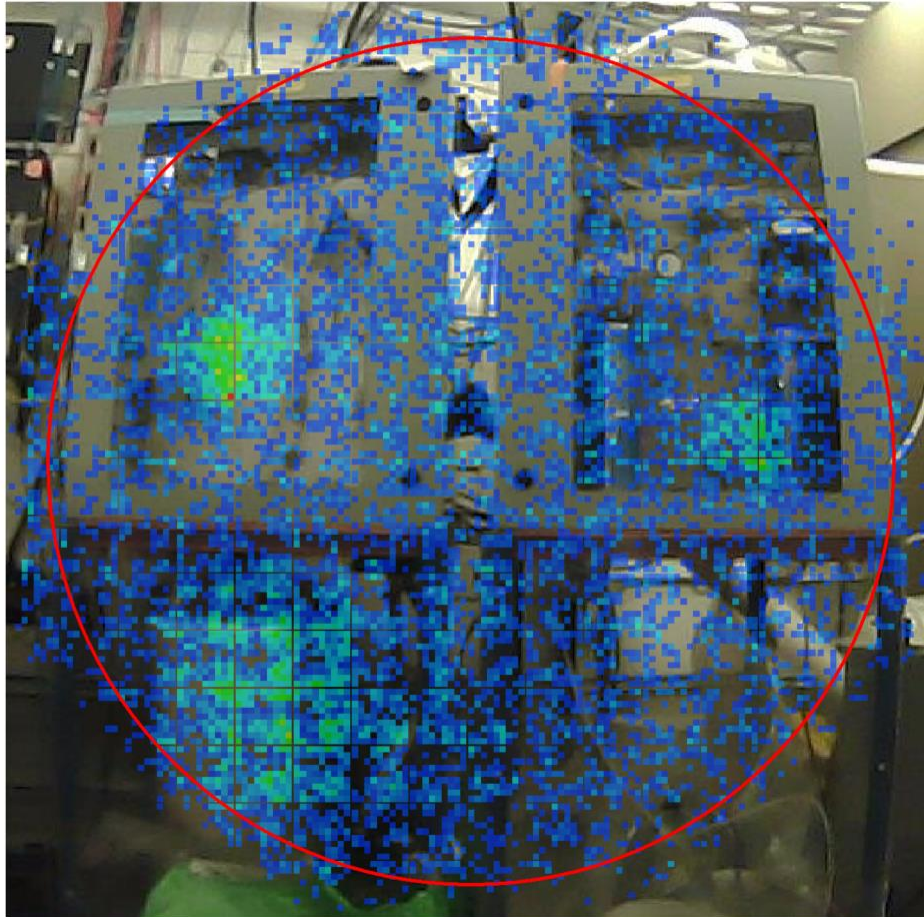
Intervening Materials

Material	Density(g... Thick(cm)

ROI Materials

ROI	Material	Density(g... Thick

There are no items to show in this view.



Units Series (C)

ROI Isotope Energy Count Activity (Ci) Radioactive Mass (g) Activity Conc. (Ci/g)

511s

There are no items to show in this view.

Summary

