

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

**Ethan Hull Ph.D** PI, CEO and Technical Director

**Matt Kiser, Ph.D.** Director of Physics

**Desmond Longford** NP Imager Product Manager and Radiochemist

**A collaboration with: ORNL (Jared Johnson)**

**MURR (Heather Hennkens and Alan Ketring)**

**NSCL (Greg Severin)**

- **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  
(8 lbs.)



Specialty  
Tactical  
(9 lbs.)



# GeGI<sup>®</sup>

Gamma-ray Imaging Spectrometer



- HPGe Isotope Identification
- Source Location Imaging
- Source Distribution Imaging
- Quantitative Imaging
- ANSI N42.42 Reachback
- Compact Hand Portable System

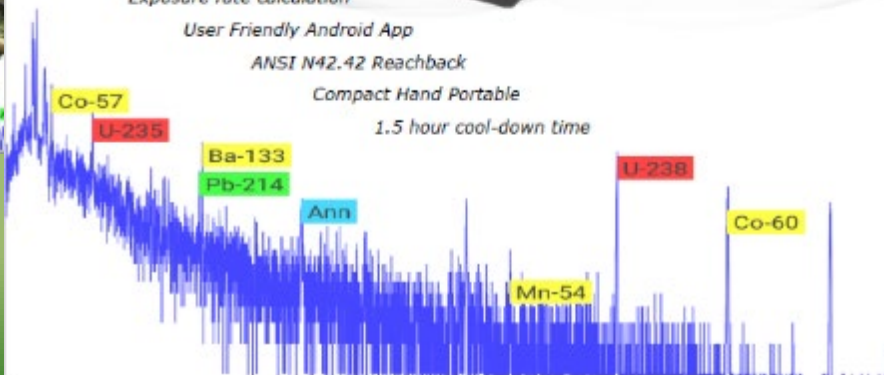


# Fulcrum<sup>®</sup>

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 ft<sup>2</sup> 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**



**Commercial**

Fabrication

**Commercial Products**

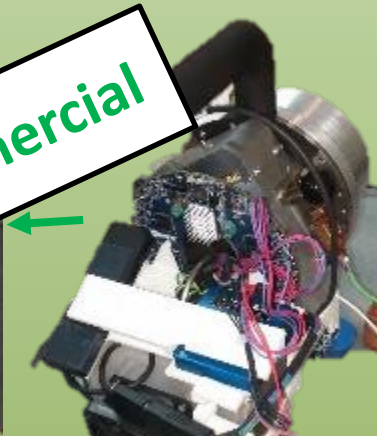
**Commercial**

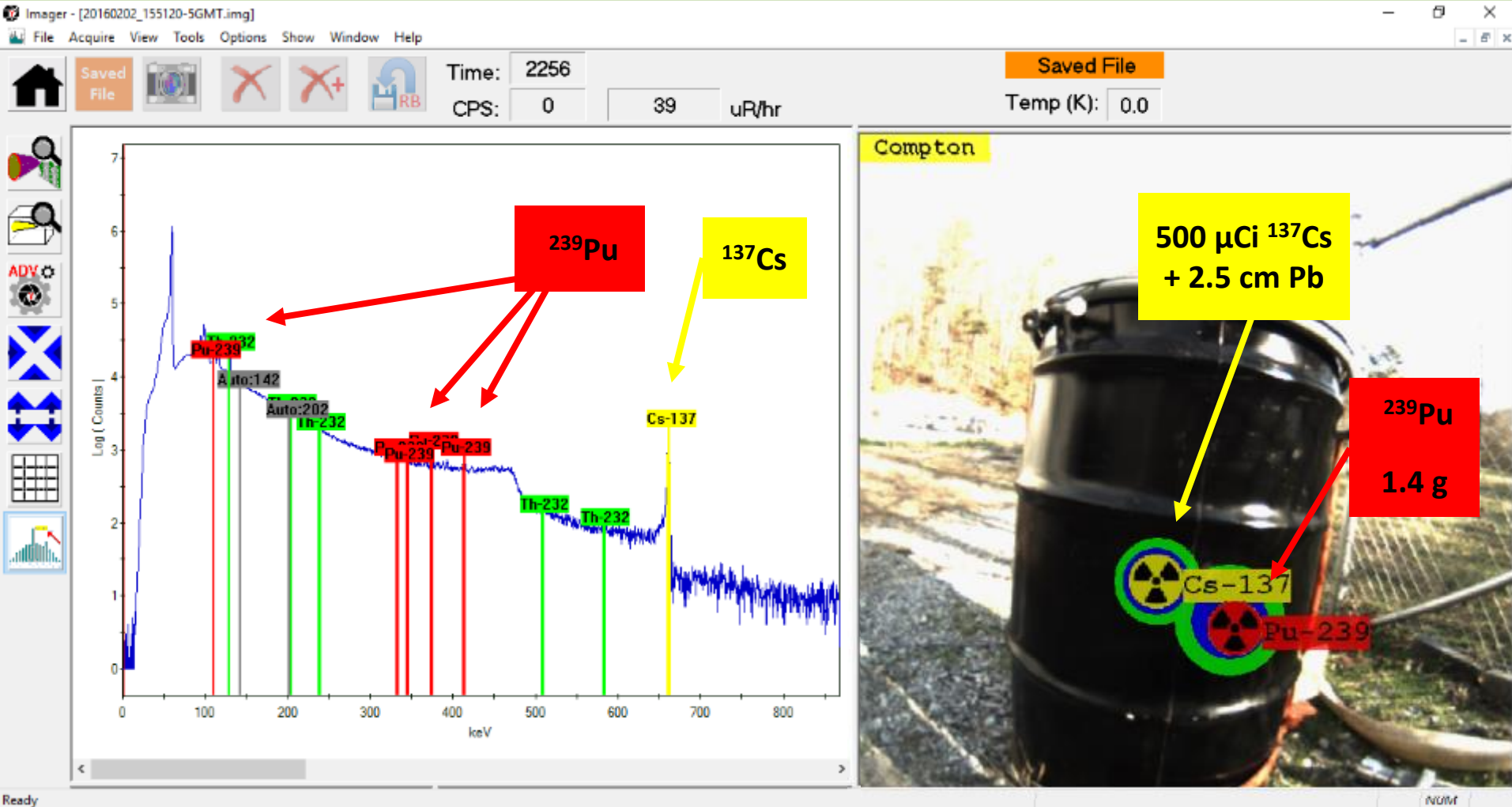
**Commercial**

Integration

Electronics

Cryogenics





# Static

# Radiochemistry is Dynamic → Motivation

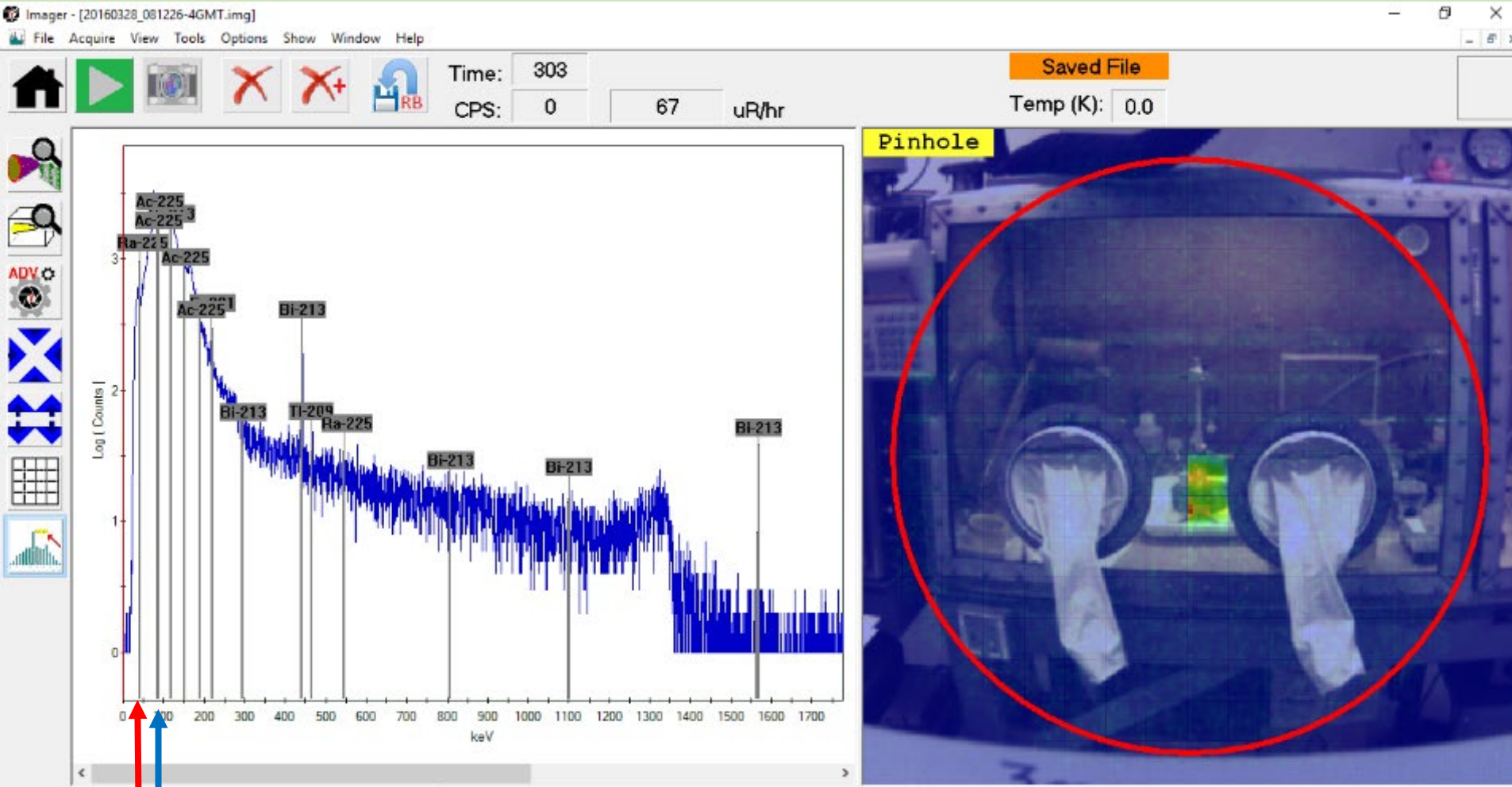
Radioisotope separation at ORNL REDC Spring 2016

Preliminary Data that enabled Phase-I, First discussions w Alan Ketring.





