High-purity Germanium Detectors for Medical Imaging

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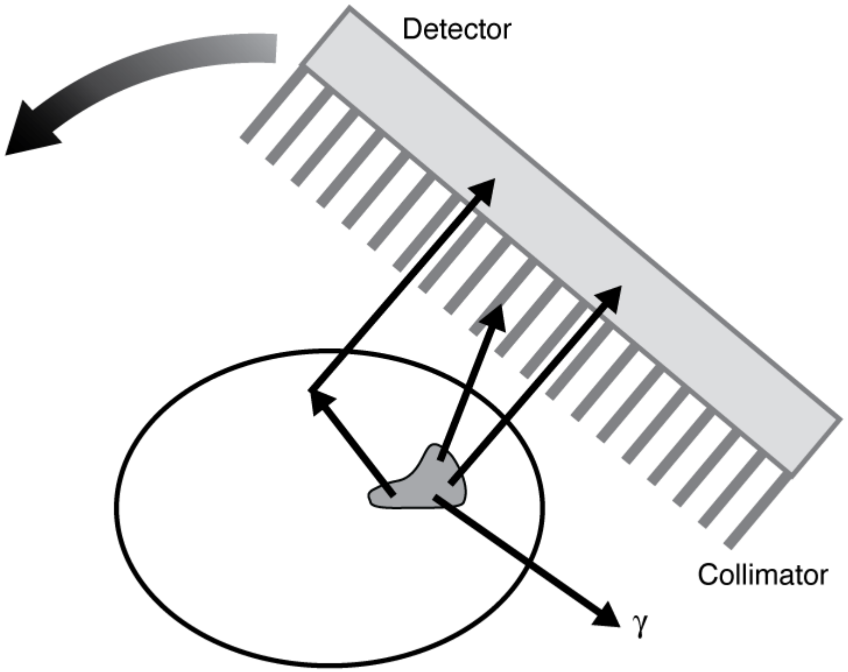
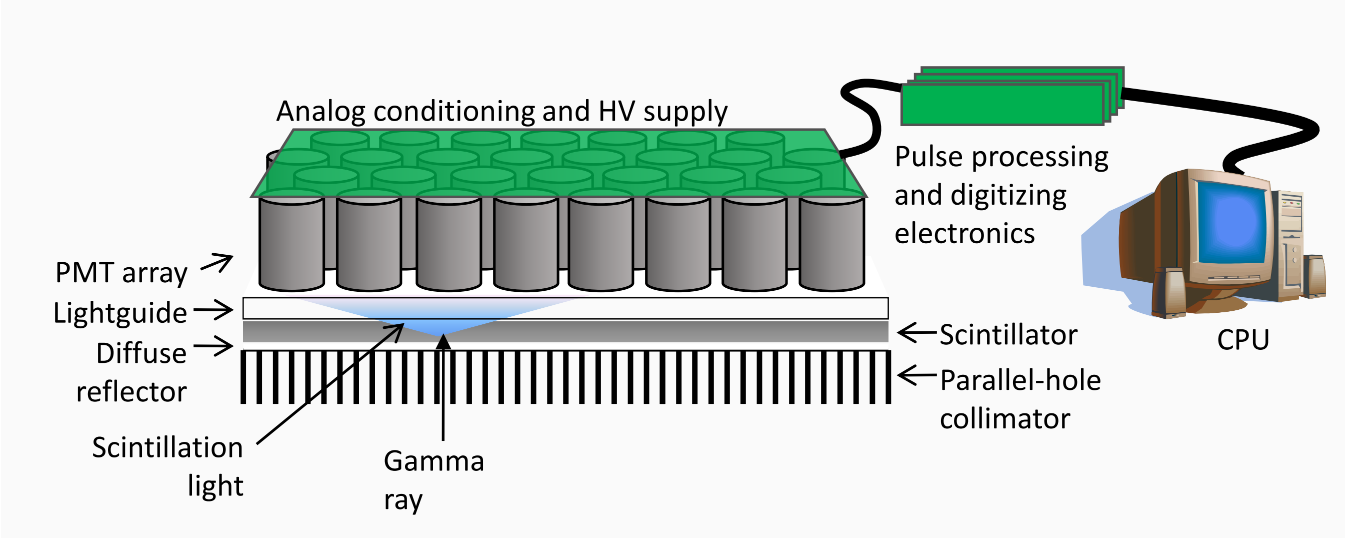
BASICS OF SPECT:
SINGLE-PHOTON EMISSION COMPUTED TOMOGRAPHY

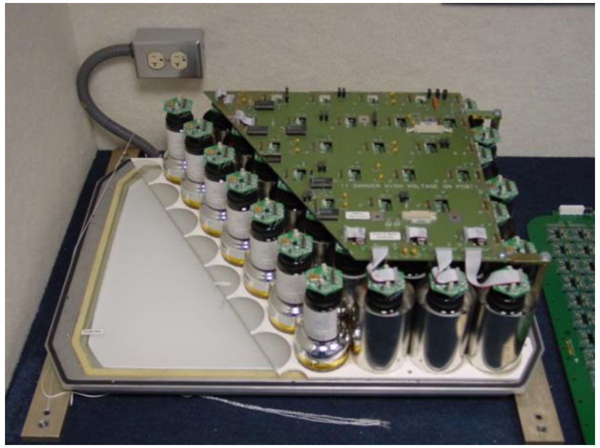
- Radiotracer
  - Molecule of interest
  - Radionuclide
- Detector
- Collimator
- Sampling
- Reconstruction Algorithm



→ Wide range of radionuclides (^{99m}Tc, ^{111}In, ^{123}I) & radiotracers
→ >15M studies/yr in US

THE ANGER CAMERA – NAI(TL)