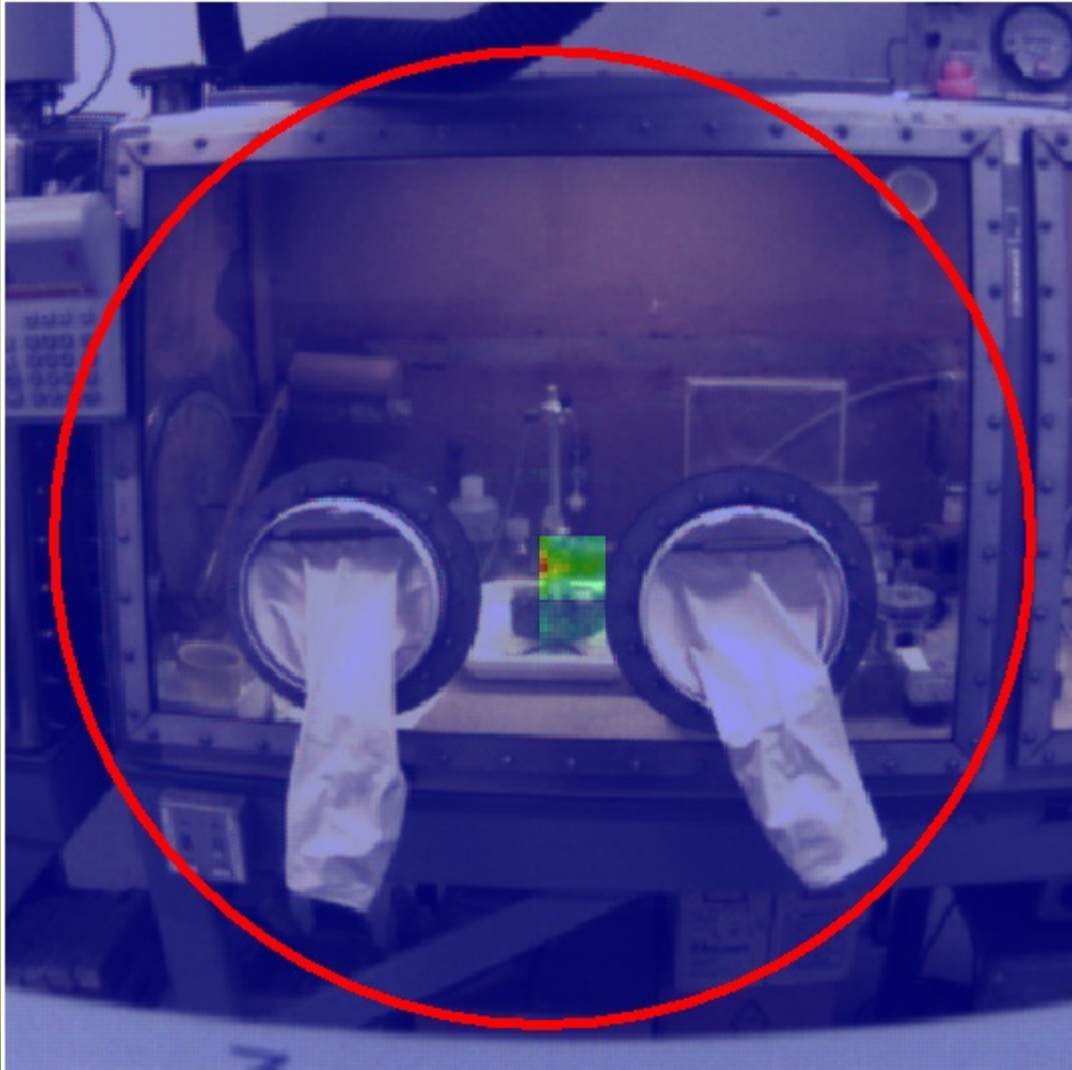
# Motivation



99.8 keV  $^{225}\text{Ac}$

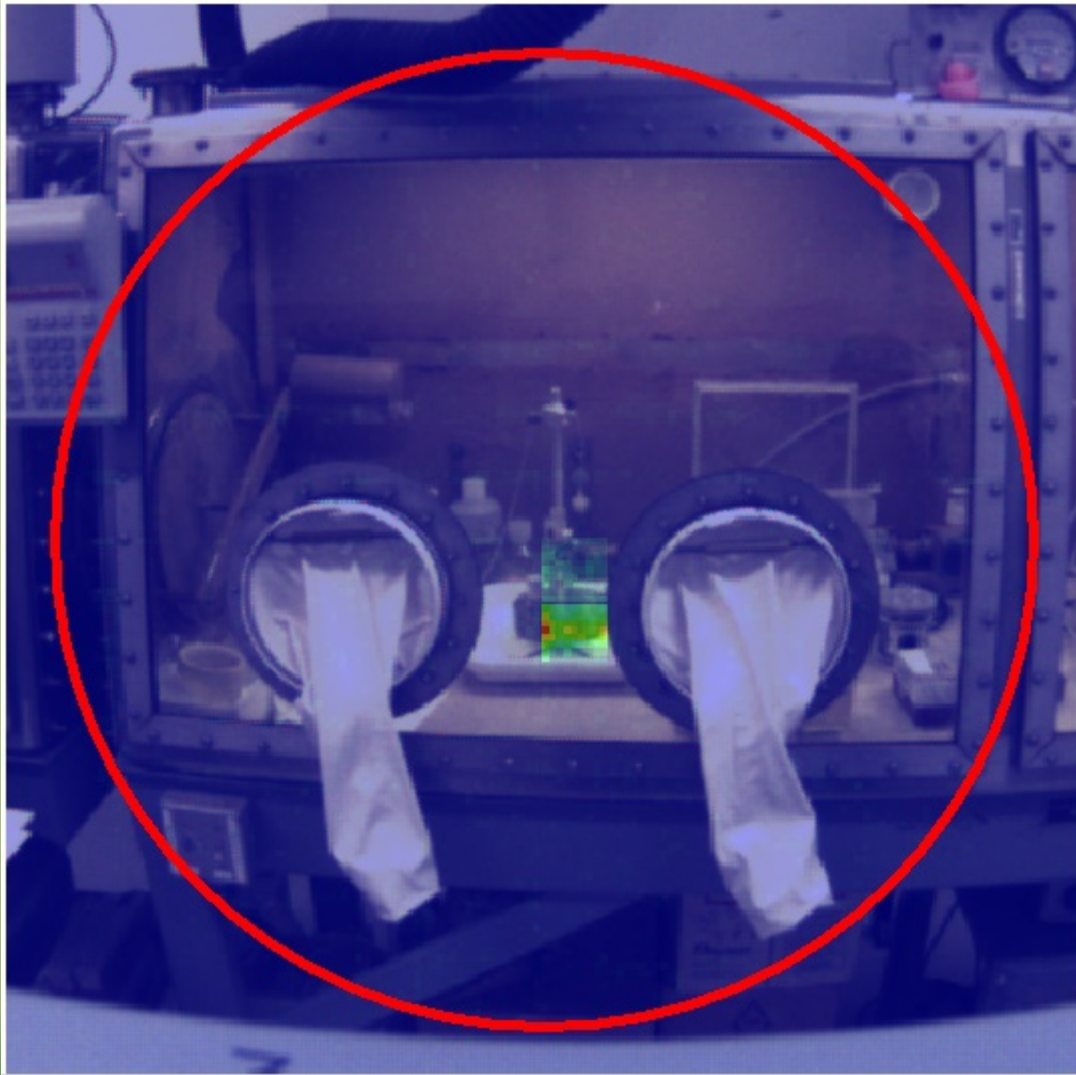
40 keV  $^{225}\text{Ra}$

40 keV  $^{225}\text{Ra}$



5 min

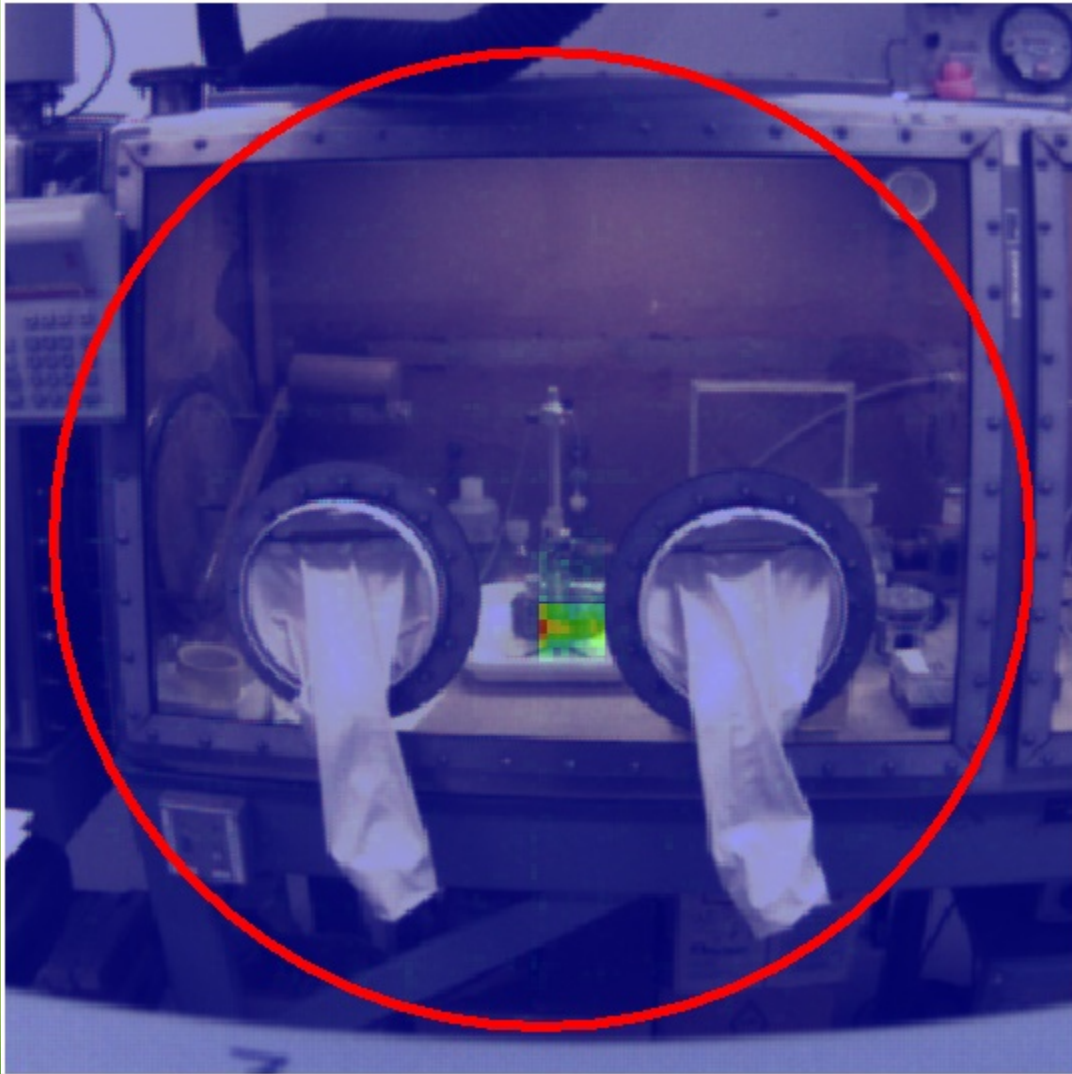
40 keV  $^{225}\text{Ra}$



10 min

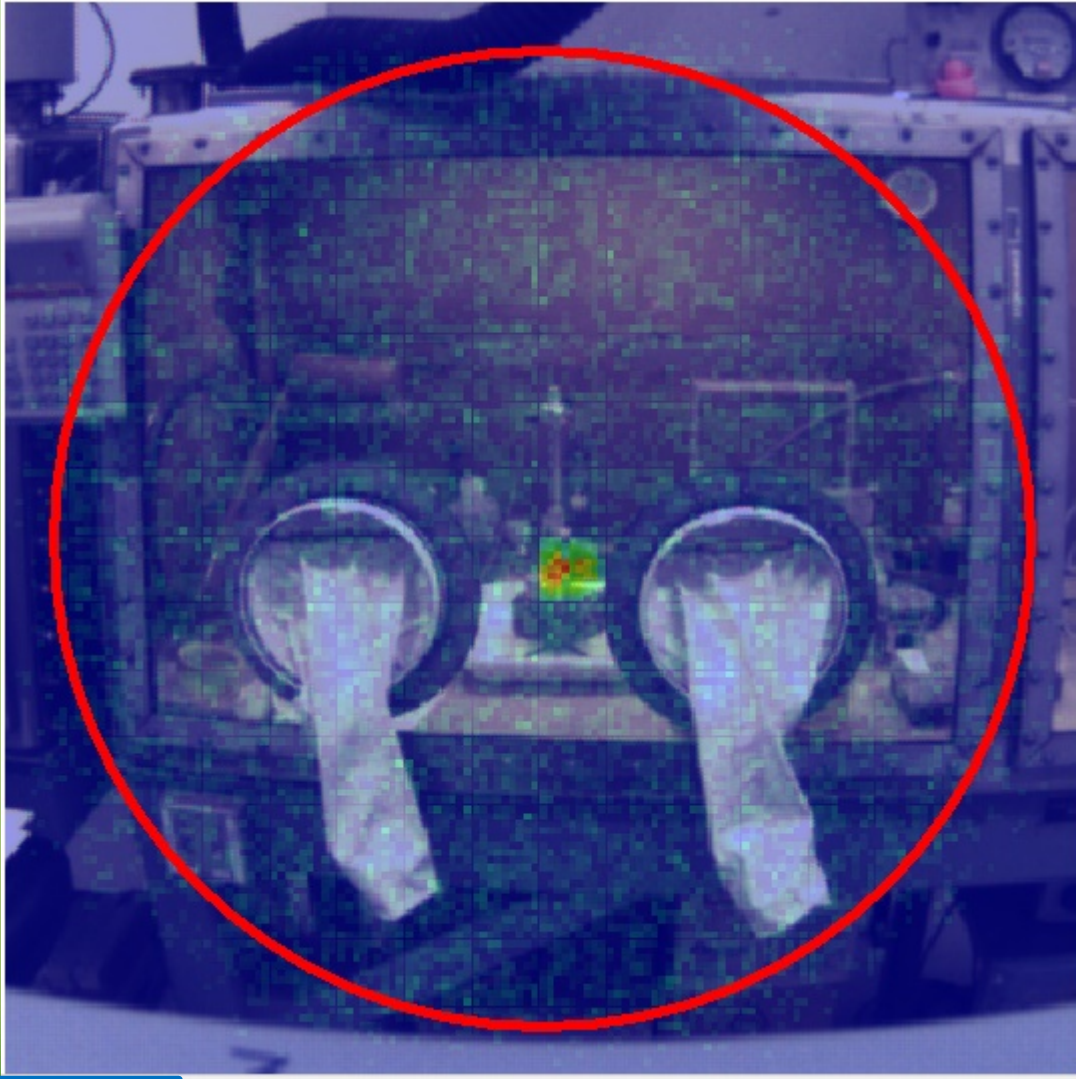


40 keV  $^{225}\text{Ra}$



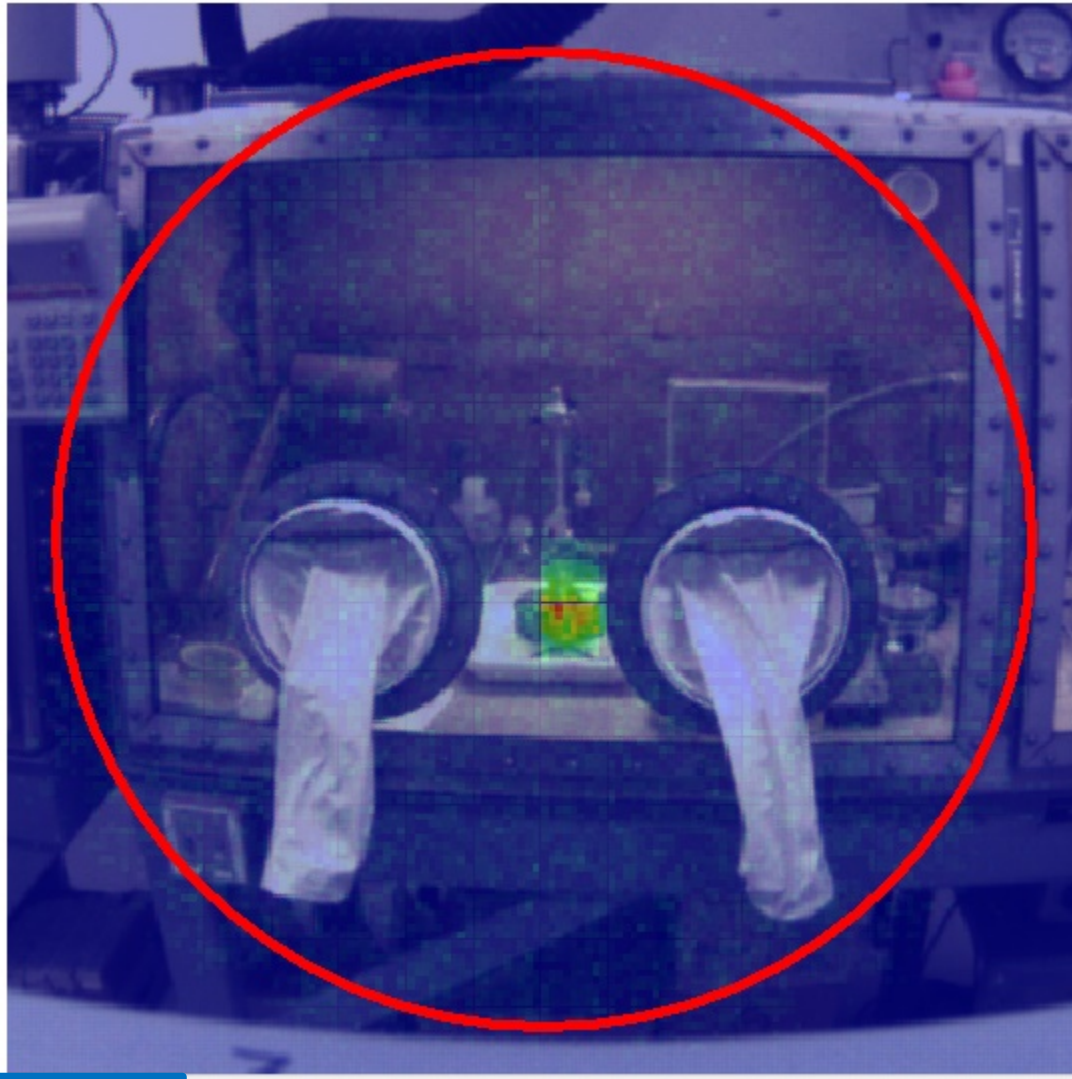
15 min

99.8 keV  $^{225}\text{Ac}$



5 min

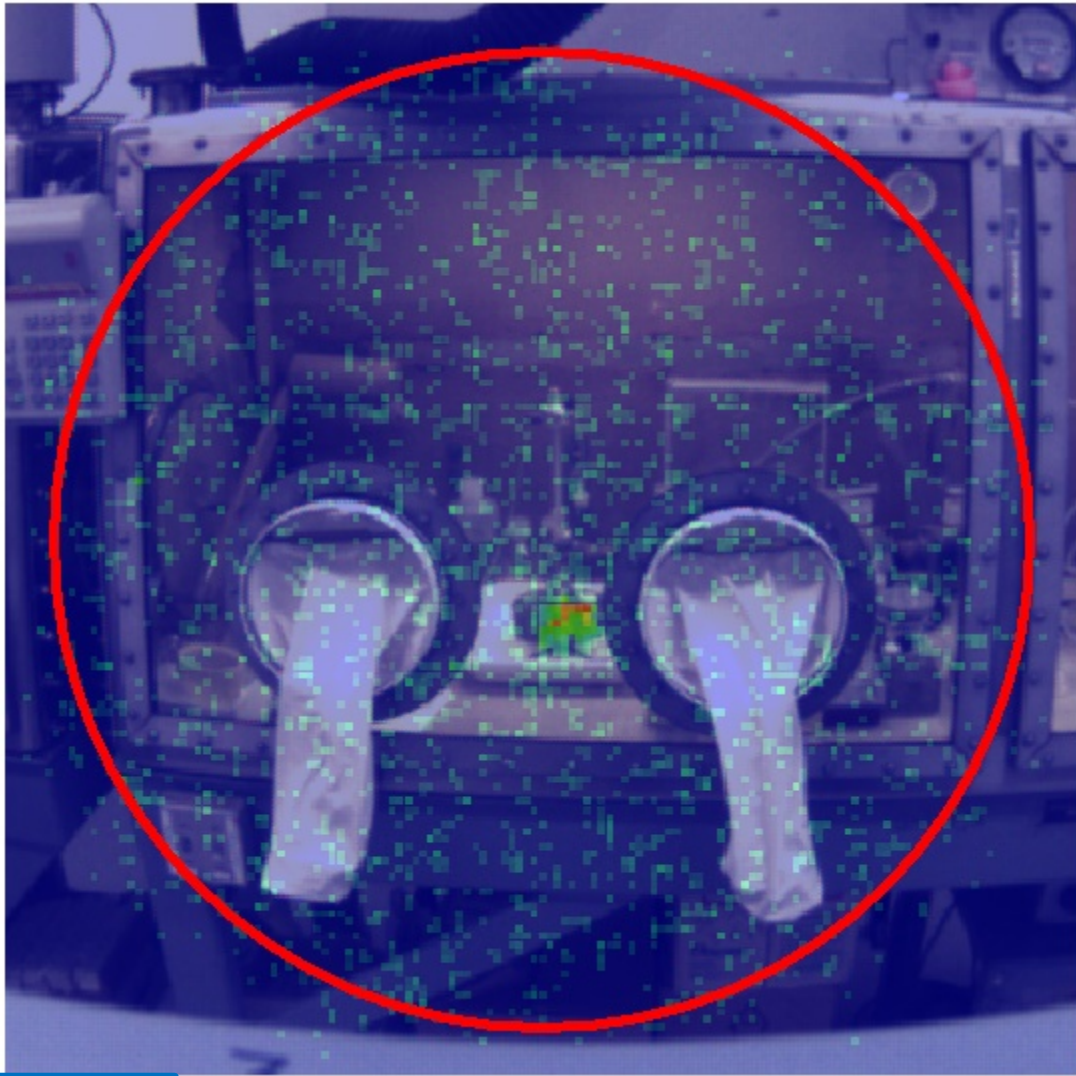
99.8 keV  $^{225}\text{Ac}$



10 min

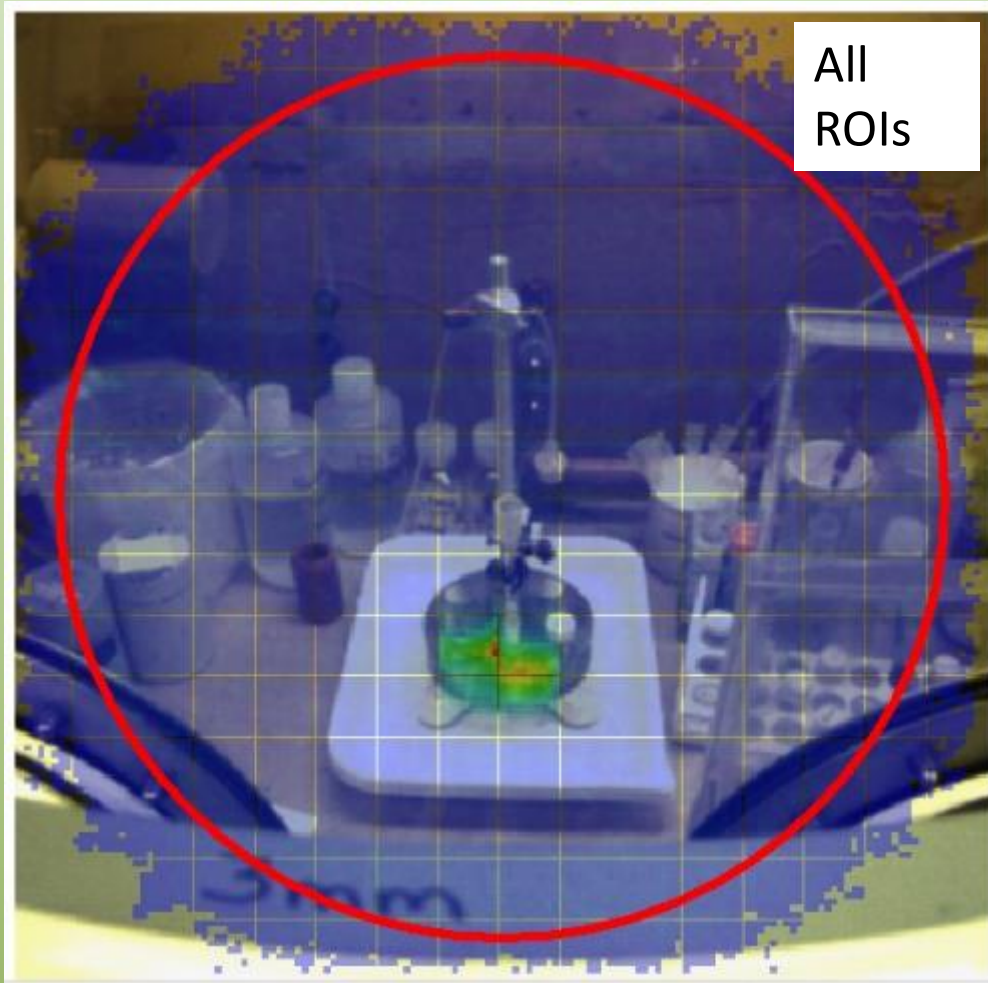


99.8 keV  $^{225}\text{Ac}$

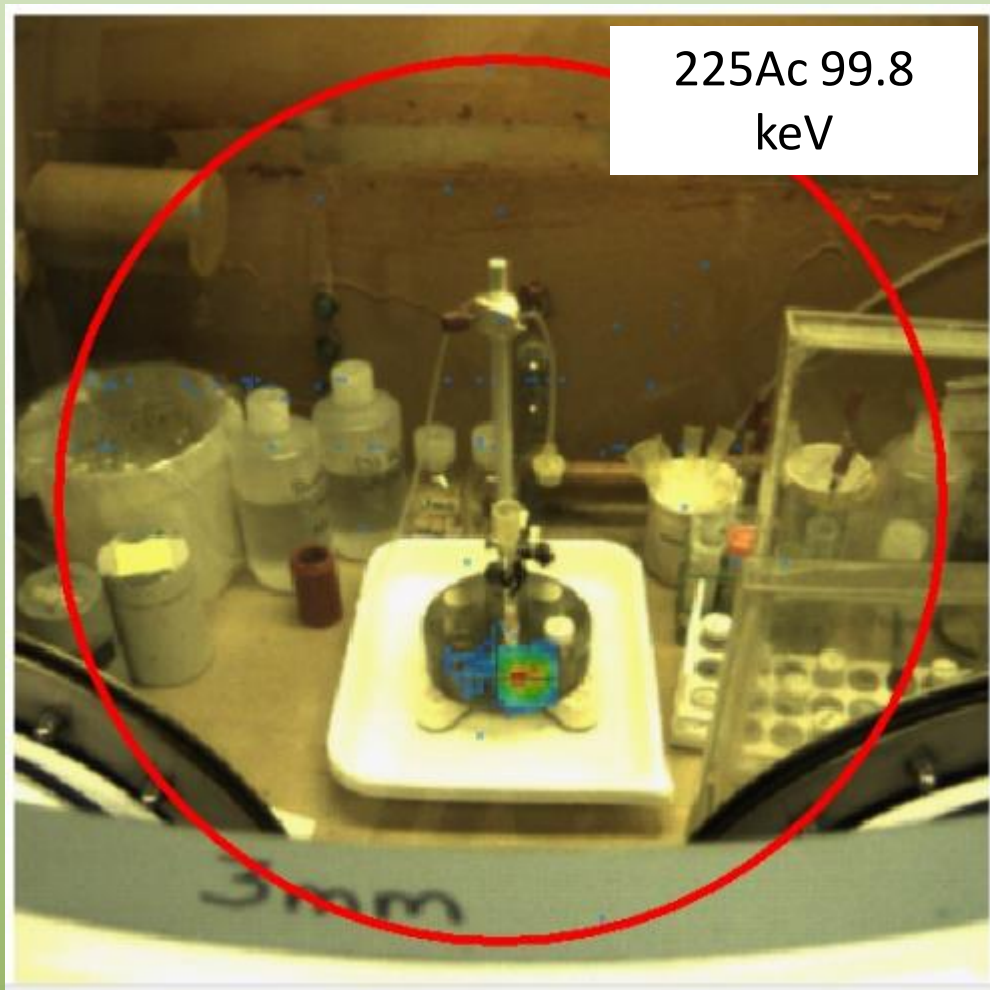


15 min

# Collection Carousel

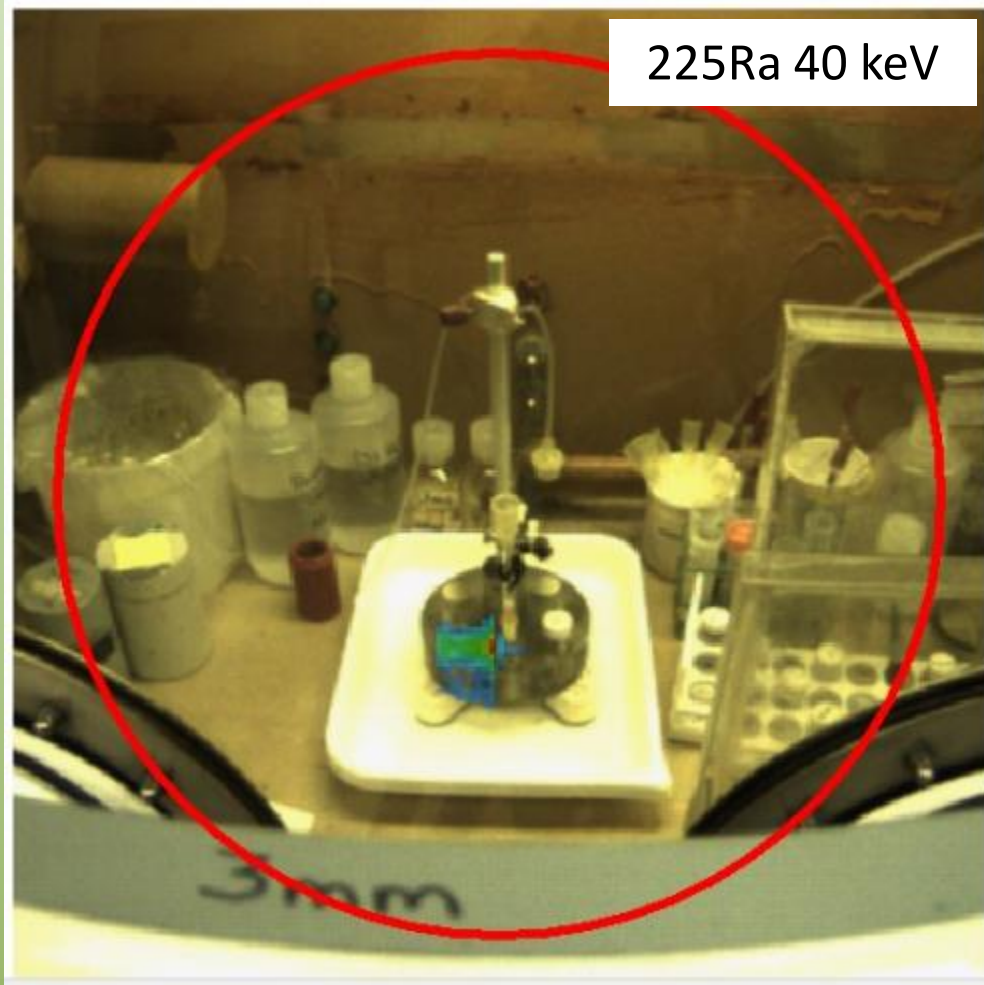


# Collection Carousel

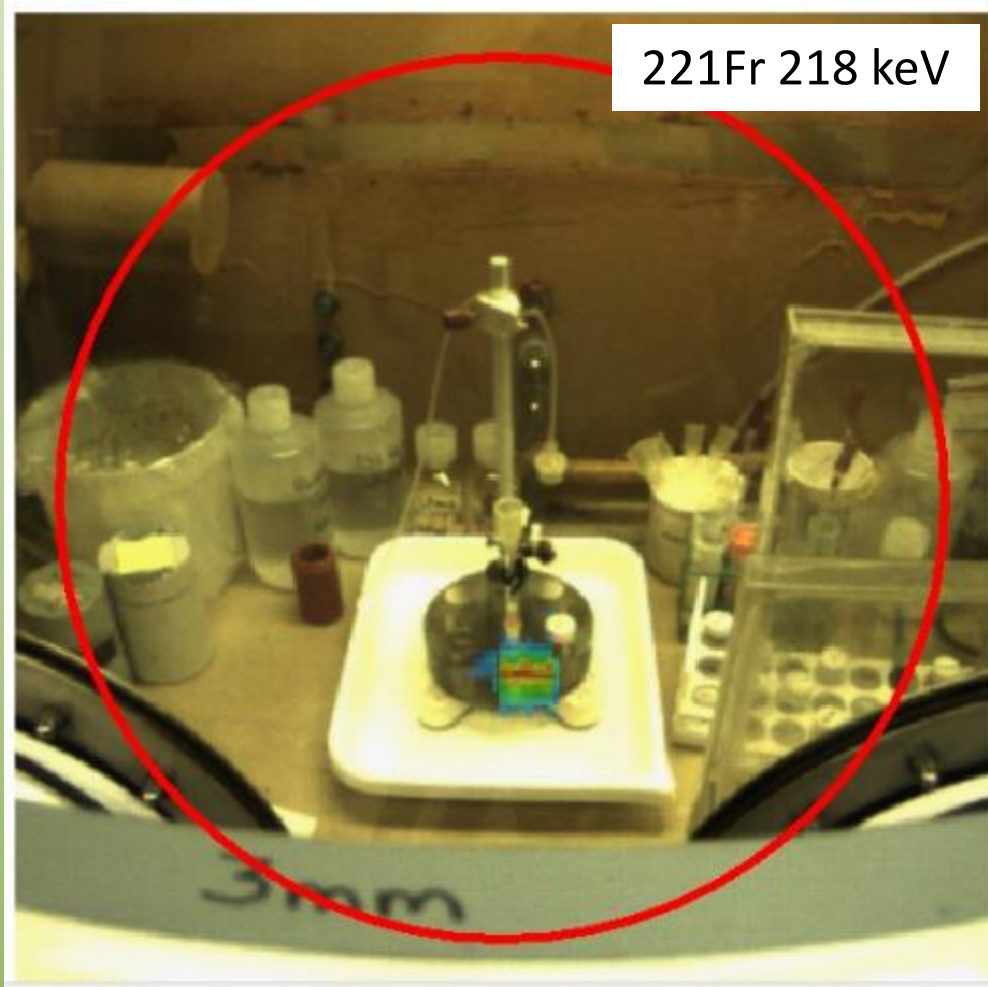




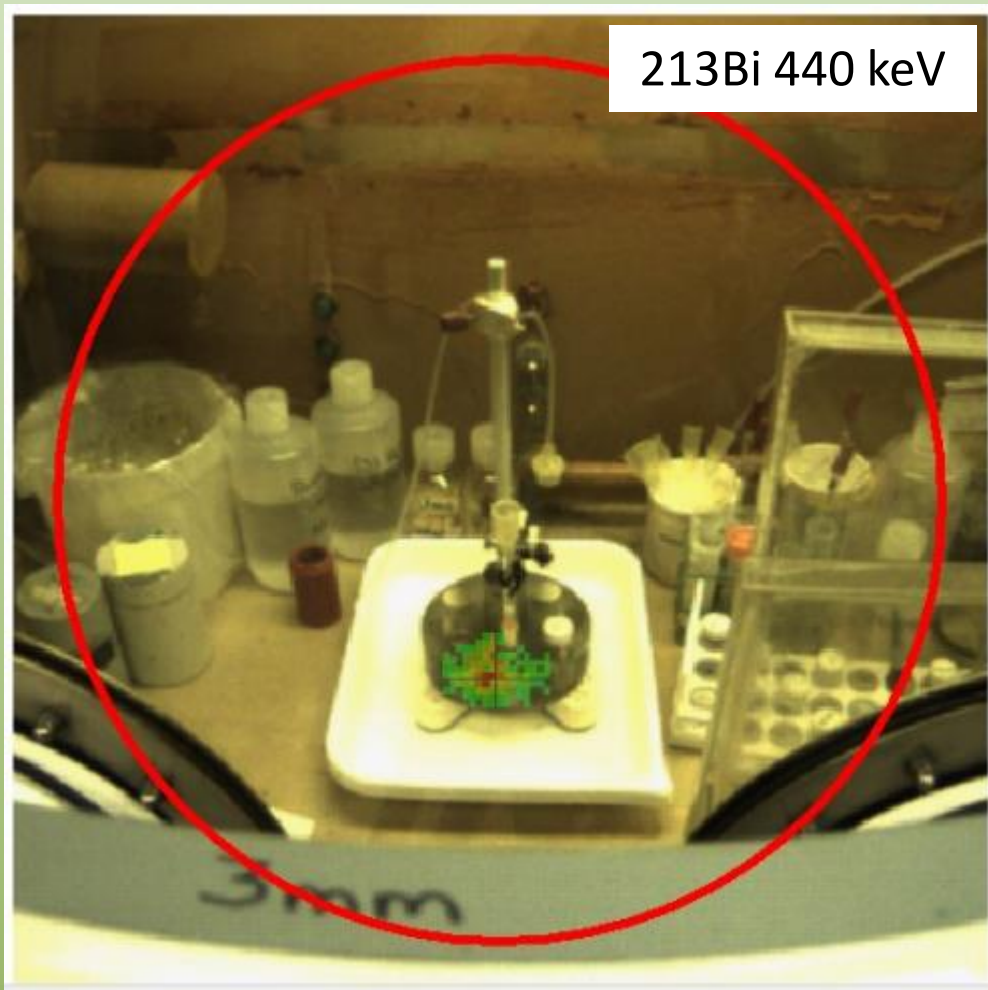
# Collection Carousel



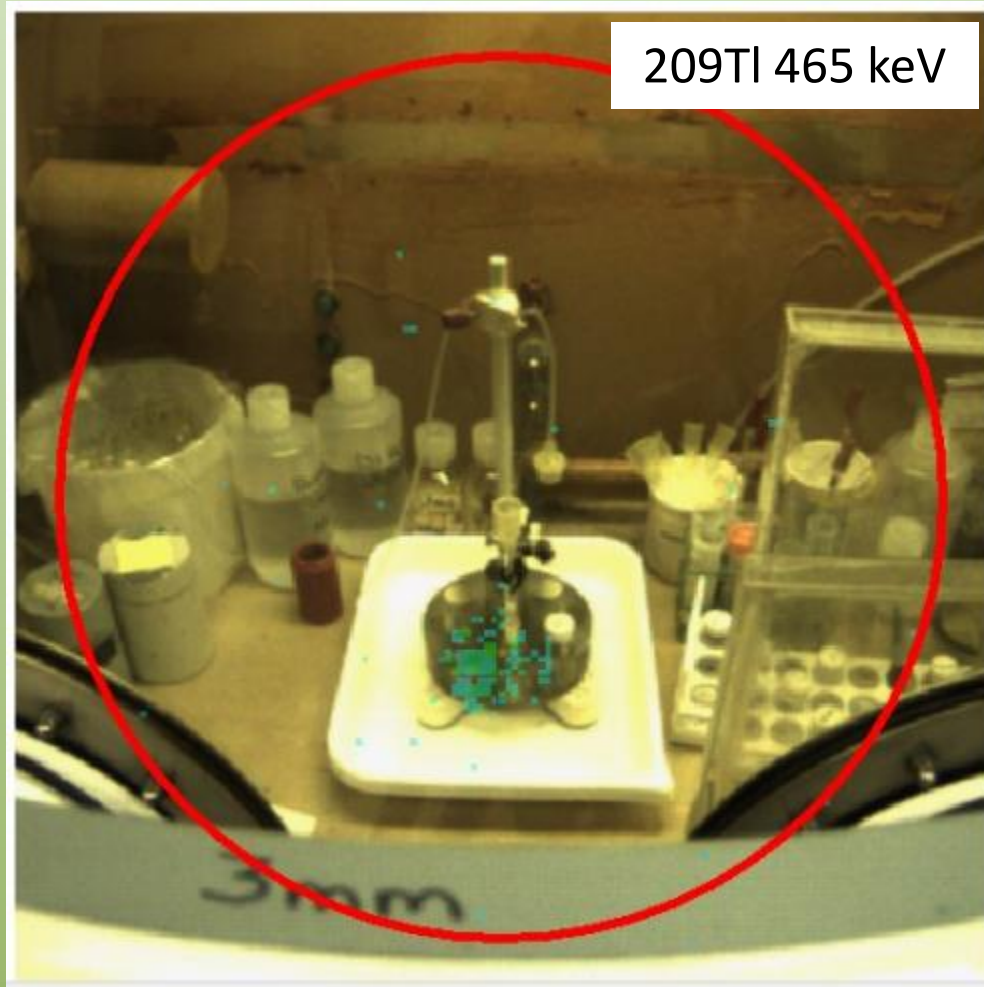
# Collection Carousel



# Collection Carousel





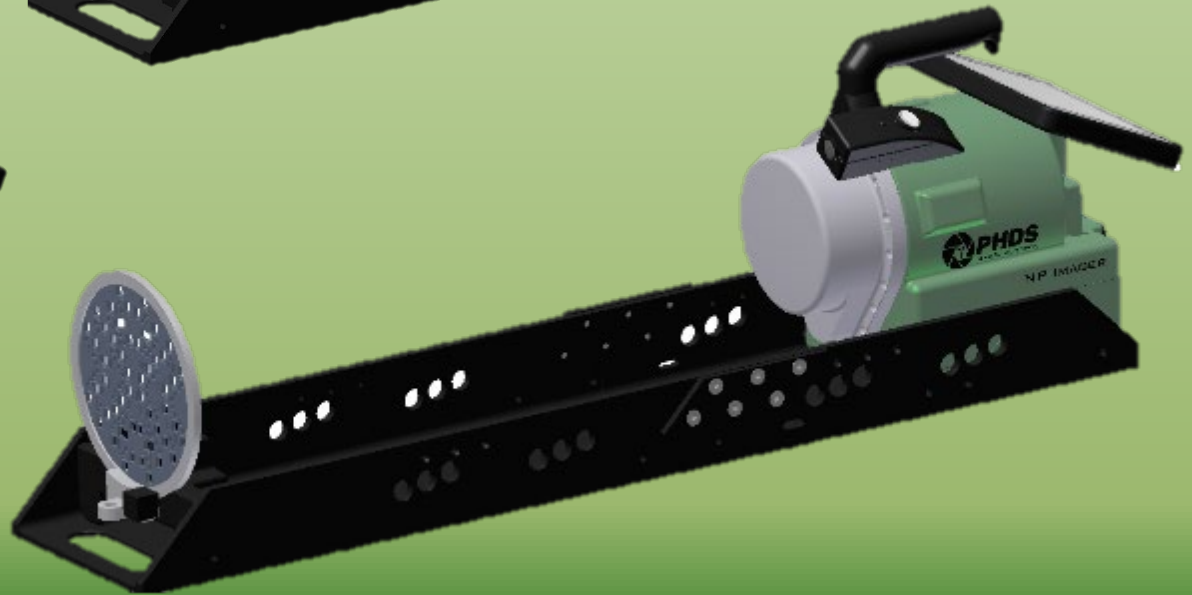
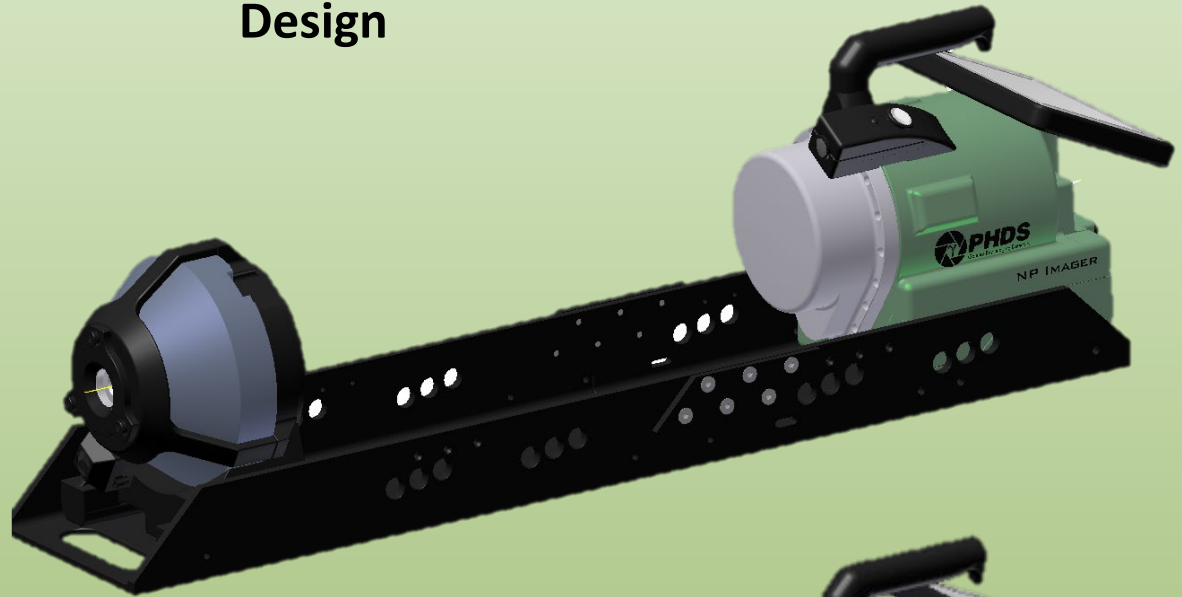


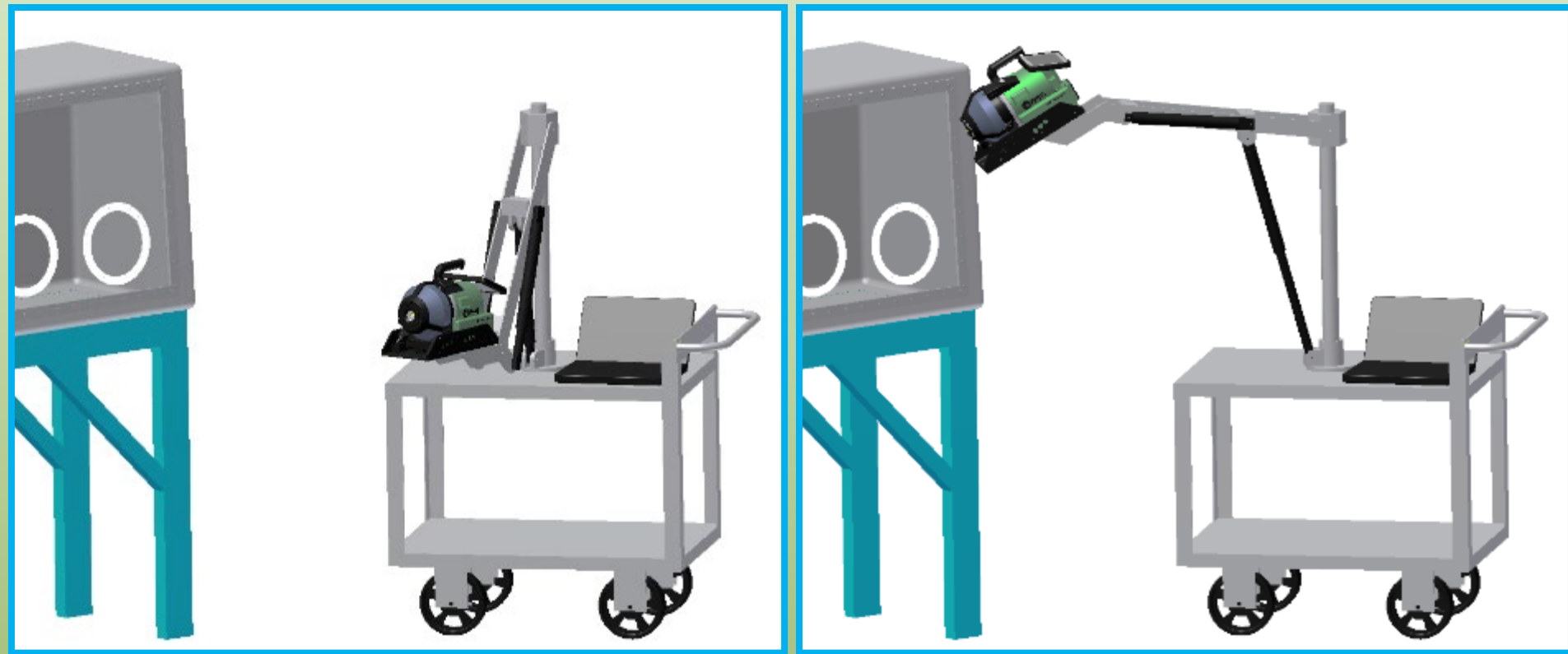
**Motivation:** The ability to observe the *dynamic* exchange of isotopes *in real time*, on the bench or glove box, would be a very useful tool to radiochemists and nuclear physicists.

# NP Imager Technical Development Phase-II Prototypes



## Design

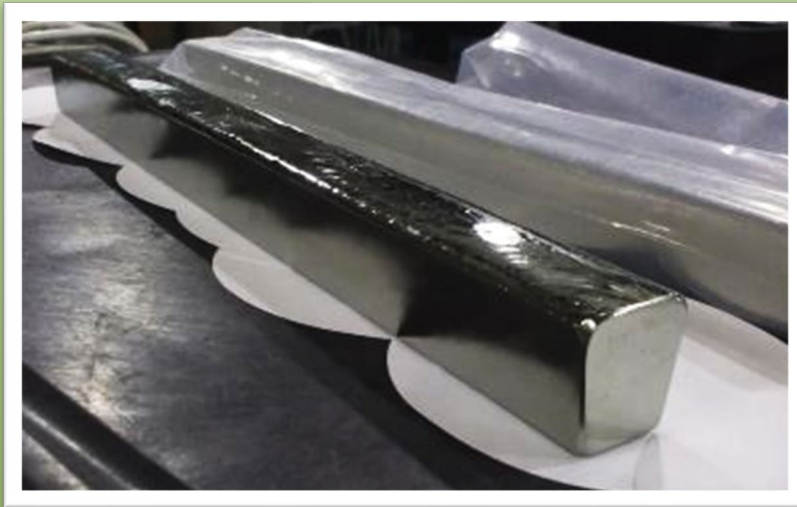




**Most radiochemistry laboratories have HPGe detectors for sample counting anyway.  
Make the next HPGe detector an NP Imager and gain the advantage of imaging!**



# NP Imager Technical Development Phase-II Prototypes



# NP Imager Technical Development Phase-II Prototypes

## Adaptation of detector manufacturing to NP Imager



**Ge Zone Refine**



**HPGe Crystal Growth**



**Analysis**



**Fabrication**



**Cryogenic system**



**NP Imager**



**Electronic and Software Integration**



**Chassis and Optics**

## NP Imager

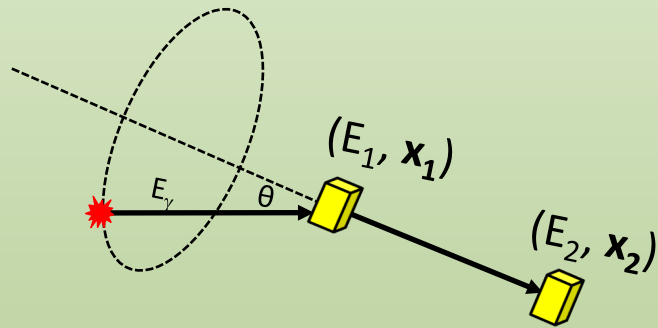


**(x, y, z)  $\Delta x \sim 1.5 \text{ mm}$**   
**Energy**

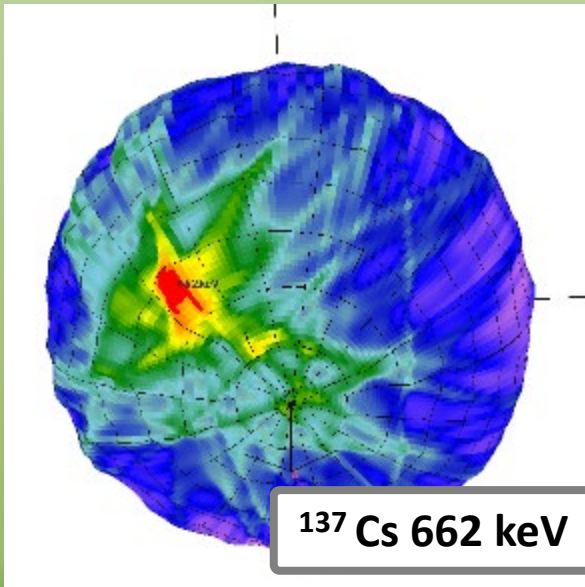
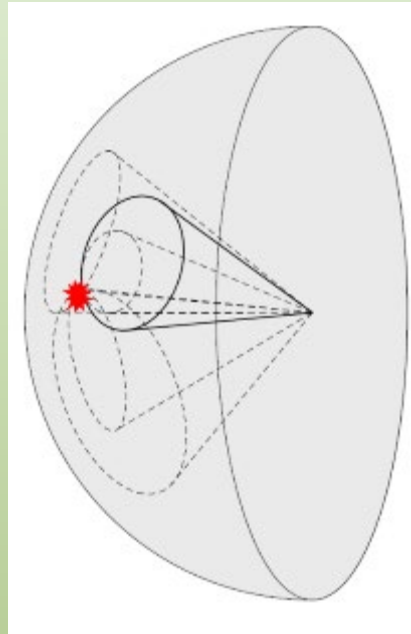
1. Compton Kinematic Imaging
2. **Pinhole Aperture Imaging**
  - **ZoomFactor**
3. *Coded Aperture – next time*



# 1. Compton Imaging



$$\cos \theta = 1 - m_e c^2 \left( \frac{E_1}{E_2(E_1 + E_2)} \right)$$

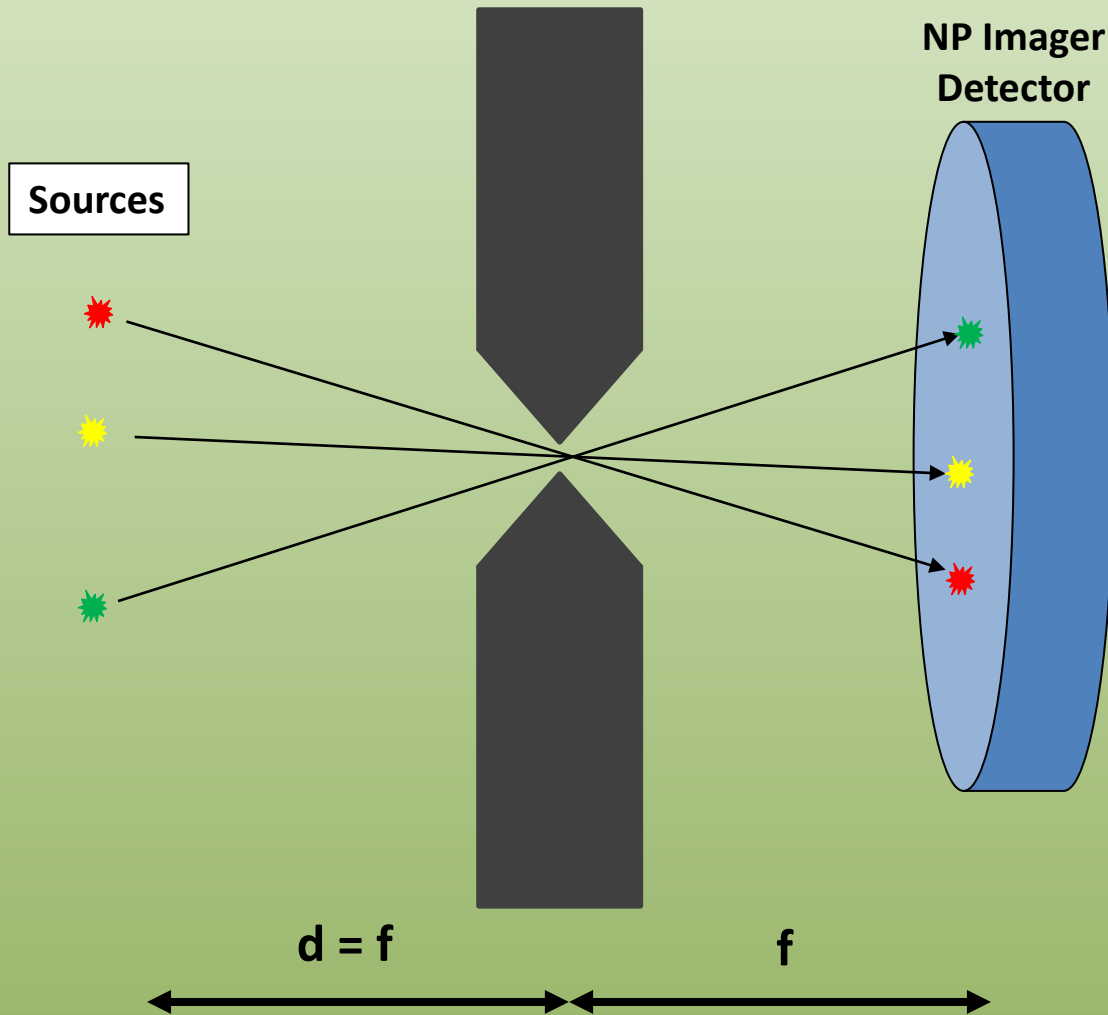


- Finds the hottest source fast
- High sensitivity
  - Detector open
  - No collimator or shielding

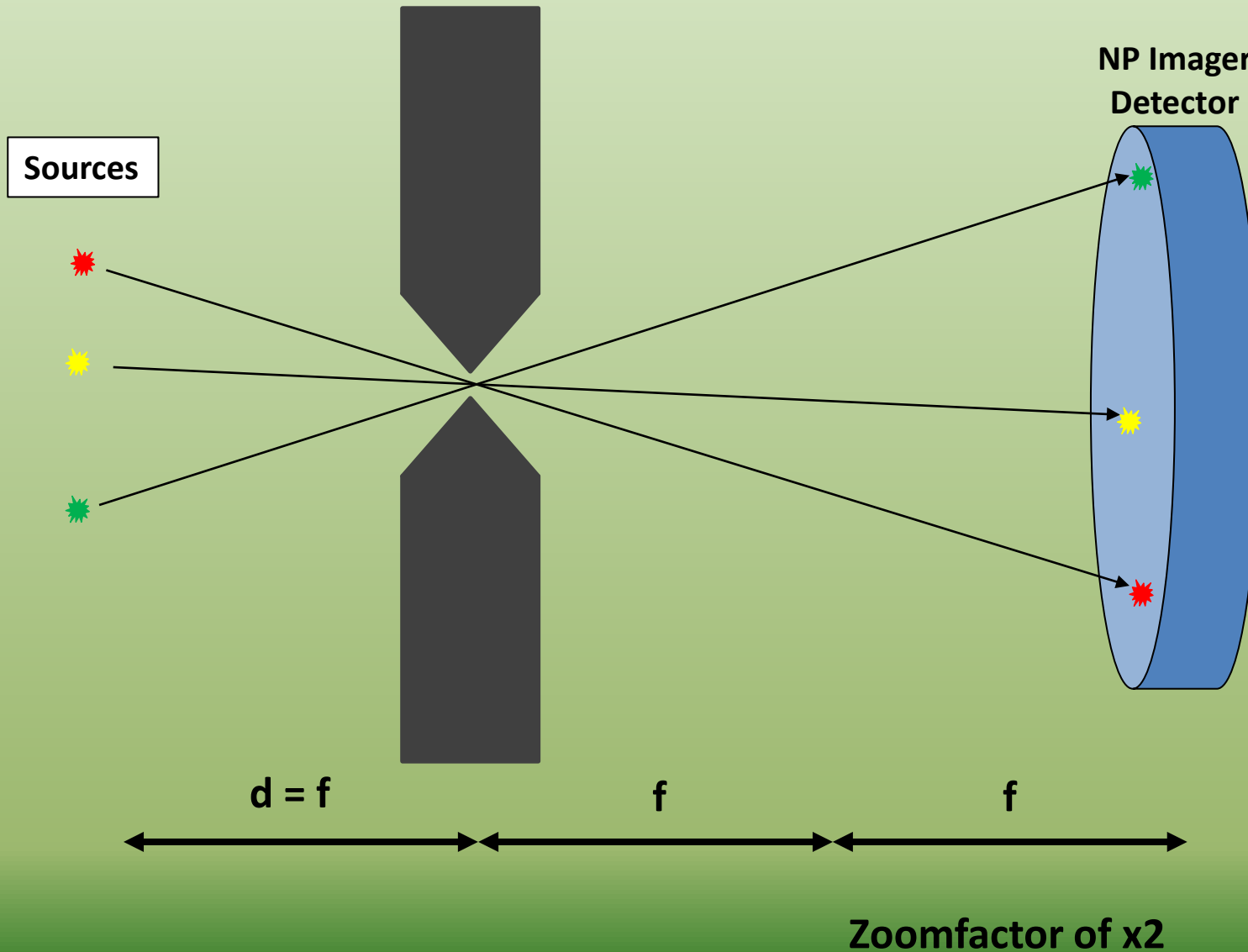
- Proven useful at MURR and ORNL during radiochemistry operations

*However, aperture imaging is the real key*

## 2. Pinhole Aperture Imaging

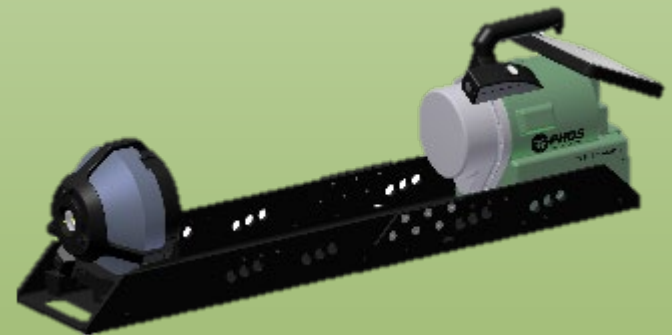
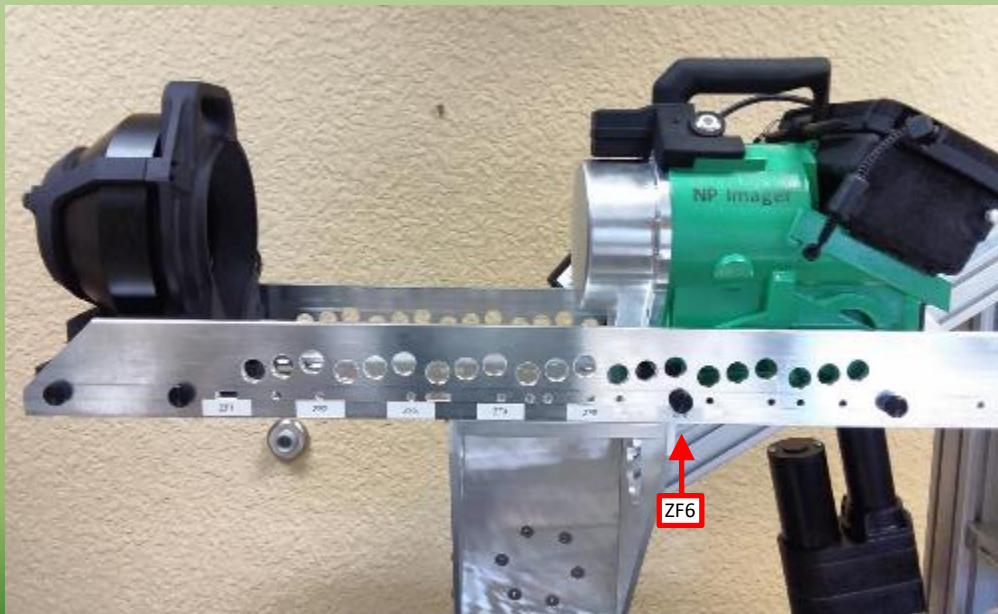
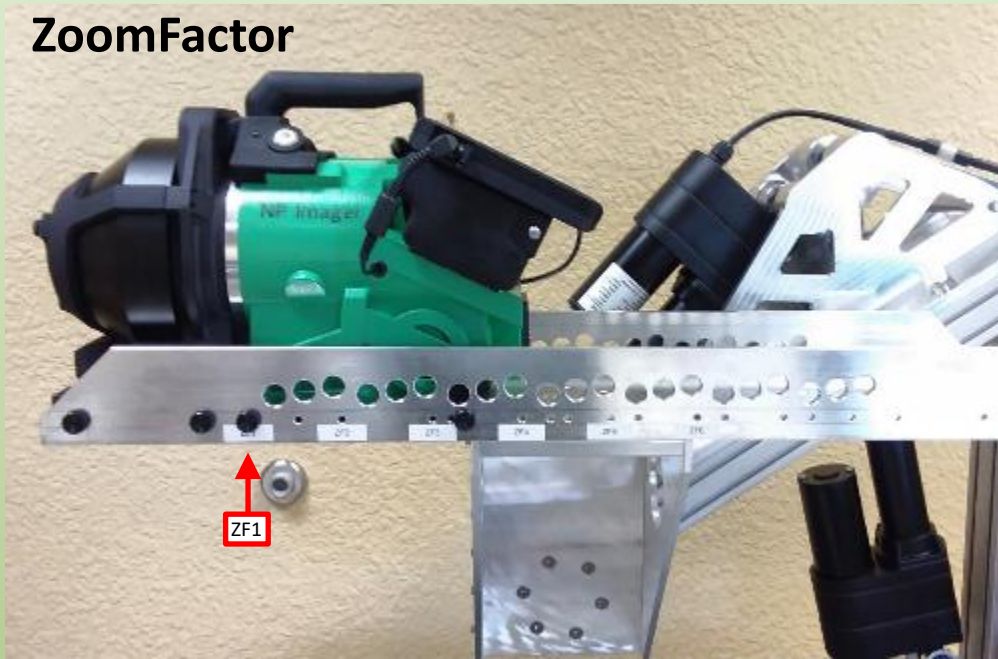


## 2. Pinhole Aperture Imaging





# ZoomFactor

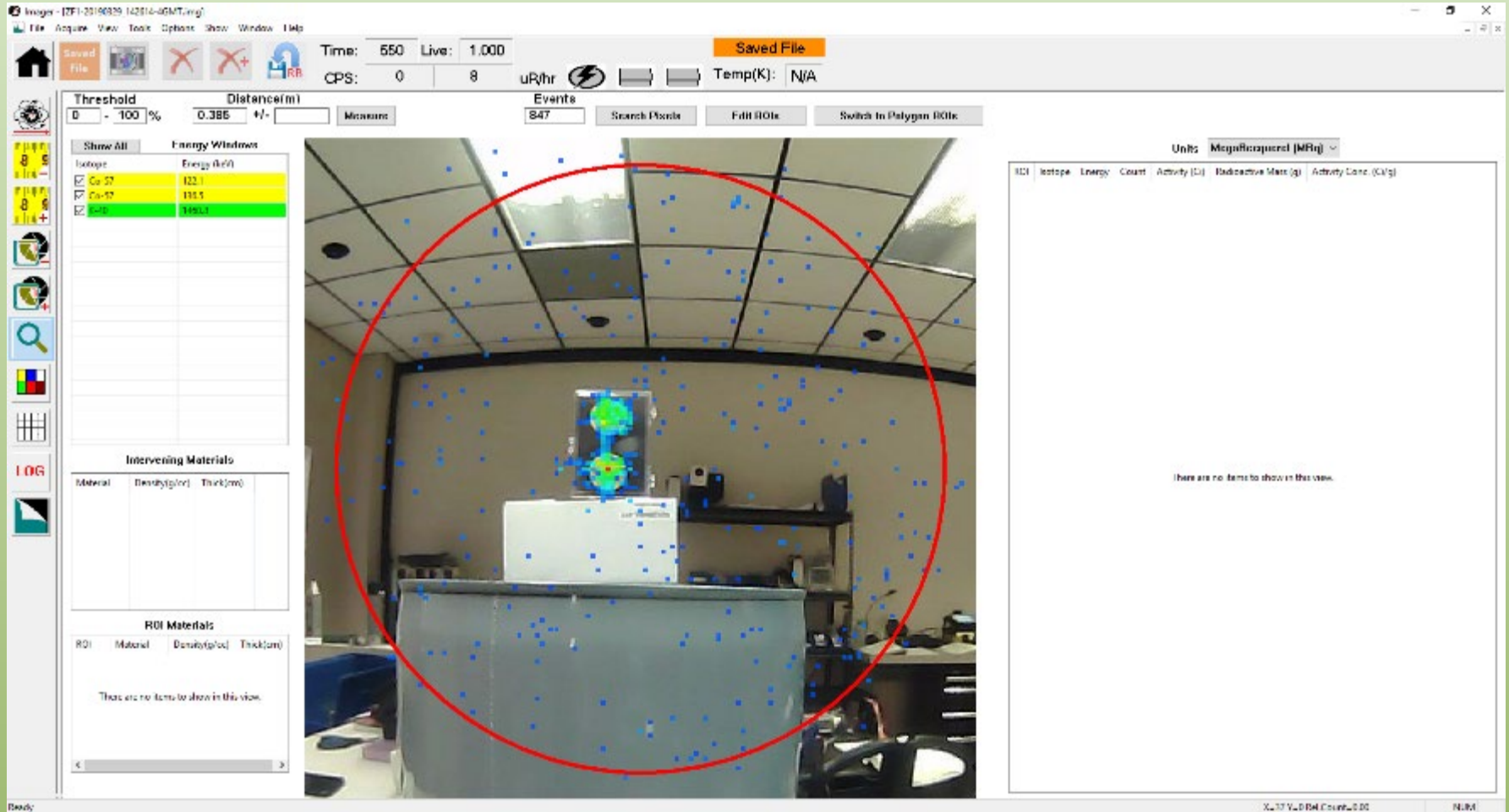




“Zoomfactor”

ZF1

2x <sup>57</sup>Co at 38.5 cm



Time: 550 Live: 1.000  
CPS: 0 8 uR/hr Temp(K): N/A

Threshold: 0 - 100% Distance(m): 0.385 Events: 847

Isotope	Energy (keV)
<input checked="" type="checkbox"/> Co-57	122.1
<input checked="" type="checkbox"/> Co-57	136.5
<input checked="" type="checkbox"/> Co-57	1480.1

Intervening Materials

Material	Density(g/cm)	Thick(cm)
This area has no items to show in this view.		

ROI Materials

ROI	Material	Density(g/cm)	Thick(cm)
This area has no items to show in this view.			

Units: MegaBecquerel (MBq)

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

Ready | XL17 VLDRM Count: 0.00 | NUM



“Zoomfactor”

ZF2

2x  $^{57}\text{Co}$  at 38.5 cm

Viewer - ZF2-20190329\_143726-46MT.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 - 100% Distance(m): 0.39 Measure Events: 885 Search Pixels: Fill 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"/> Co-57	1480.3

Intervening Materials

Material	Density(g/cm)	Thick(cm)

ROI Materials

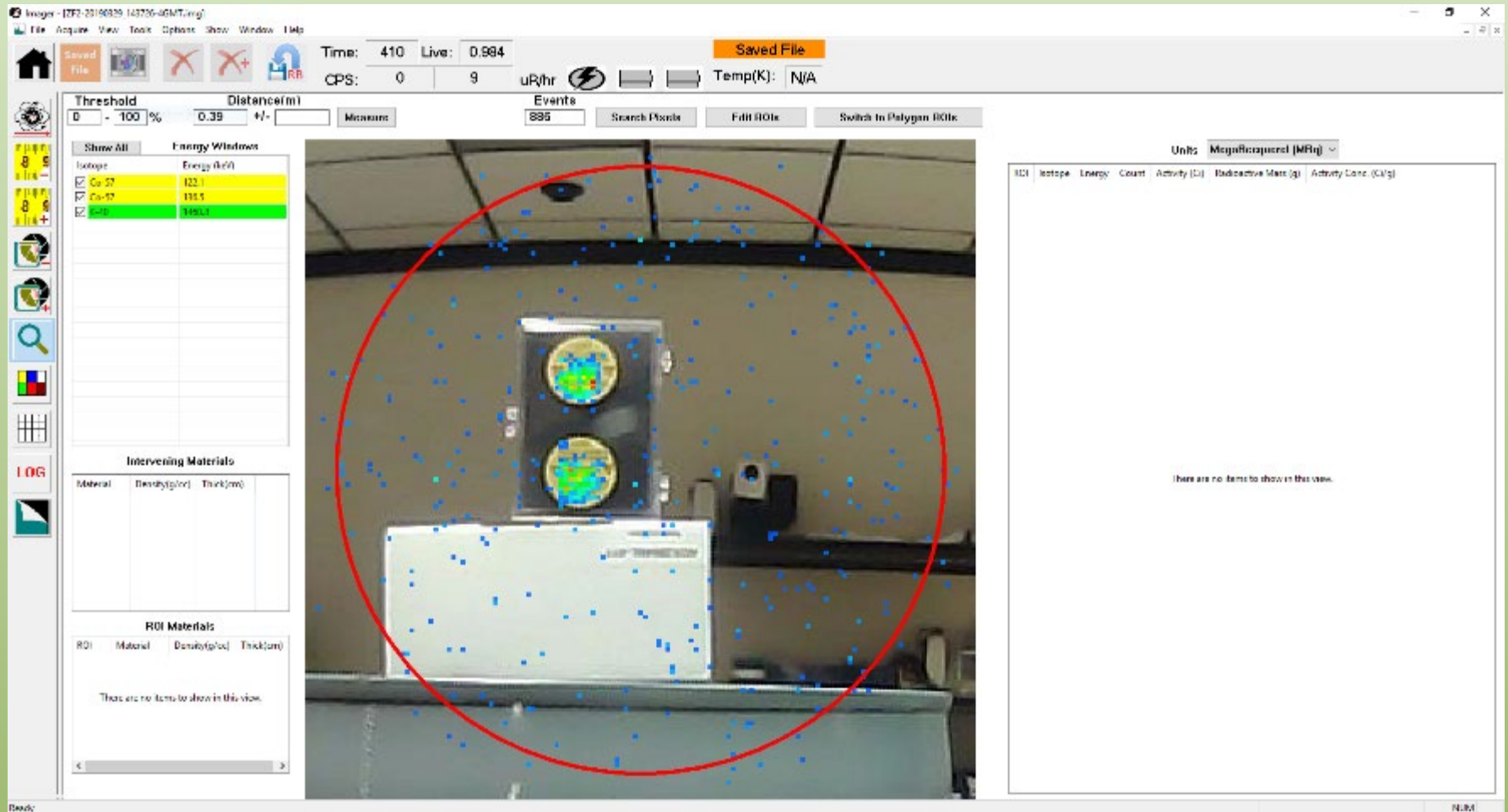
ROI	Material	Density(g/cm)	Thick(cm)

There are no items to show in this view.

Units: MegaBecquerel (MBq)

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

Ready N/A

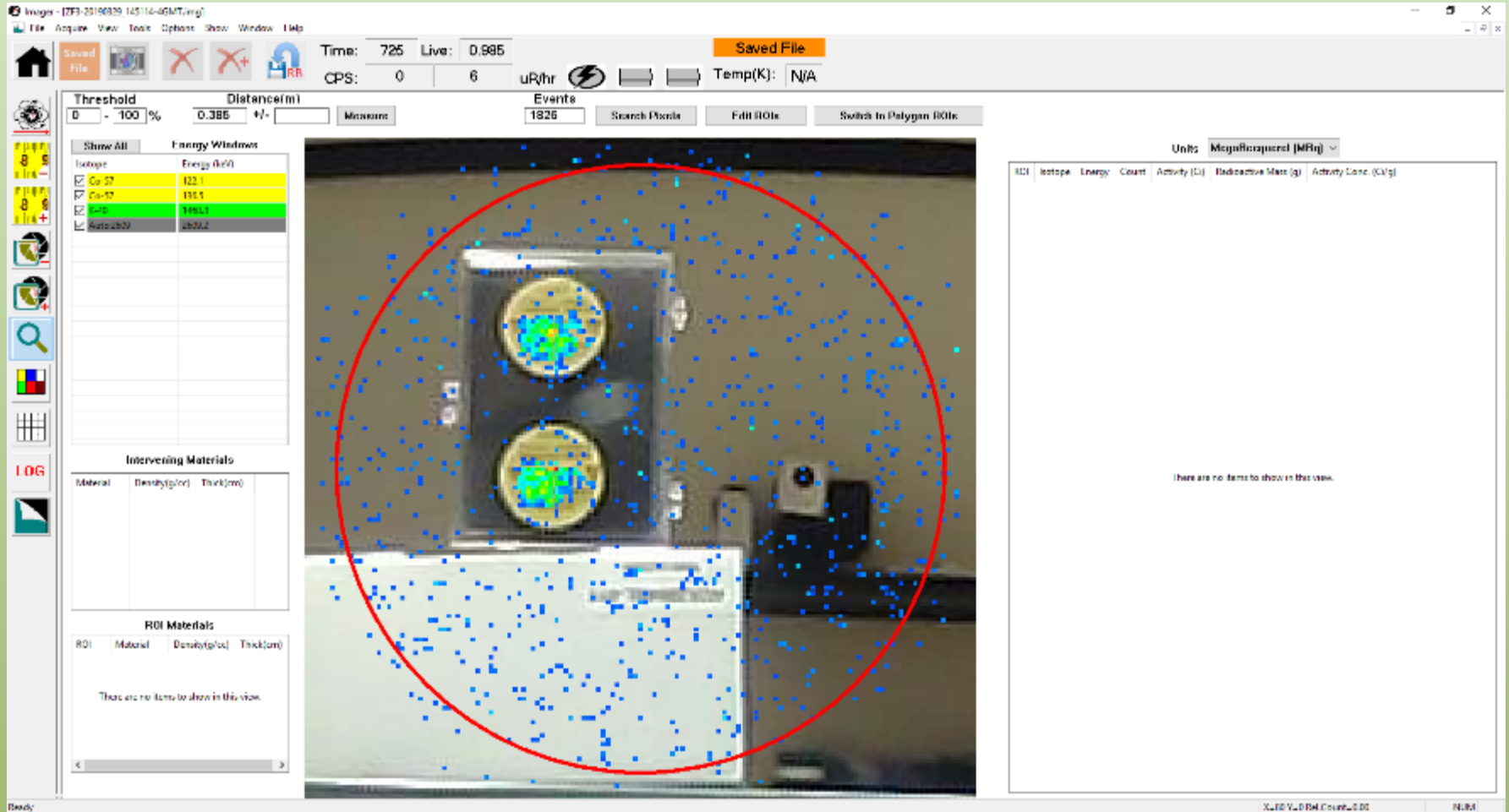




“Zoomfactor”

ZF3

2x <sup>57</sup>Co at 38.5 cm



**Software Interface: Inveon - ZF3-20190329\_145114-46MT2img**

**Top Status Bar:** Time: 725 Live: 0.985 Saved File  
CPS: 0 6 uR/hr Temp(K): N/A

**Threshold:** 0 - 100% Distance(m): 0.385 Measure

**Events:** 1826 Search Pixels Fill ROIs Switch to Polygon ROIs

**Energy Windows Table:**

Isotope	Energy (keV)
<input checked="" type="checkbox"/> Co-57	123.1
<input checked="" type="checkbox"/> Co-57	133.5
<input checked="" type="checkbox"/> Co-57	1460.3
<input checked="" type="checkbox"/> AutoSub?	2550.2

**Intervening Materials Table:**

Material	Density(g/cm)	Thick(cm)
This area has no items to show in this view.		

**ROI Materials Table:**

ROI	Material	Density(g/cm)	Thick(cm)
This area has no items to show in this view.			

**Right Sidebar Table:**

Units: MegaBecquerel (MBq)

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

**Bottom Status Bar:** Ready XLFD\_VL\_DPM\_Count\_000 NUM

“Zoomfactor”

ZF4

2x  $^{57}\text{Co}$  at 38.5 cm

Viewer - ZF4-20190329 120901-46MT.Dmg

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 - 100% Distance(m): 0.385 Events: 2723

Search Pixels Fill ROIs Switch to Polygon ROIs

Show All Energy Windows

Isotope	Energy (keV)
<input checked="" type="checkbox"/> Co-57	123.1
<input checked="" type="checkbox"/> Co-57	133.5
<input checked="" type="checkbox"/> Bi-214	1120.3
<input checked="" type="checkbox"/> Bi-214	609.3
<input checked="" type="checkbox"/> Th-232	233.0
<input checked="" type="checkbox"/> Th-232	26.45

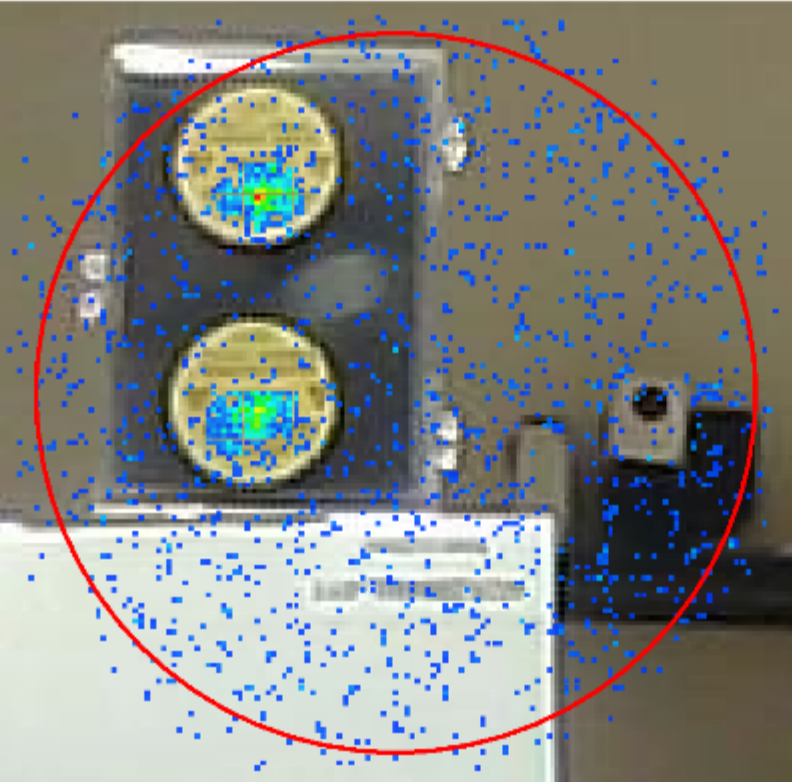
Intervening Materials

Material	Density(g/cm)	Thick(cm)

ROI Materials

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

There are no items to show in this view.



Units: MegaBecquerel (MBq)

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

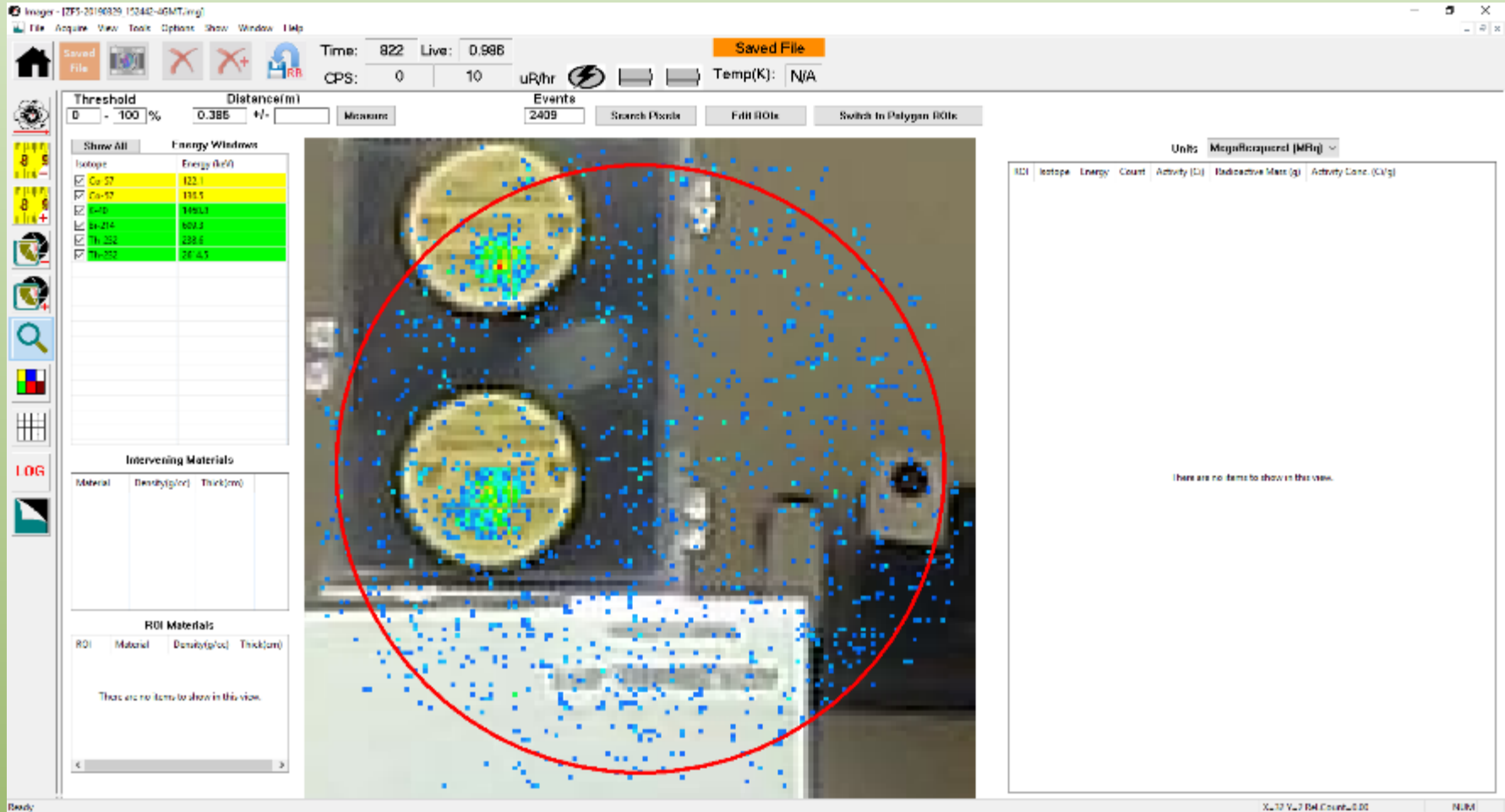
Ready

XL-13 YL-DRM Count=0.00 NUM

“Zoomfactor”

ZF5

2x <sup>57</sup>Co at 38.5 cm



The screenshot shows the Inveon software interface for a ZF5 detector. The main window displays a gamma-ray image of two sources, with a red circle highlighting a zoomed-in region. The interface includes a menu bar, a toolbar, and several panels for data and settings.

**Top Panel:** Time: 822, Live: 0.986, Saved File, CPS: 0, 10, uR/hr, Temp(K): N/A

**Threshold Panel:** Threshold: 0, Distance(m): 0.385, Events: 2409

**Energy Windows Panel:**

Isotope	Energy (keV)
<input checked="" type="checkbox"/> Co-57	123.1
<input checked="" type="checkbox"/> Cs-137	137.5
<input checked="" type="checkbox"/> Bi-214	1120.3
<input checked="" type="checkbox"/> Bi-214	609.3
<input checked="" type="checkbox"/> Th-232	220.4
<input checked="" type="checkbox"/> Th-232	2614.5

**Intervening Materials Panel:**

Material	Density(g/cm)	Thick(cm)

**ROI Materials Panel:**

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

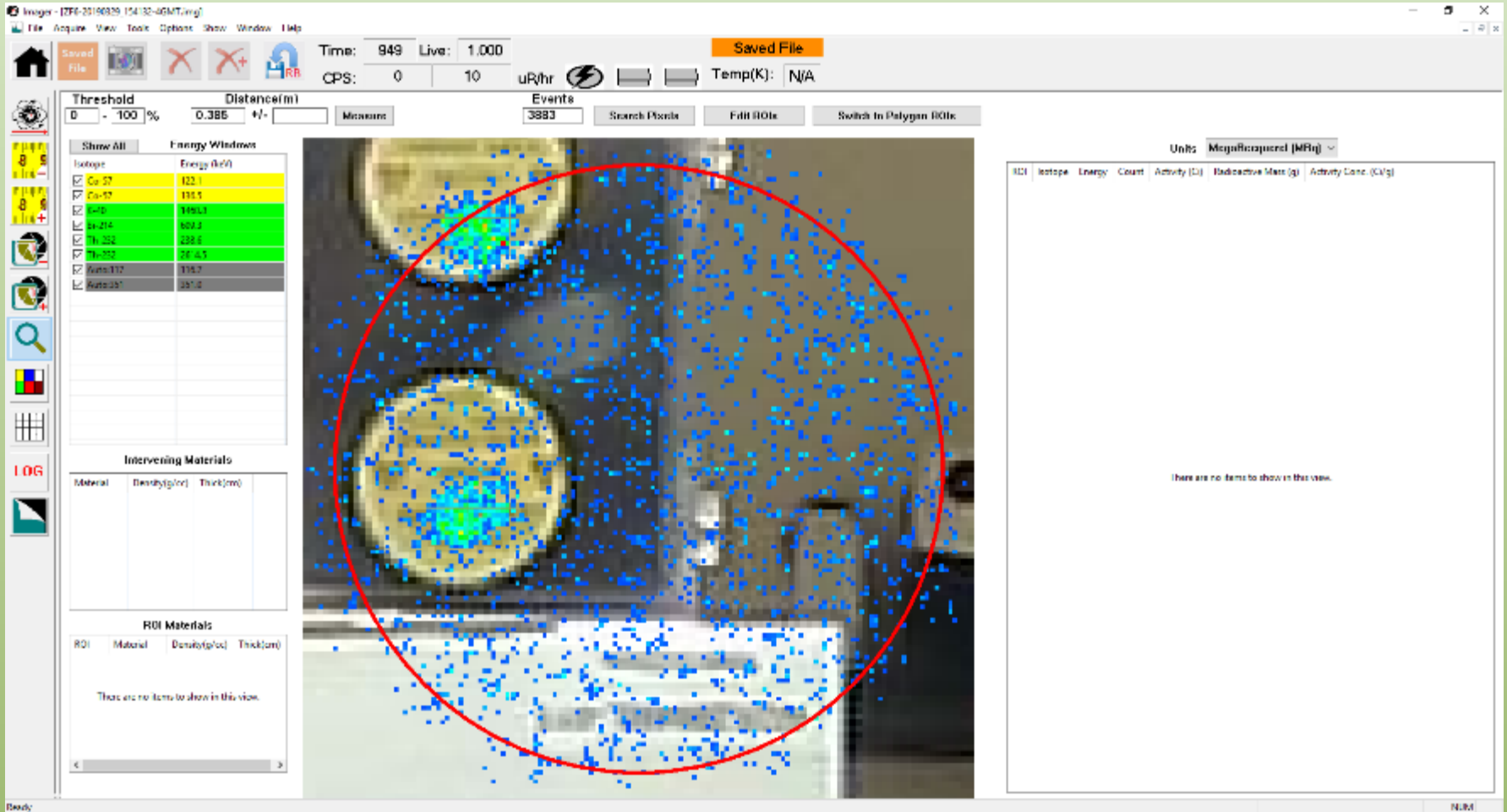
**Right Panel:** Units: MegaBecquerel (MBq). Table with columns: ROI, Isotope, Energy, Count, Activity (Bq), Radioactive Mass (g), Activity Conc. (Ci/g). Message: There are no items to show in this view.

**Status Bar:** Ready, XL17 VL7 RM Count=0.00, NUM

“Zoomfactor”

ZF6

2x <sup>57</sup>Co at 38.5 cm



**Time:** 949 **Live:** 1.000 **Saved File**

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

**Threshold:** 0 - 100% **Distance(m):** 0.385 **Events:** 3883

**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"/> Gd-153	106.3
<input checked="" type="checkbox"/> Gd-153	203.8
<input checked="" type="checkbox"/> Tl-208	2614.5
<input checked="" type="checkbox"/> Gm-137	1120.2
<input checked="" type="checkbox"/> Background	257.0

**Intervening Materials**

Material	Density(g/cm)	Thick(cm)
This area has no items to show in this view.		

**ROI Materials**

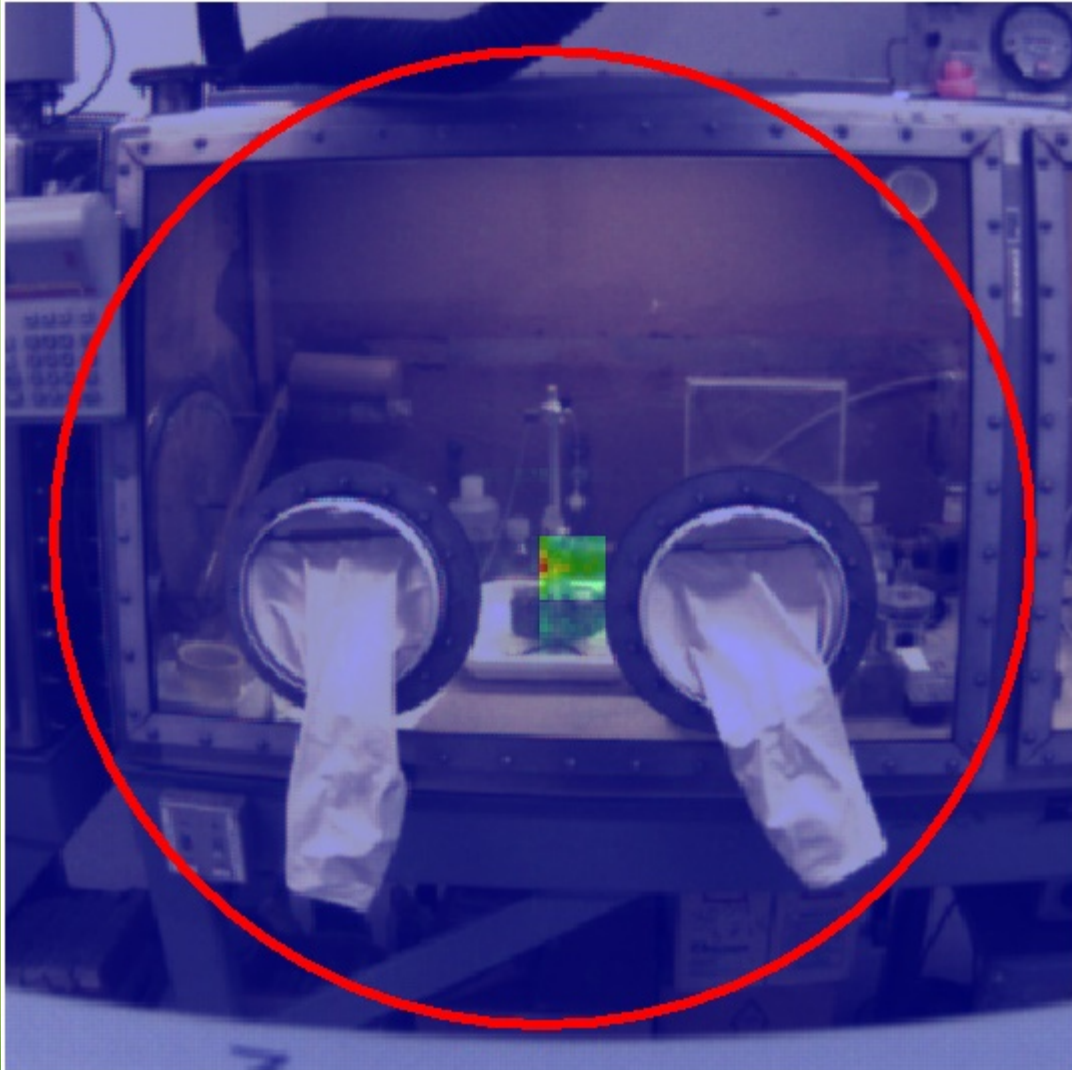
ROI	Material	Density(g/cm)	Thick(cm)
This area has no items to show in this view.			

**Units:** MegaBecquerel (MBq)

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

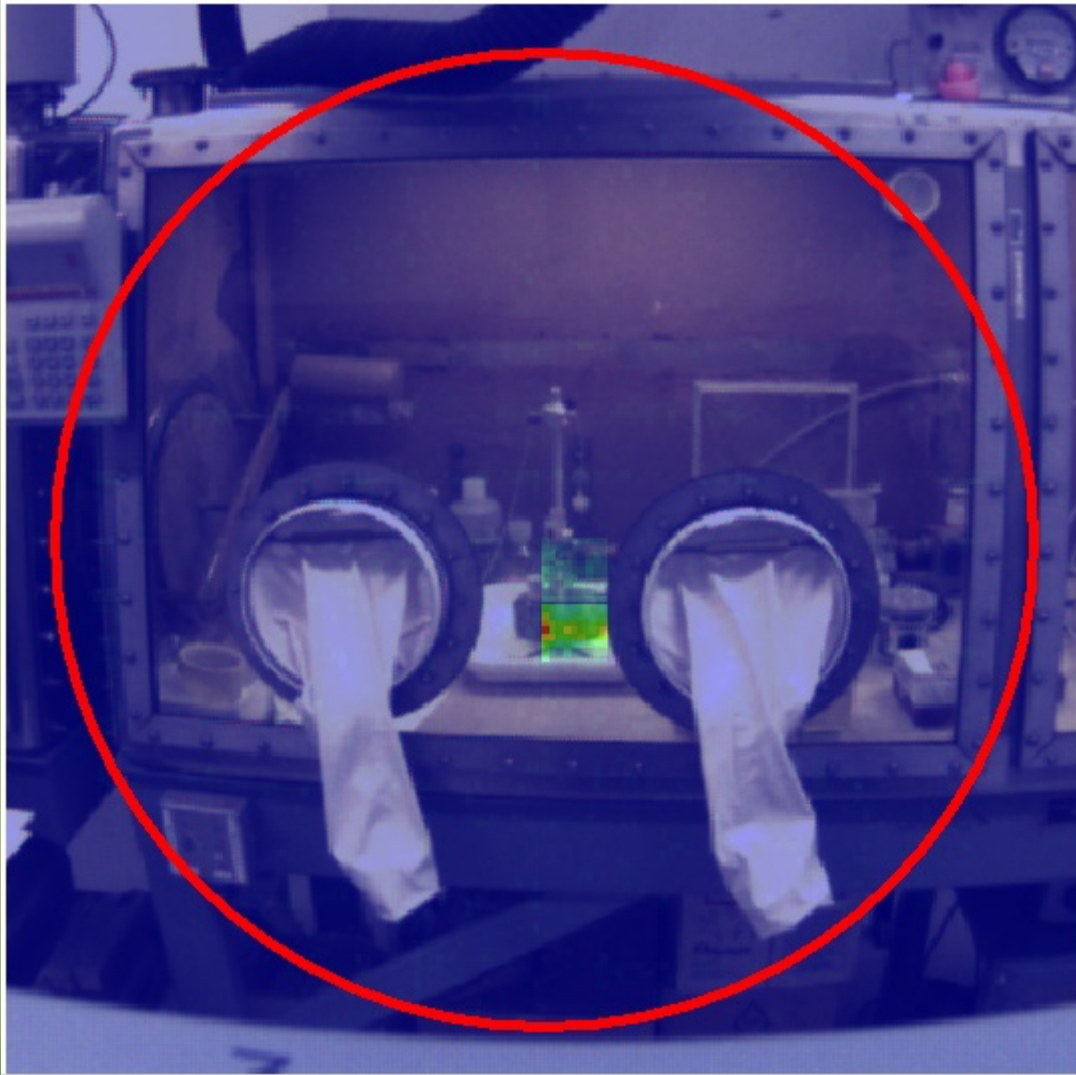


40 keV  $^{225}\text{Ra}$



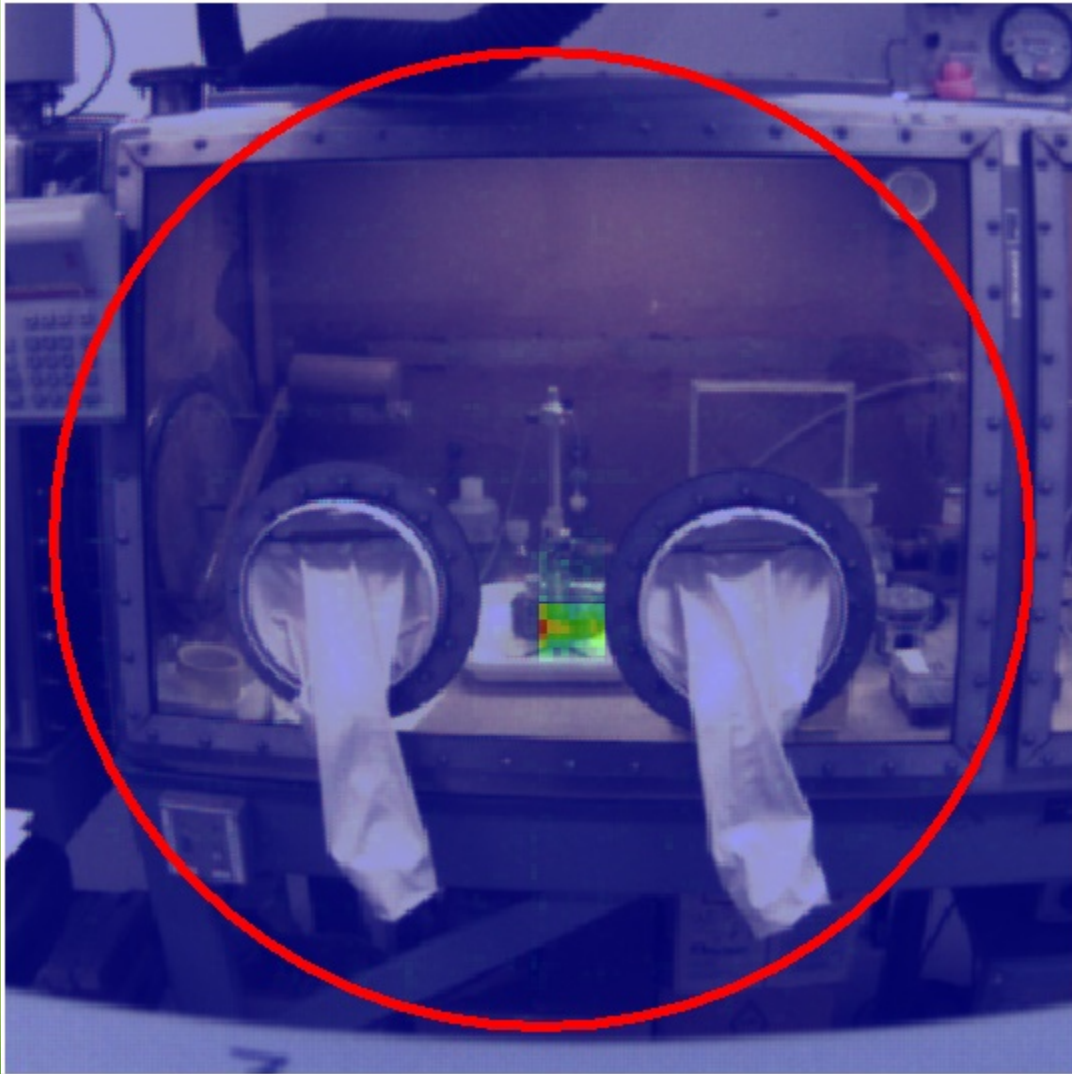
5 min

40 keV  $^{225}\text{Ra}$



10 min

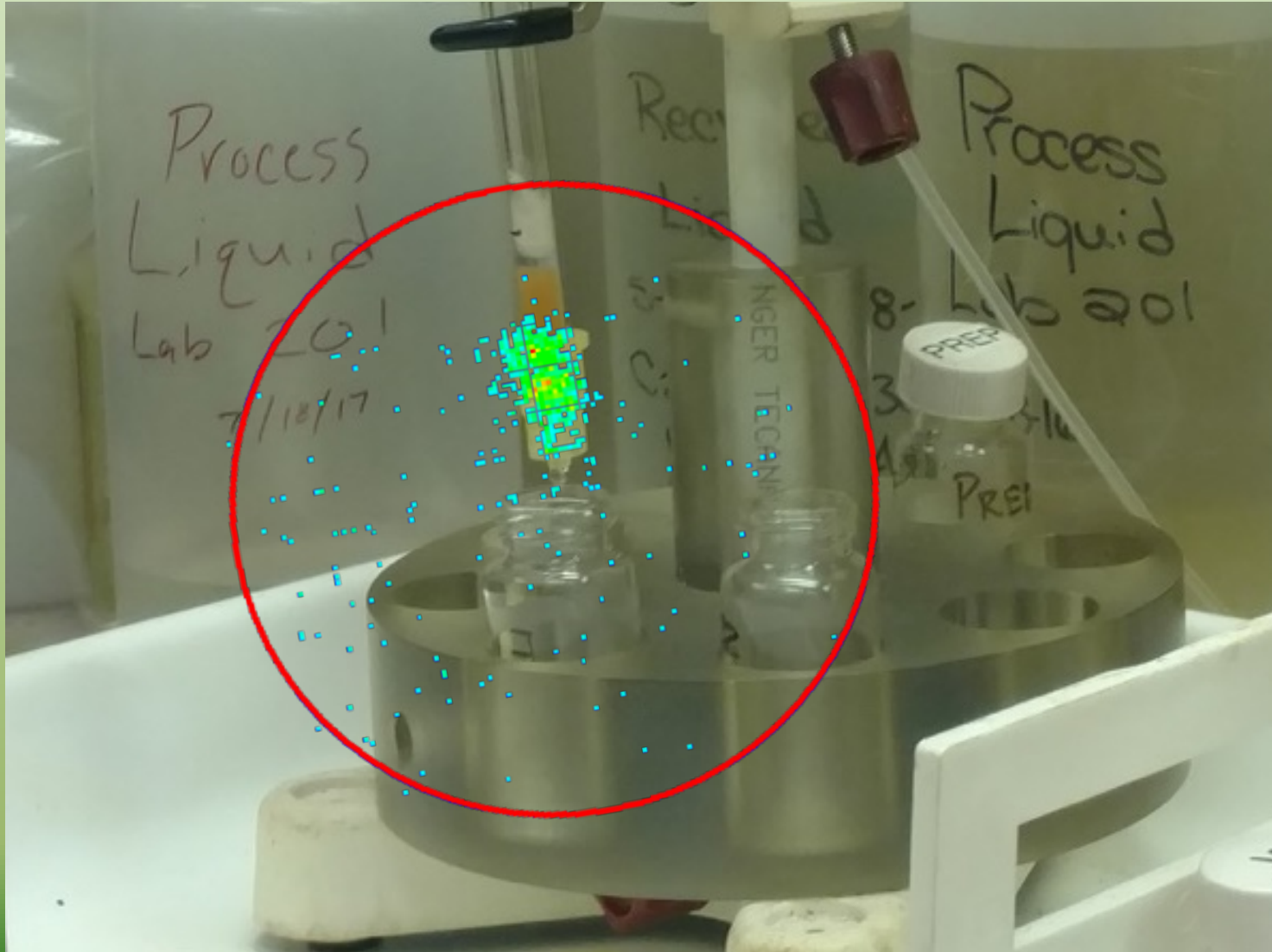
40 keV  $^{225}\text{Ra}$



15 min

# $^{225}\text{Ra}$ Wash (0 min)

ORNL

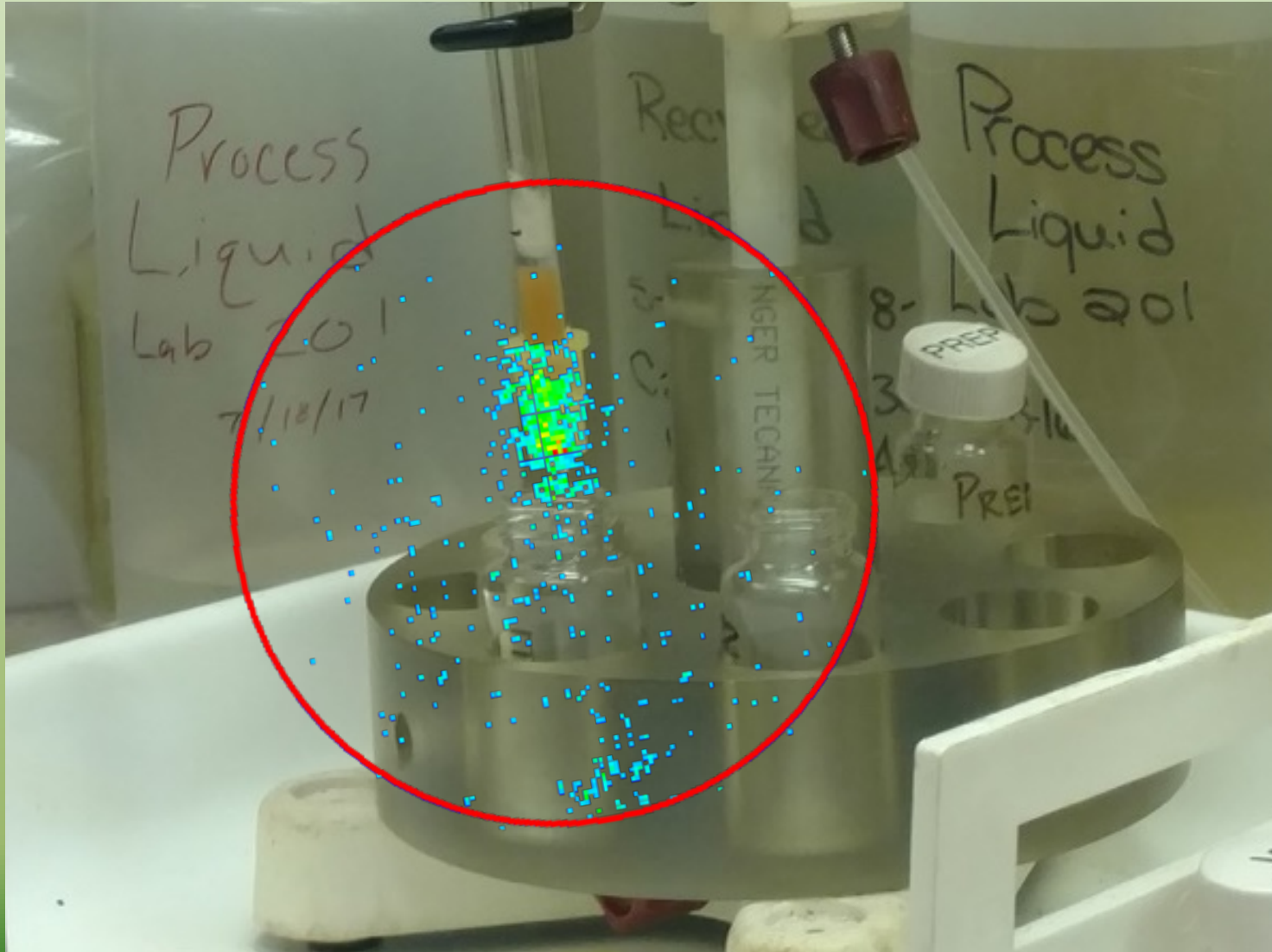


8x  
Larger  
than  
before



# $^{225}\text{Ra}$ Wash (5 min)

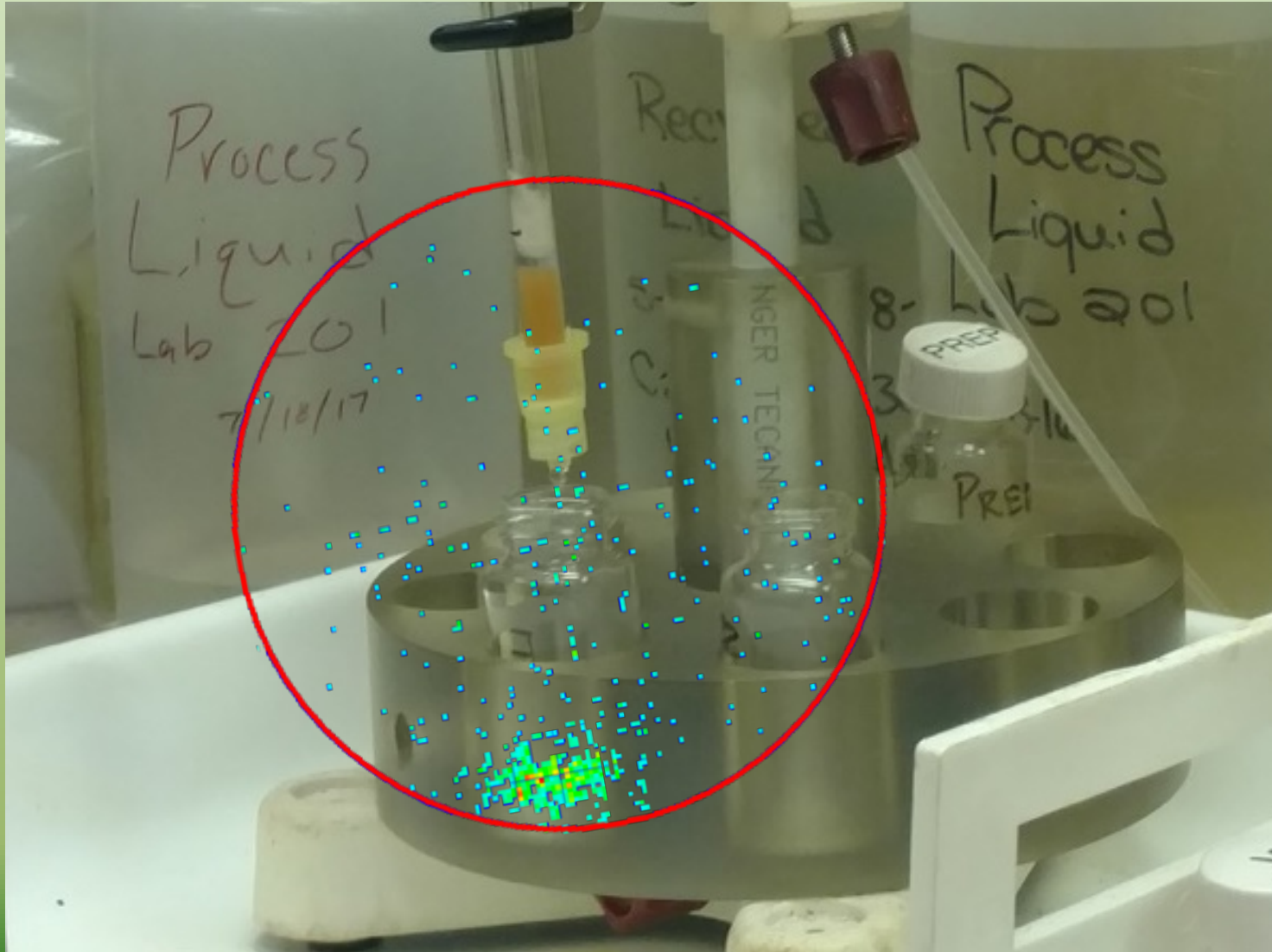
ORNL



8x  
Larger  
than  
before

# $^{225}\text{Ra}$ Wash (10 min)

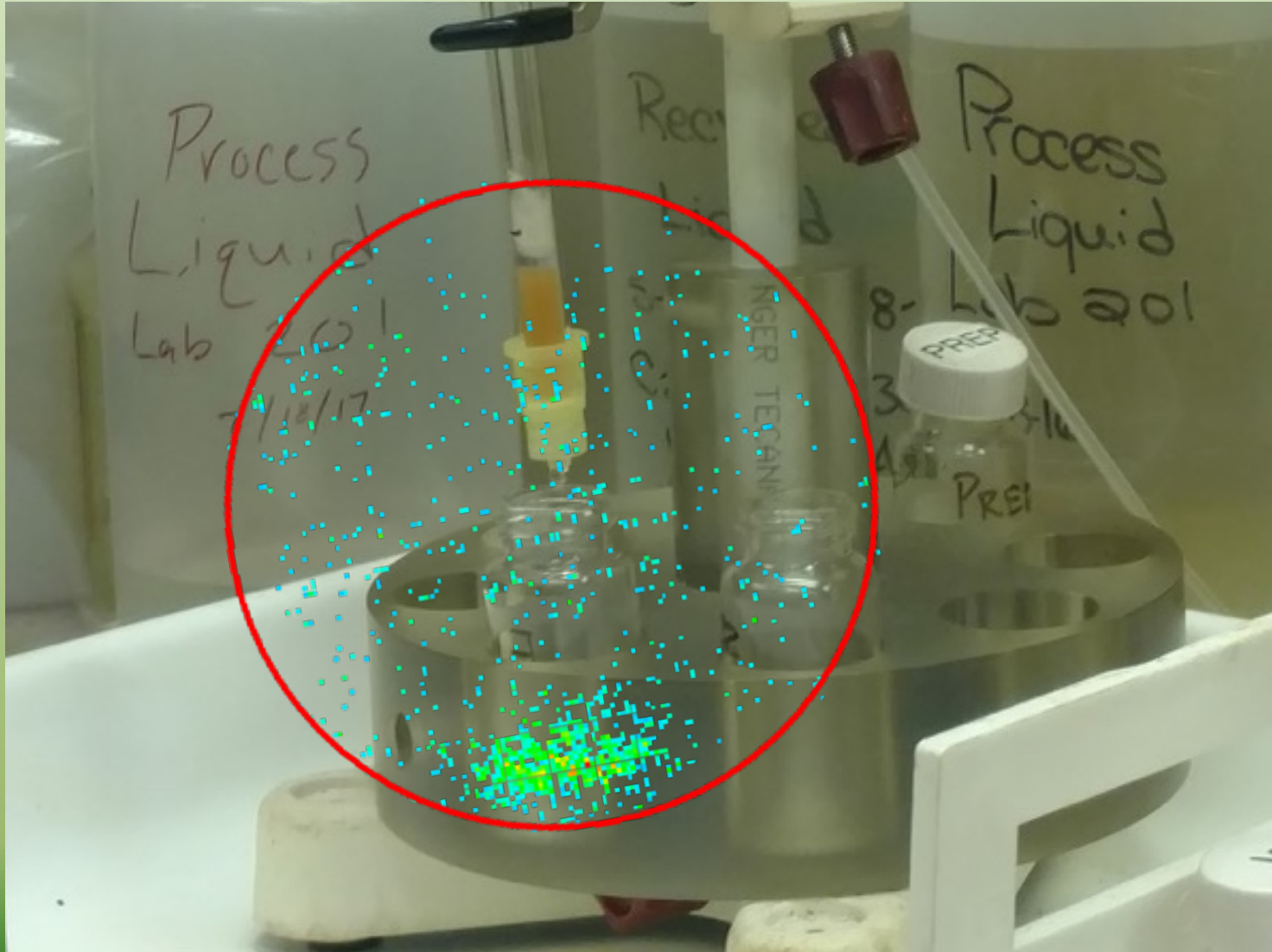
ORNL



8x  
Larger  
than  
before

# $^{225}\text{Ra}$ Wash (15 min)

ORNL

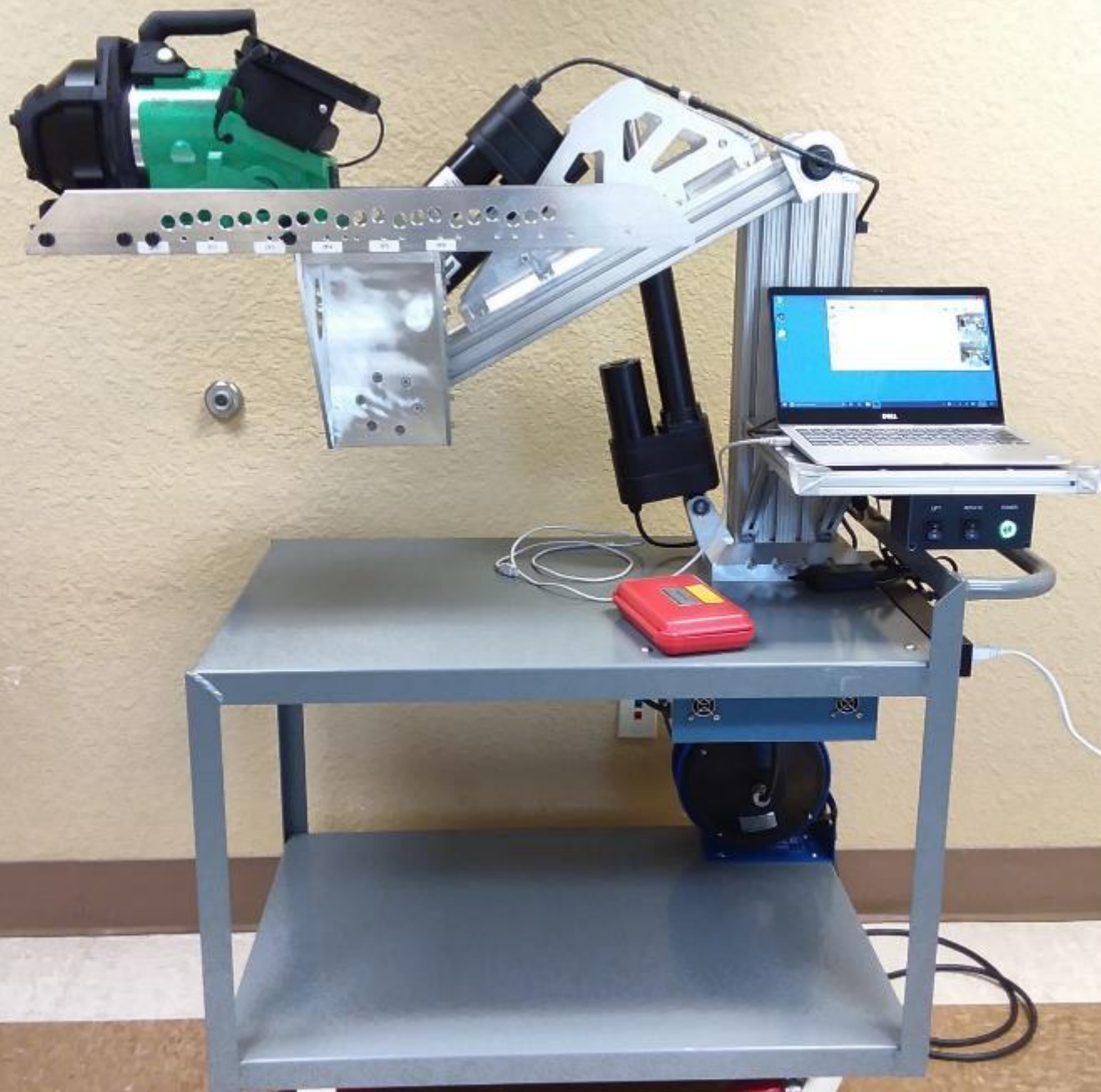


8x  
Larger  
than  
before

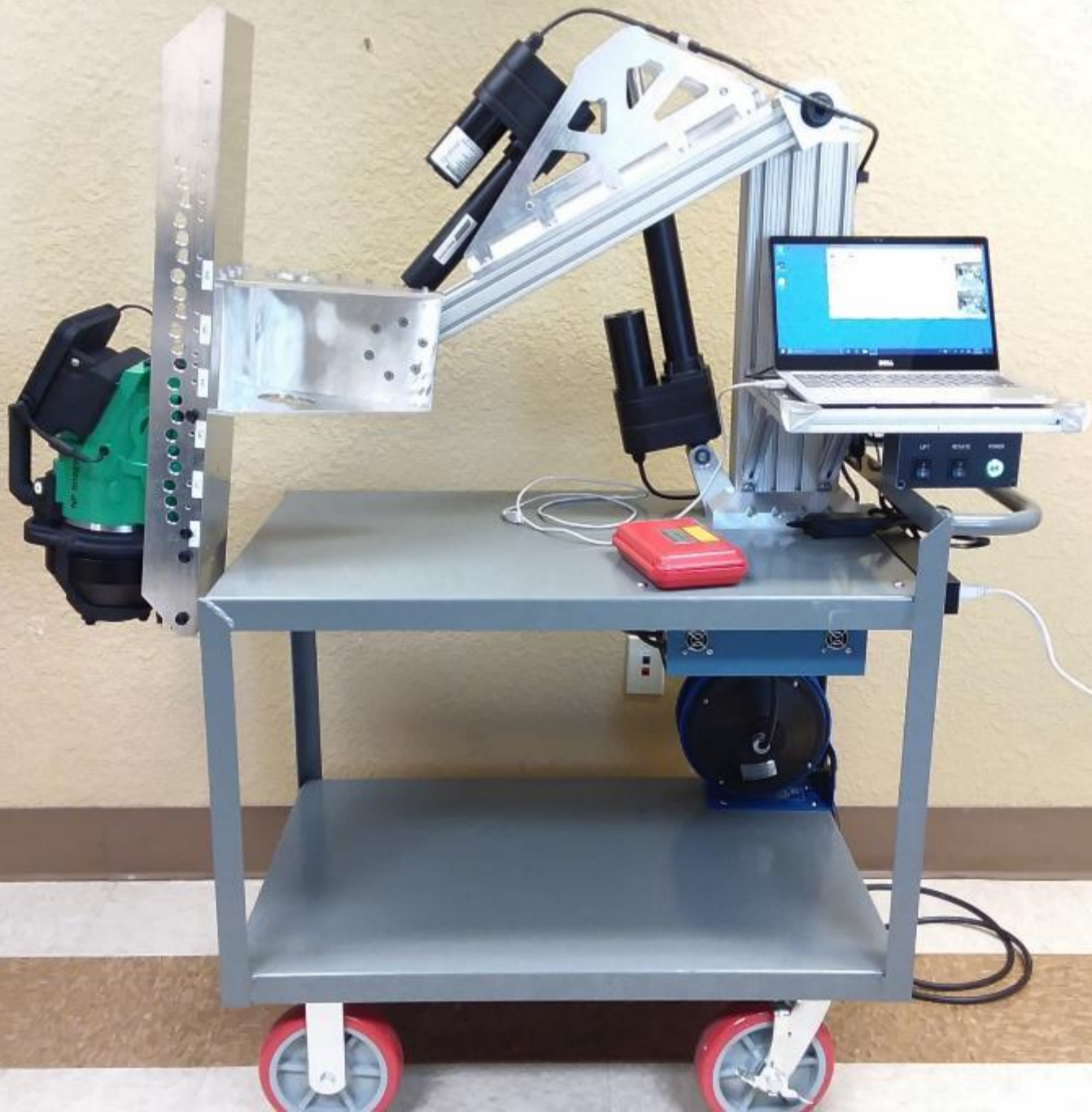






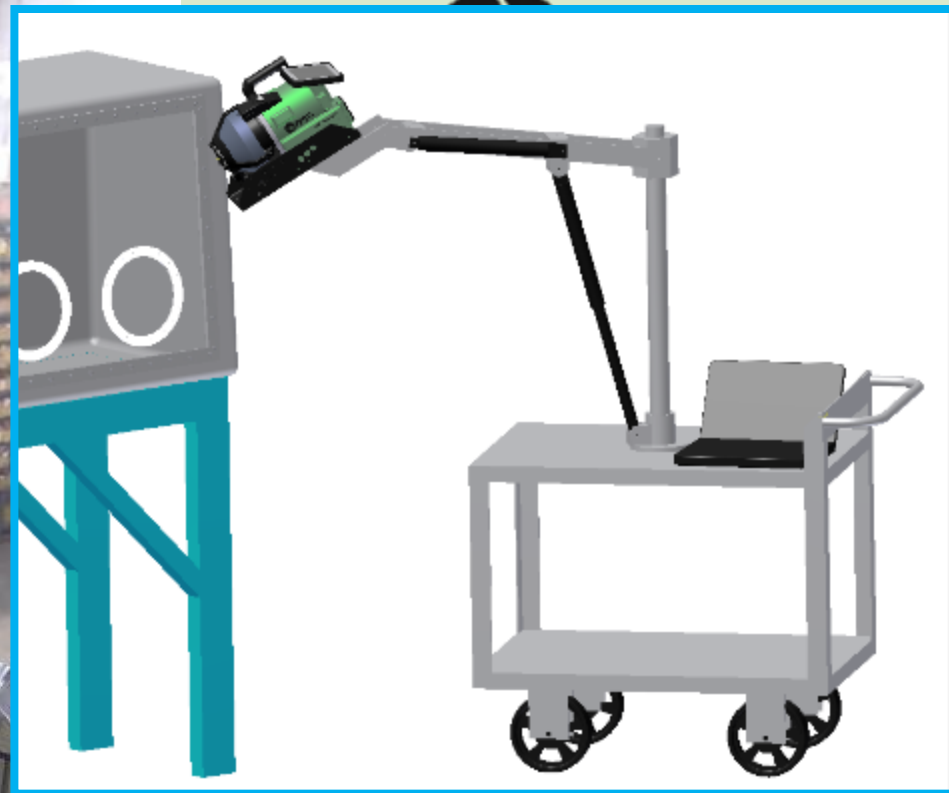














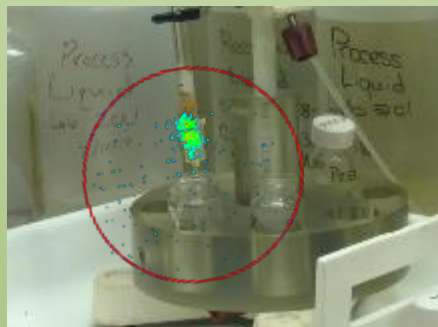




**PHDS**  
Gamma Ray Imaging Detectors

# Radiochemistry Imaging Examples

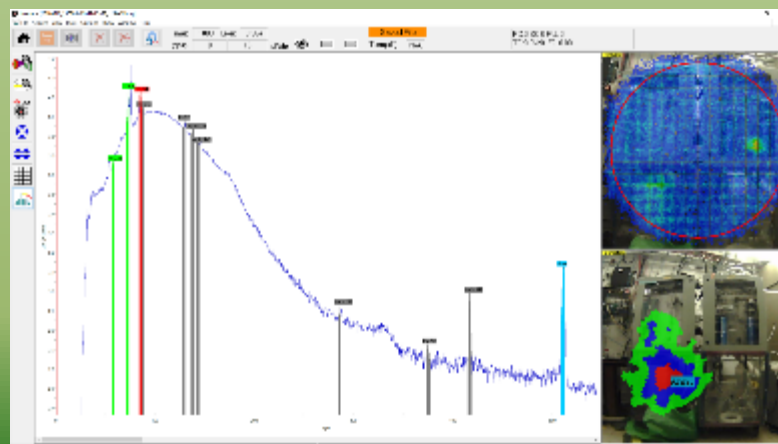
ORNL



MURR



NSCL





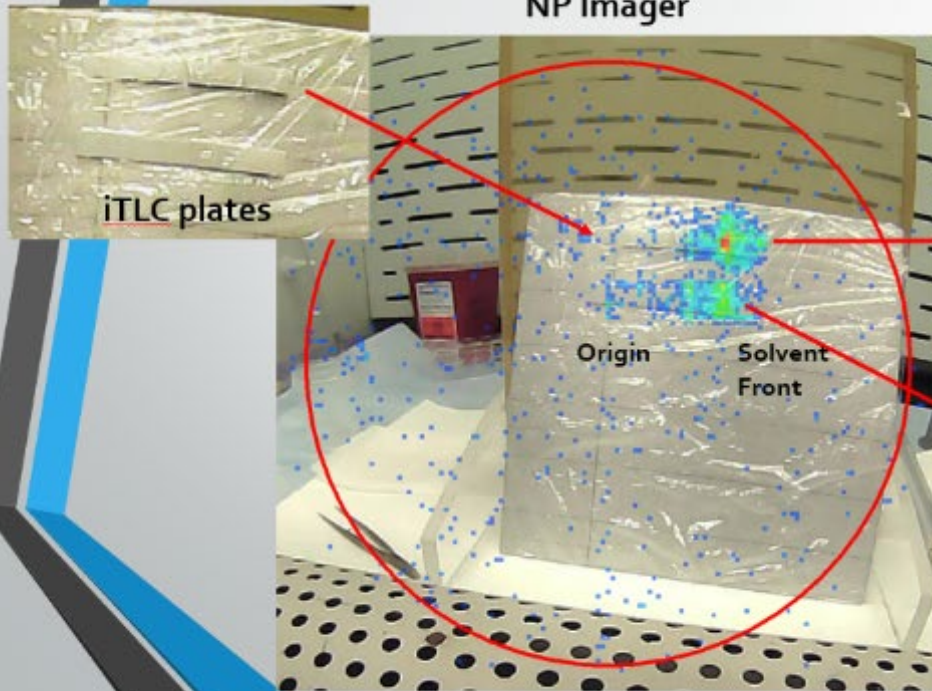
MURR



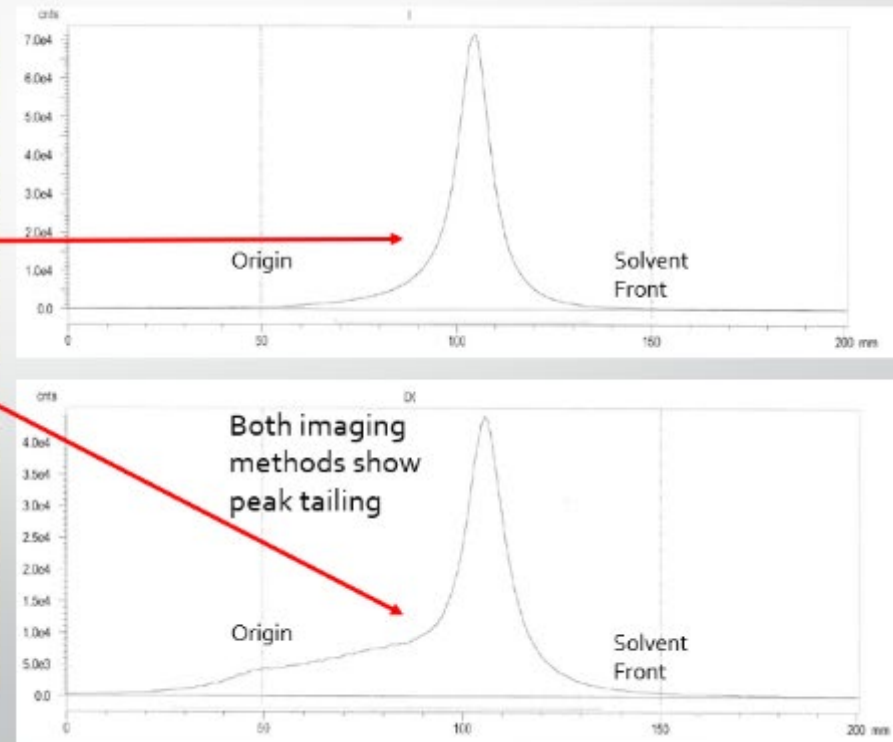
**PHDS**  
Gamma Ray Imaging Detectors

# iTLC plates of Tb-161/Gd-159 mixture developed in acidified saline

NP Imager



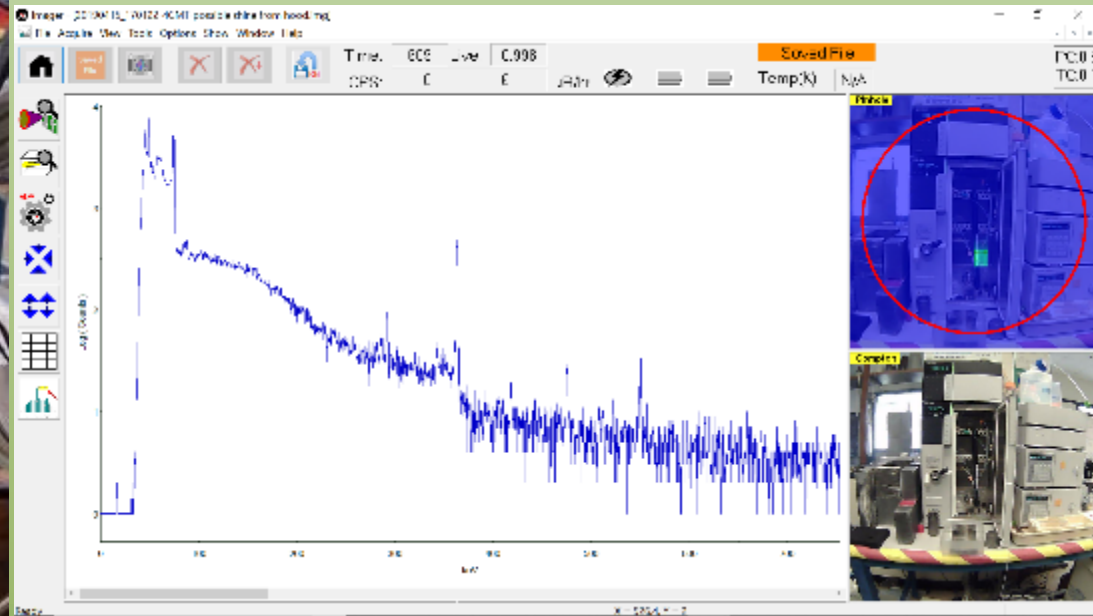
RadioTLC



Example of a useful static measurement

MURR

# HPLC separation of $^{159}\text{Gd}$ and $^{161}\text{Tb}$ (High pressure liquid chromatography)



20190415 Day 1 at MURR for delivery of the first NP Imager Prototype

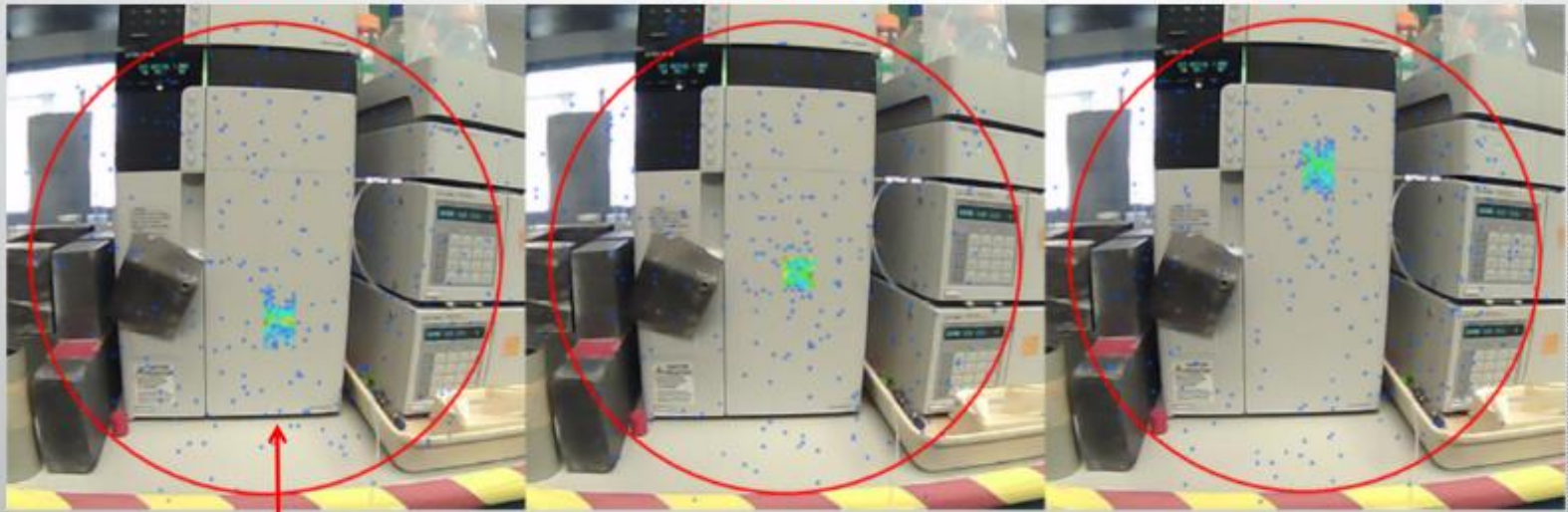


## HPLC isolation of Tb-161 from Gd, showing movement of Tb-161/Gd-159 through the column over time

At 8 min

At 43 min

At 69 min



HPLC column housing: the column inside this chamber has a vertical orientation with a flow inlet at the bottom and a flow outlet at the top



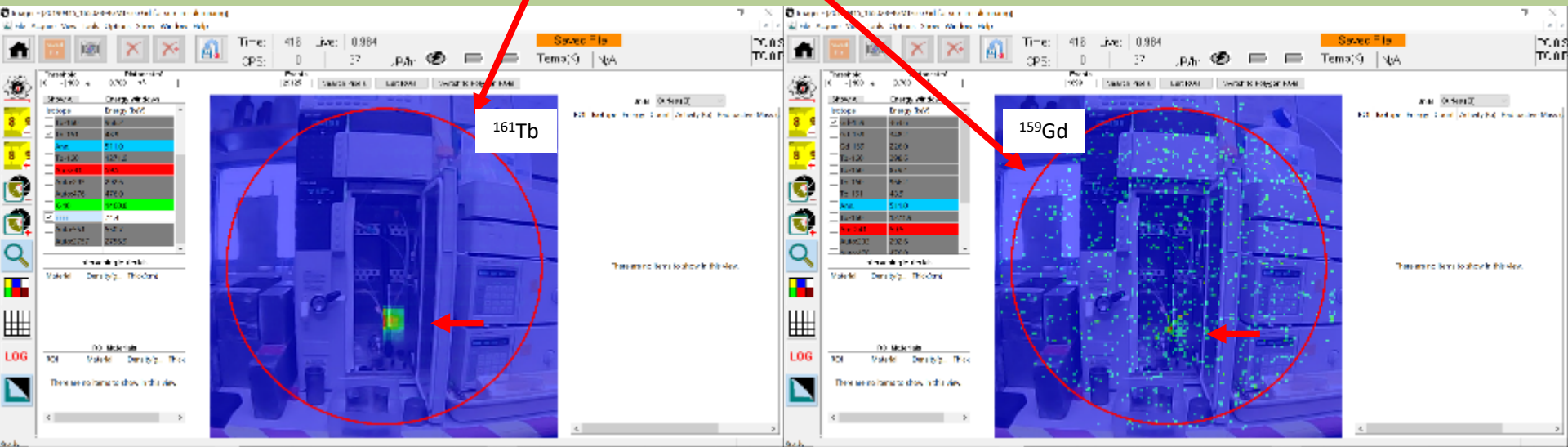
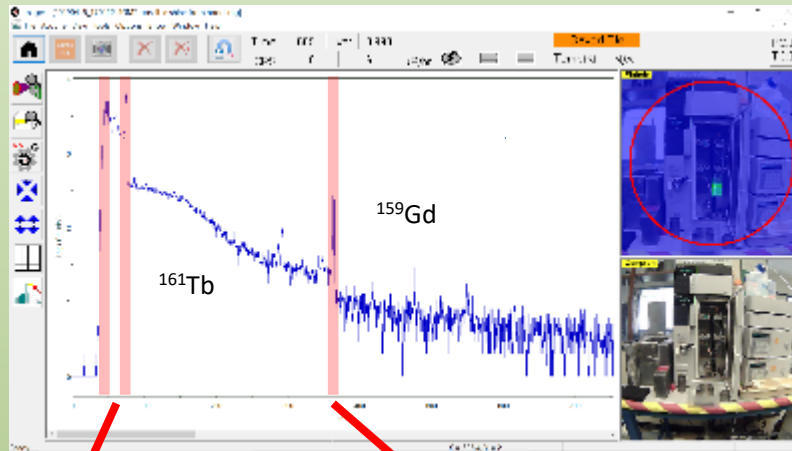
# MURR

49 keV

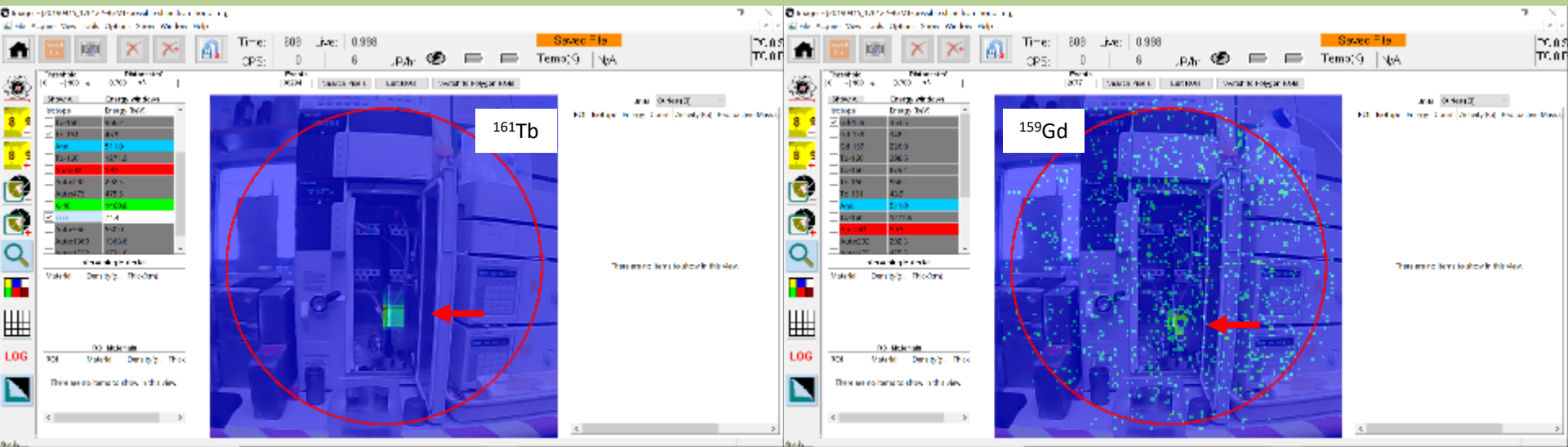
74 keV

363 keV

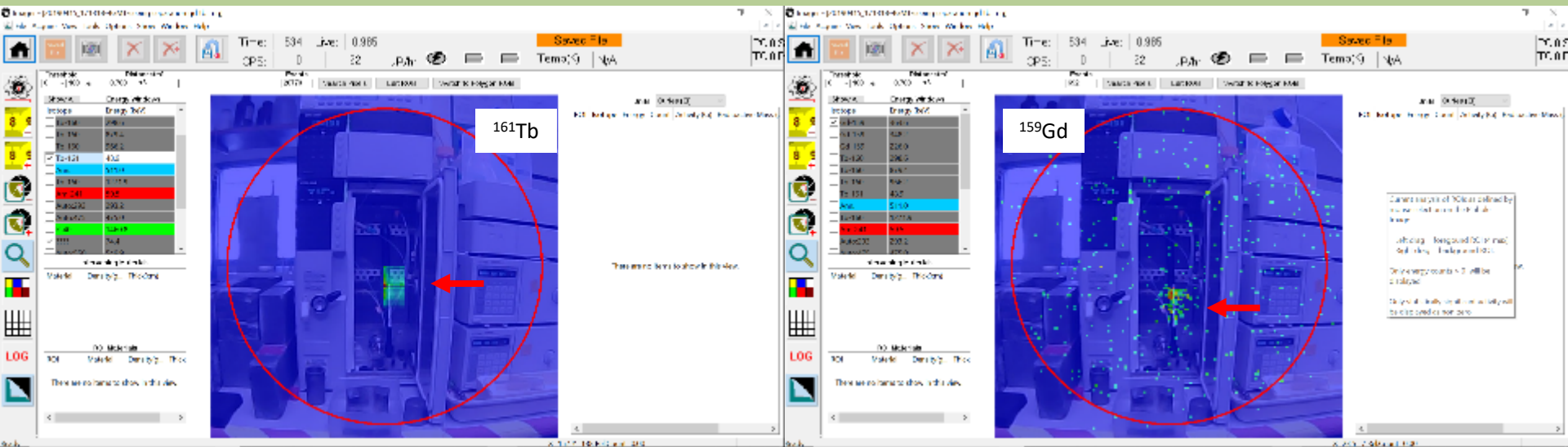
7 min



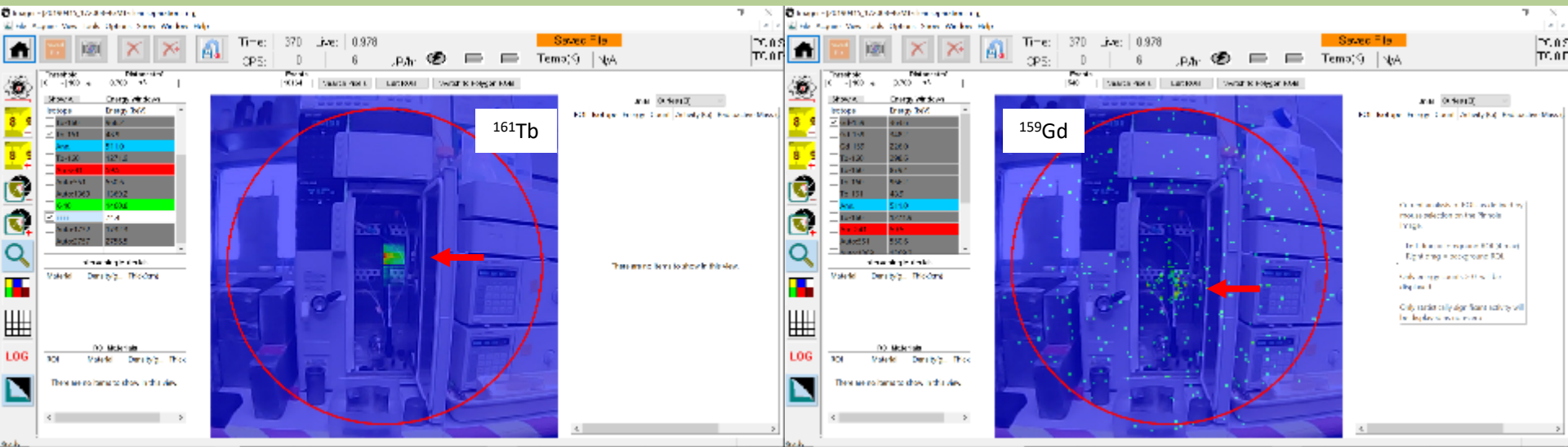
18 min



30 min

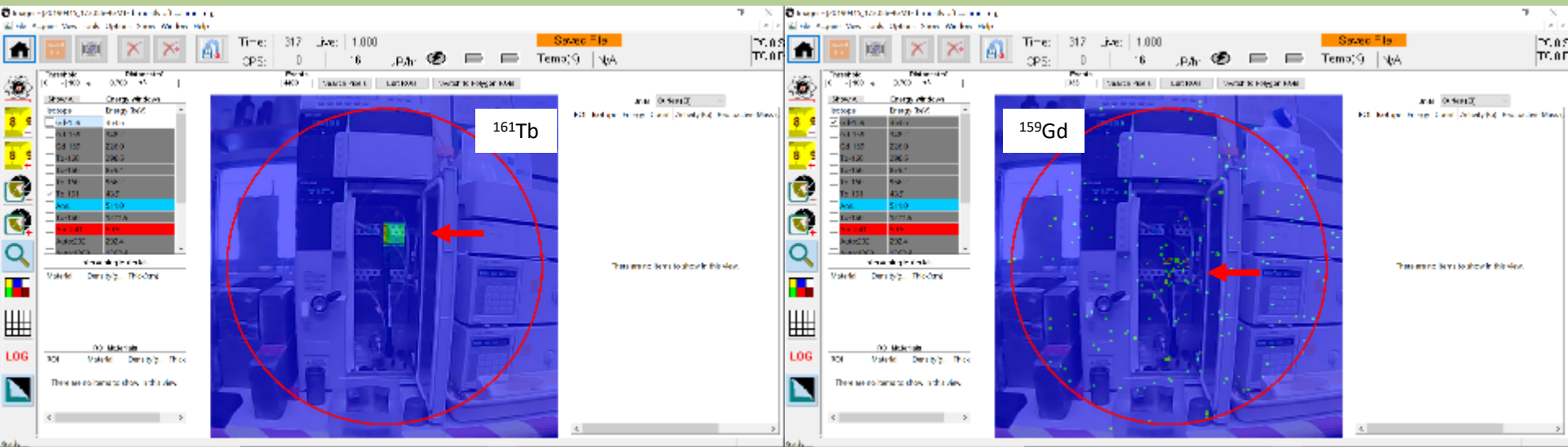


37 min





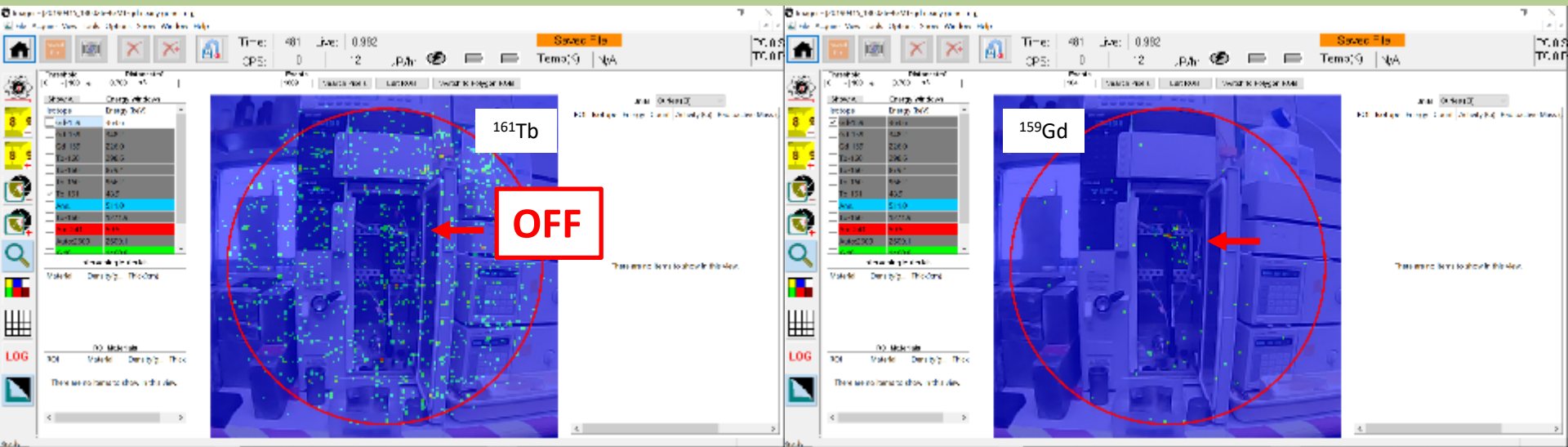
47 min







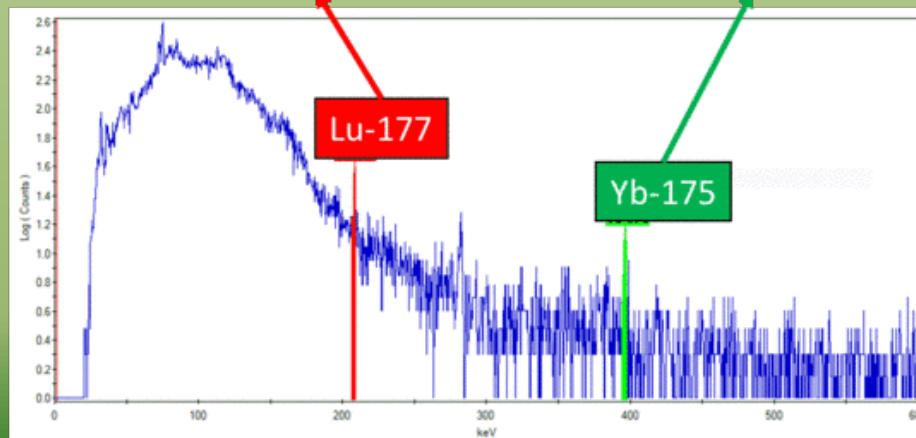
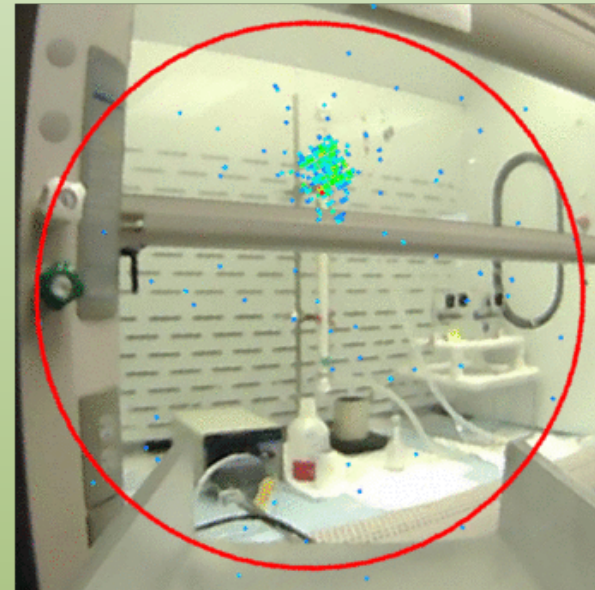
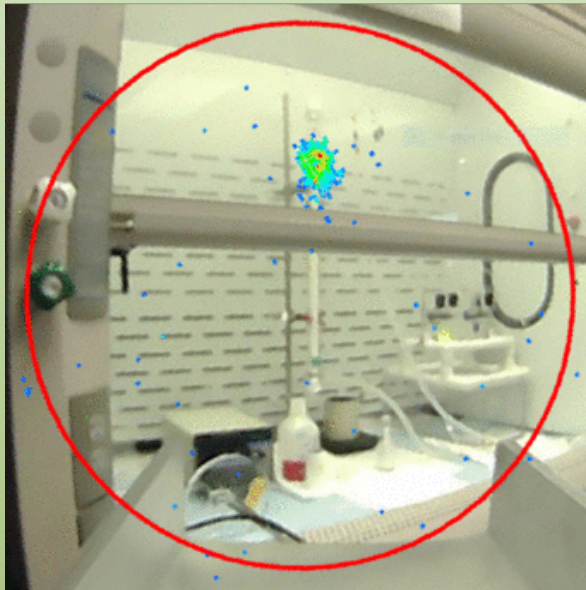
77 min





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

t = 0 - 10 minutes

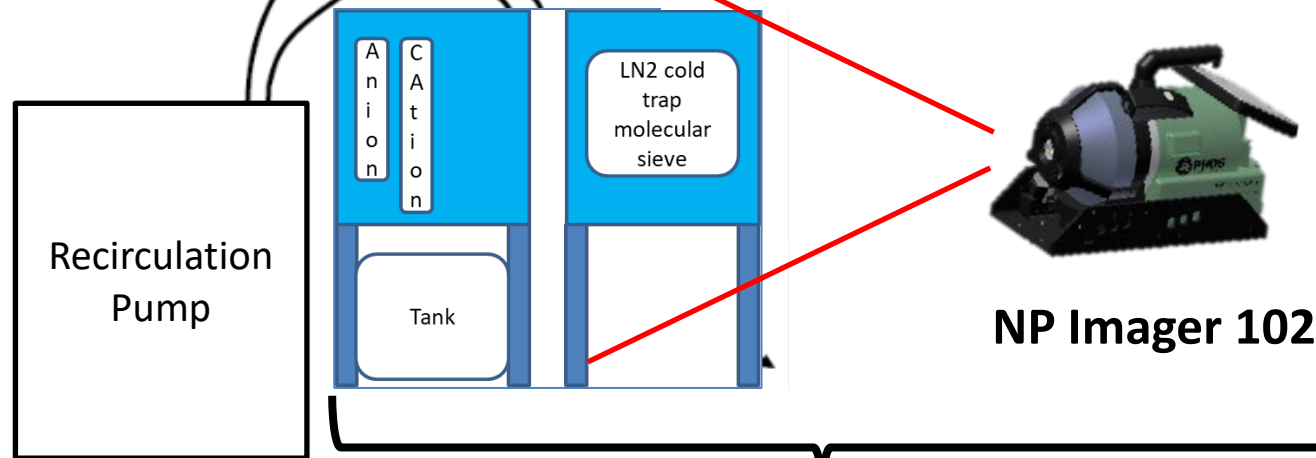


**Beam Stop**

Beam strikes front face of blocker  
(0.5 mm thick SS, 25mm Water)

$^{78}\text{Kr}$

Thermocouple  
on exit tube



9 meters down stream from beam stop at ~ 30°

Imager - [20190510\_230705-4GMT-Kry77\_120kvV.img]

File Acquire View Tools Options Show Window Help

Time: 1003 Live: 0.964 Saved File

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

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

Threshold: 0 - 999 % Distance(m): 1.700

Events: 4164 Search Blank Edit ROIs Switch to Polygon ROIs

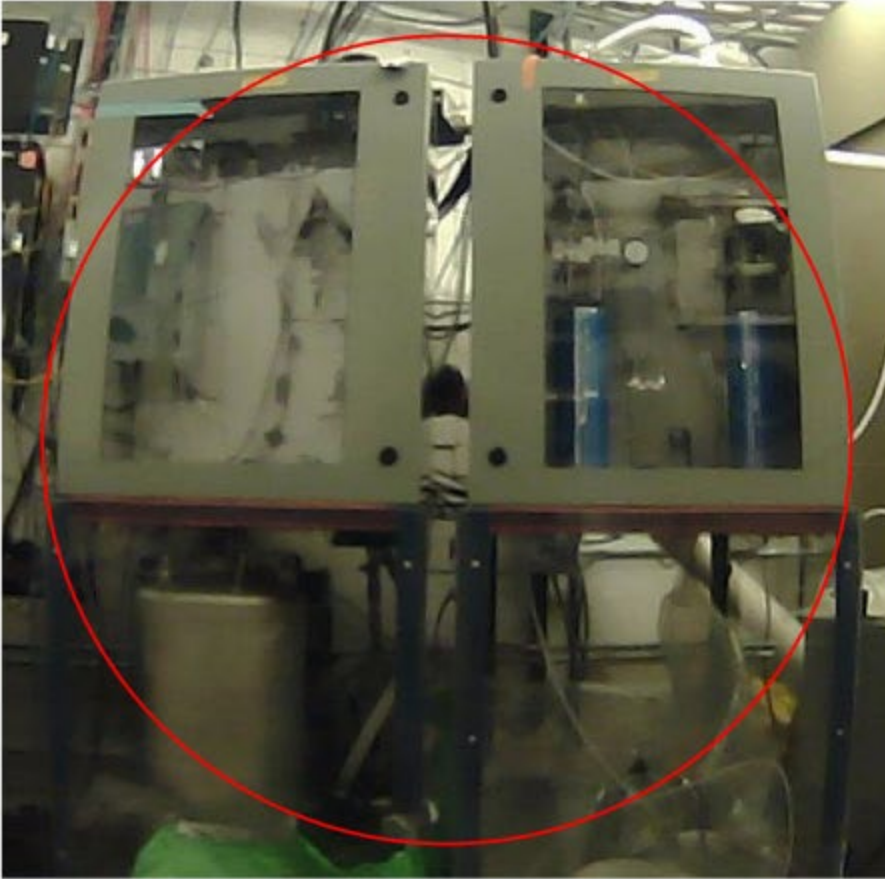
Isotope	Energy (keV)
<input type="checkbox"/> Th-232	97.8
<input type="checkbox"/> Th-232	72.8
<input type="checkbox"/> Auto:67	97.3
<input type="checkbox"/> Res.	911.0
<input type="checkbox"/> U-238	109.1
<input type="checkbox"/> U-238	88.8
<input type="checkbox"/> Auto:138	137.8
<input type="checkbox"/> NE12047	145.9
<input type="checkbox"/> Auto:141	143.3
<input type="checkbox"/> Auto:206	206.0
<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.		



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

There are no items to show in this view.

Ready

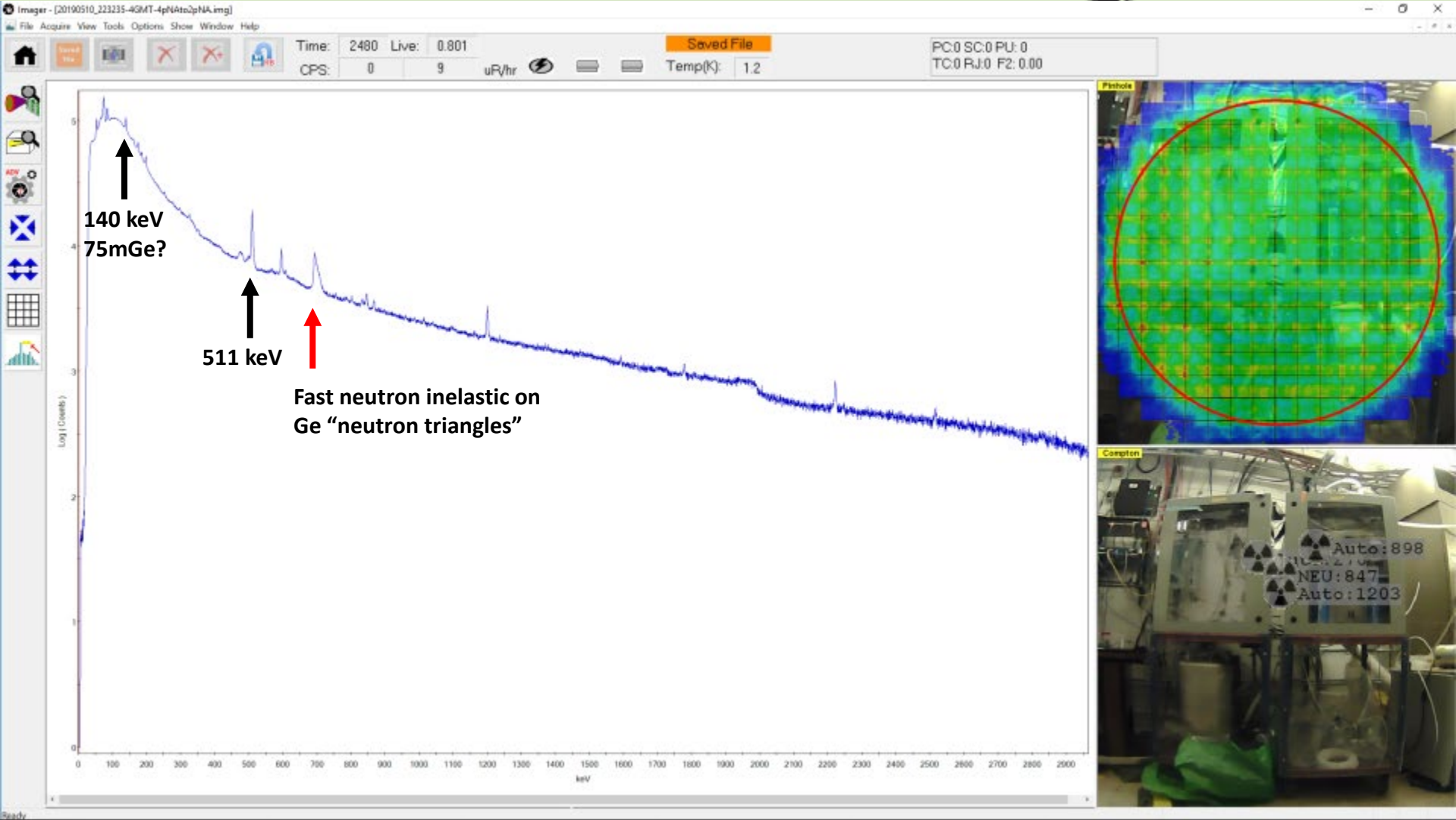


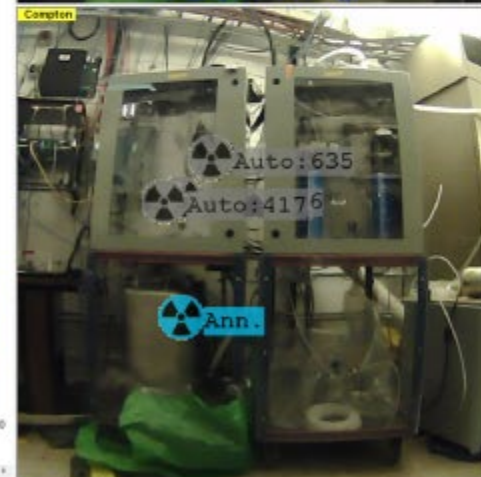
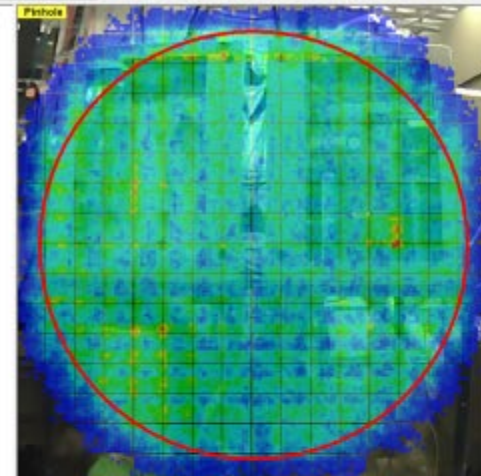
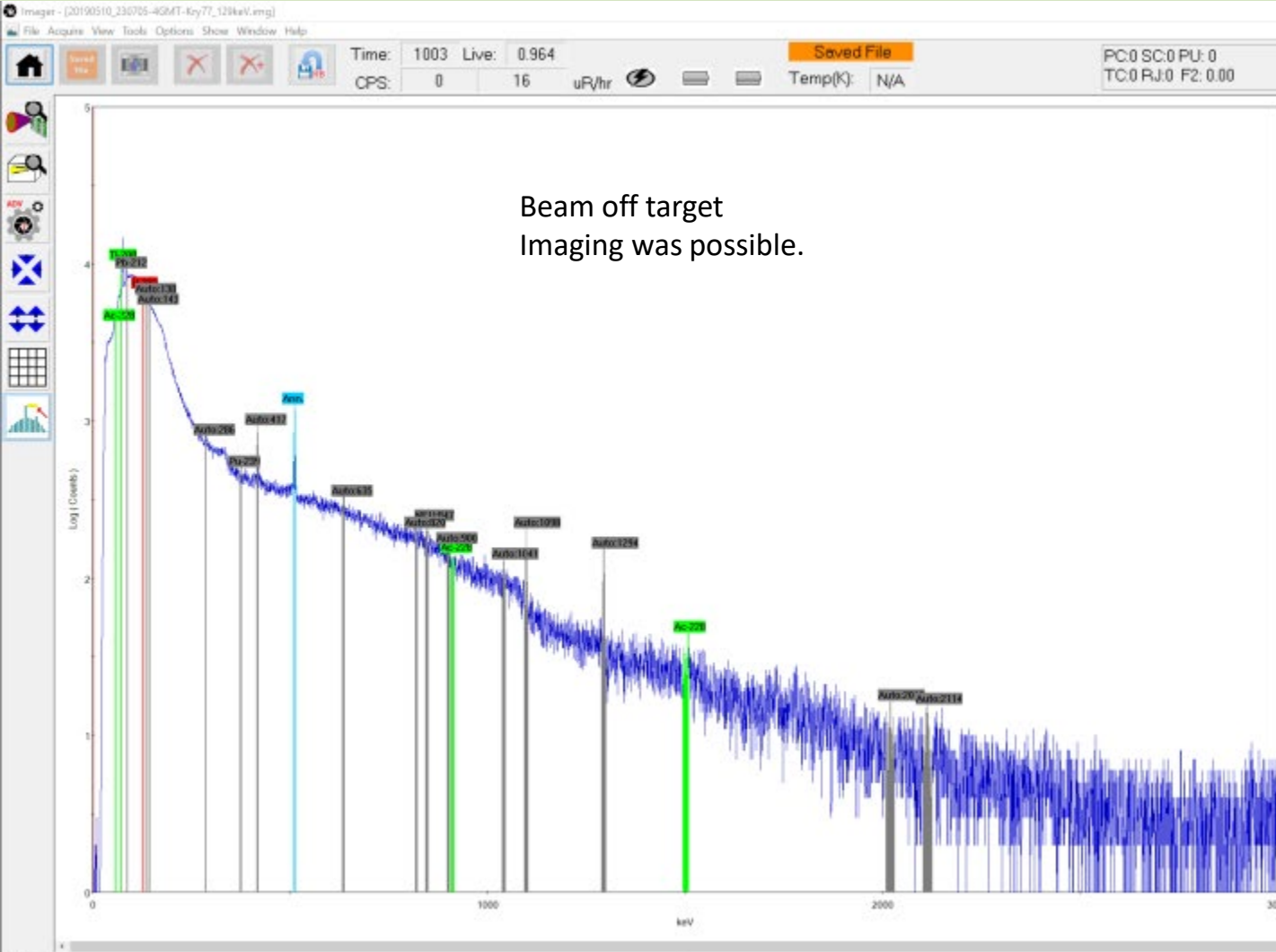
NSCL

## NP Imager 102













Imager - [20190510\_230705-4GMT-Kry77\_120korV.img]

File Acquire View Tools Options Show Window Help

Time: 1003 Live: 0.964 Saved File

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

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

Threshold: 0 - 100 % Distance: 1.700 cm

Events: 40000 Search Plots Edit ROIs Switch to Polygon ROIs

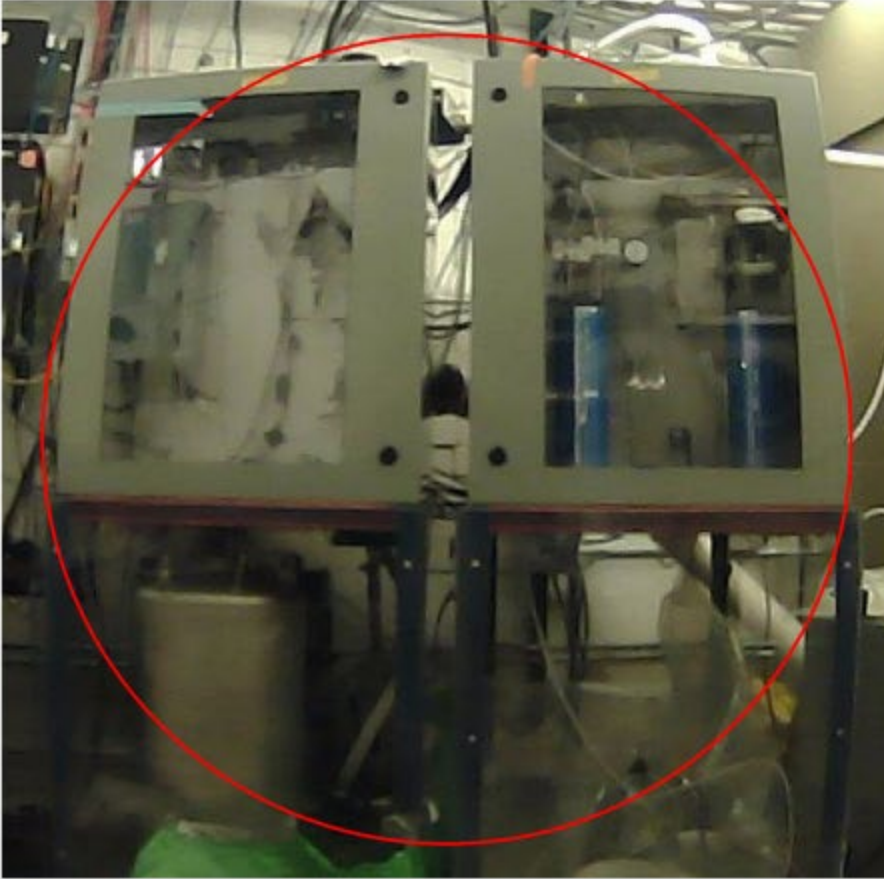
Isotope	Energy (keV)
<input type="checkbox"/> Pb-232	97.8
<input type="checkbox"/> Pb-232	92.8
<input type="checkbox"/> Auto:67	97.3
<input type="checkbox"/> Fe-55	511.0
<input checked="" type="checkbox"/> U-232	129.1
<input type="checkbox"/> U-232	86.8
<input type="checkbox"/> Auto:138	137.8
<input type="checkbox"/> Ni11047	845.9
<input type="checkbox"/> Auto:143	143.3
<input type="checkbox"/> Auto:286	286.0
<input type="checkbox"/> Auto:175	175.1
<input type="checkbox"/> Auto:417	417.1
<input type="checkbox"/> Auto:635	635.5
<input type="checkbox"/> Pb-232	91.2
<input type="checkbox"/> Auto:670	670.7
<input type="checkbox"/> Auto:500	500.4
<input type="checkbox"/> Pb-232	1201.6
<input type="checkbox"/> Auto:1041	1041.1
<input type="checkbox"/> Auto:1096	1097.7
<input type="checkbox"/> Auto:1284	1284.4

Intervening Materials

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

ROI Materials

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



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

There are no items to show in this view.



Imager - [20190510\_230705-4GMT-Kry77\_120korV.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(cm): 1.700 +/- 0.000

Events: 40000 Search Plots Edit ROIs Switch to Polygon ROIs

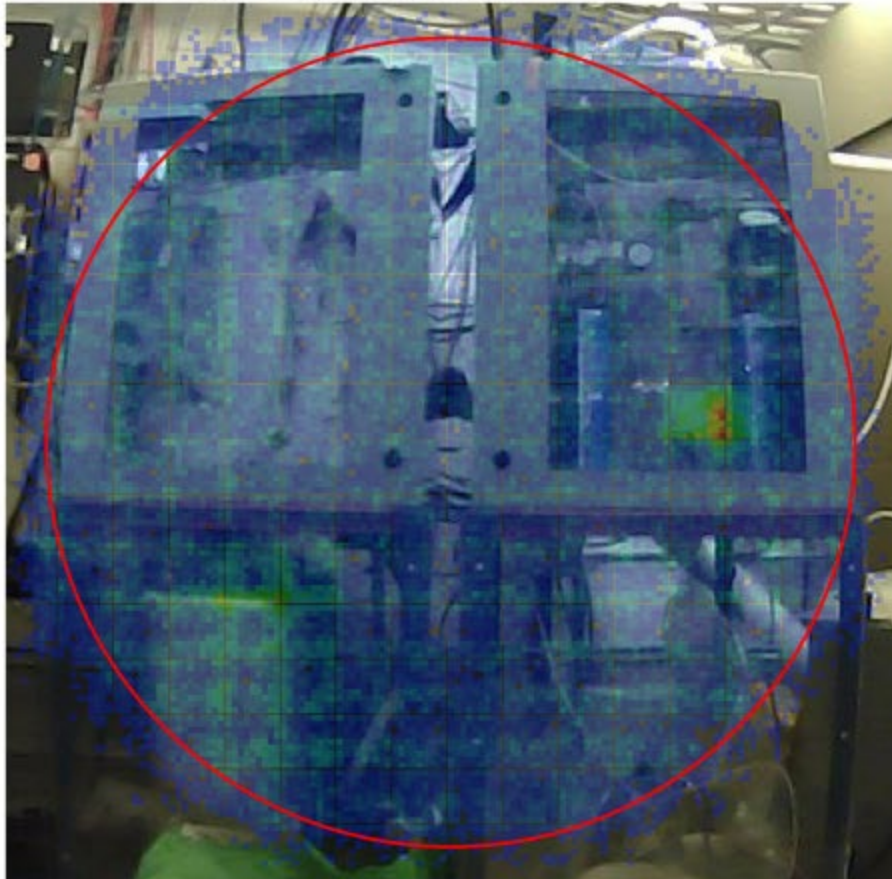
Isotope	Energy (keV)
<input type="checkbox"/> Pb-232	97.8
<input type="checkbox"/> Pb-232	92.8
<input type="checkbox"/> Auto:67	97.3
<input type="checkbox"/> Fe-55	551.0
<input checked="" type="checkbox"/> U-232	129.1
<input checked="" type="checkbox"/> U-232	86.8
<input type="checkbox"/> Auto:138	137.8
<input type="checkbox"/> Ni11047	845.9
<input type="checkbox"/> Auto:143	143.3
<input type="checkbox"/> Auto:286	286.0
<input type="checkbox"/> Auto:175	175.1
<input type="checkbox"/> Auto:417	417.1
<input type="checkbox"/> Auto:635	635.5
<input type="checkbox"/> Pb-232	91.2
<input type="checkbox"/> Auto:670	670.7
<input type="checkbox"/> Auto:500	500.4
<input type="checkbox"/> Pb-232	1501.6
<input type="checkbox"/> Auto:1041	1041.1
<input type="checkbox"/> Auto:1098	1097.7
<input type="checkbox"/> Auto:1284	1284.4

Intervening Materials

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

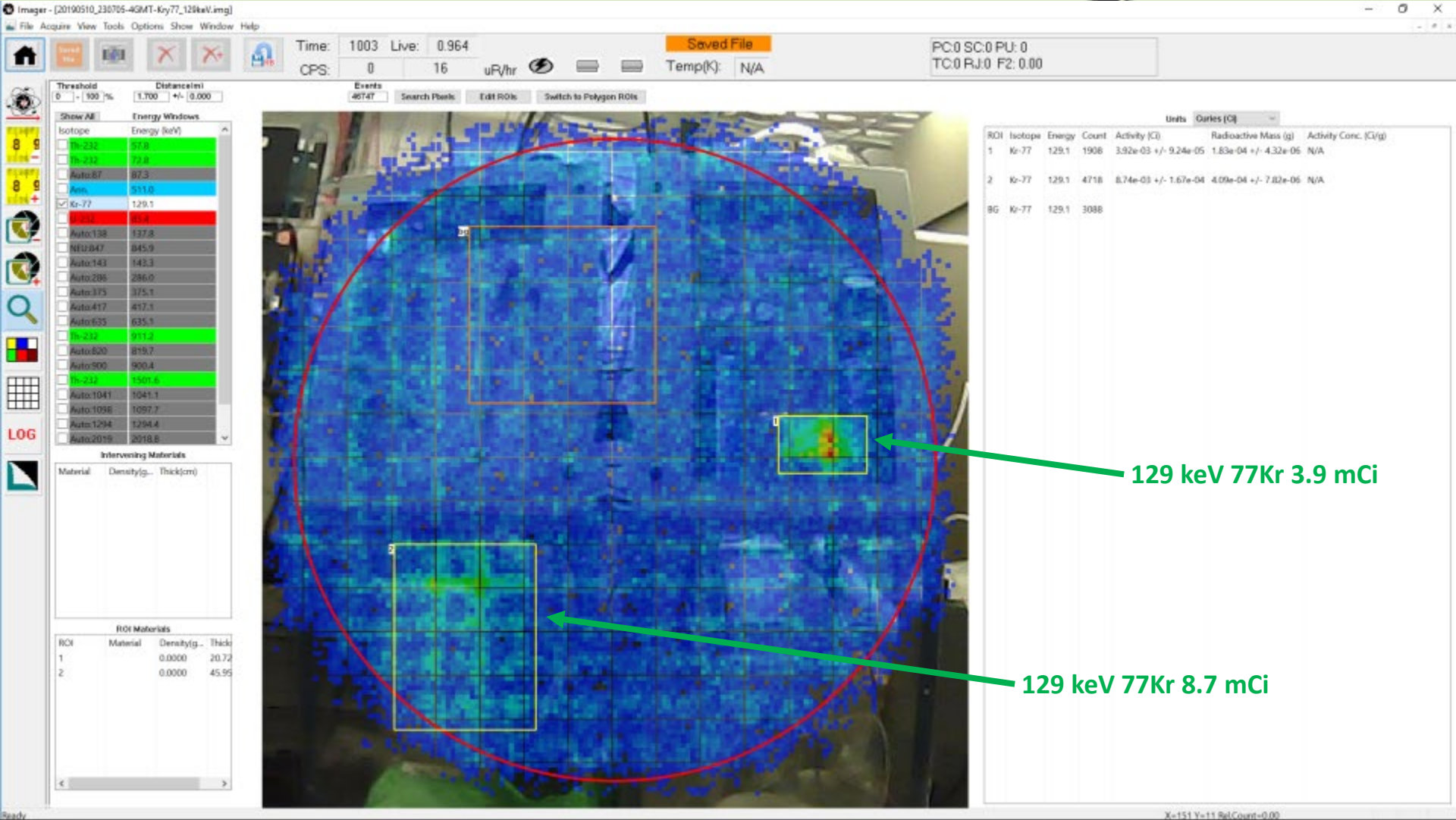
ROI Materials

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



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

There are no items to show in this view.





Imager - (20190510\_230705-4GMT-Ky77\_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 +/- 0.000

Events 11456

Search Peaks Edit ROIs Switch to Polygon ROIs

Show All Energy Windows

Isotope	Energy (keV)
<input type="checkbox"/> Pb-212	97.8
<input type="checkbox"/> Pb-212	72.8
<input type="checkbox"/> Auto-87	87.3
<input checked="" type="checkbox"/> Am-241	511.0
<input type="checkbox"/> Co-77	129.1
<input type="checkbox"/> Po-212	89.8
<input type="checkbox"/> Auto-138	127.8
<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"/> Pb-212	911.3
<input type="checkbox"/> Auto-820	819.7
<input type="checkbox"/> Auto-900	900.4
<input type="checkbox"/> Pb-212	1501.6
<input type="checkbox"/> Auto-1041	1041.1
<input type="checkbox"/> Auto-1098	1097.7
<input type="checkbox"/> Auto-1294	1294.4
<input type="checkbox"/> Auto-2019	2018.6

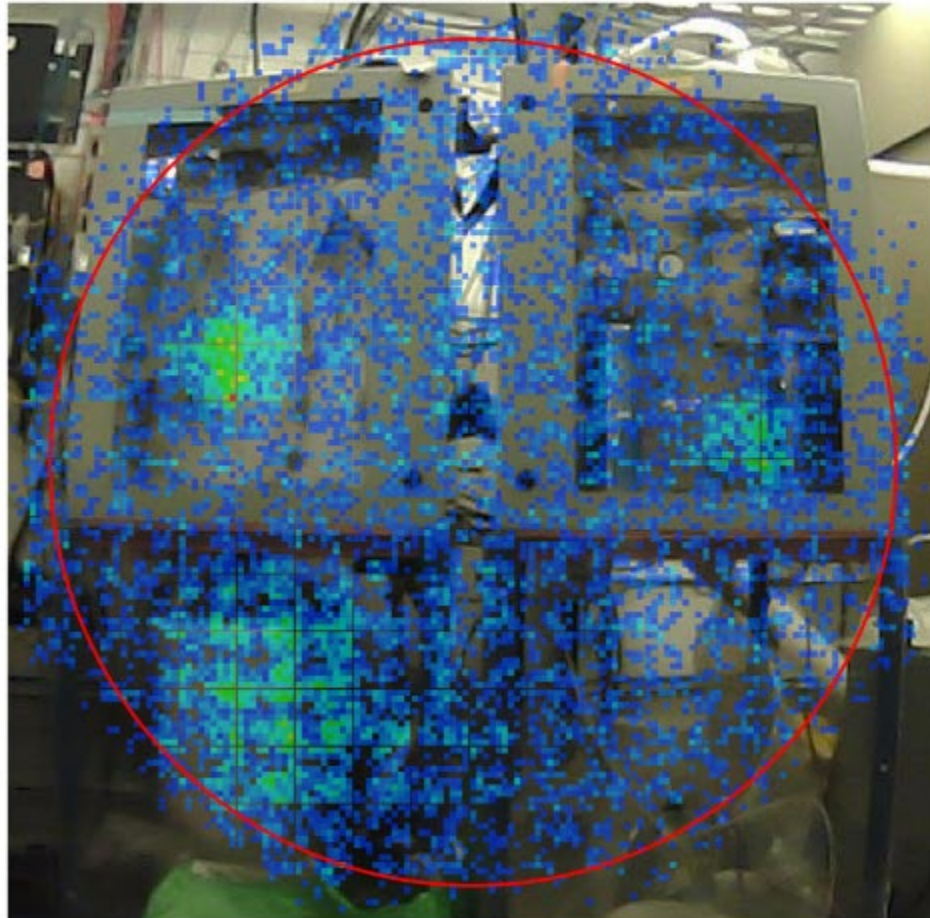
Intervening Materials

Material	Density(g/cm <sup>3</sup> )	Thick(cm)
----------	-----------------------------	-----------

ROI Materials

ROI	Material	Density(g/cm <sup>3</sup> )	Thick
-----	----------	-----------------------------	-------

There are no items to show in this view.



Units: Counts (C)

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

511s

There are no items to show in this view.

X=138 Y=118 Count=0.00

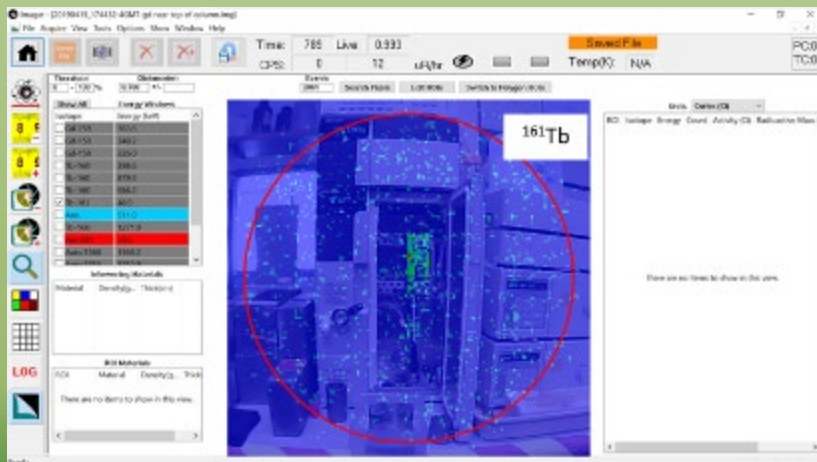
# Summary



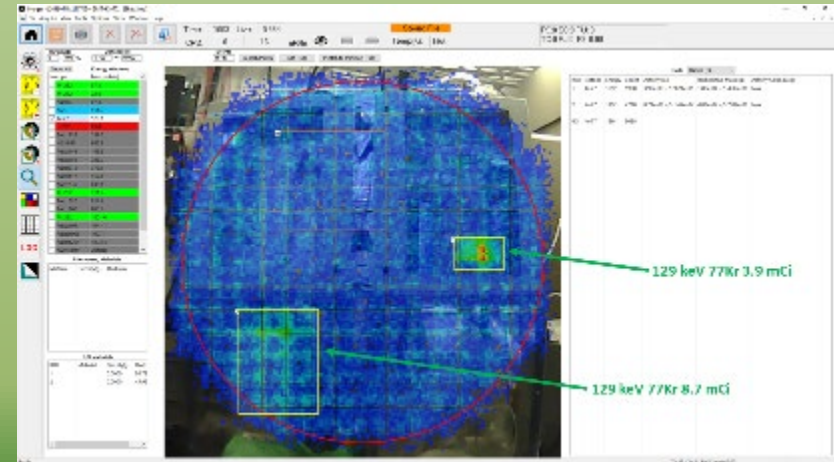
## NP Imager Prototype



## ORNL



## MURR



## NSCL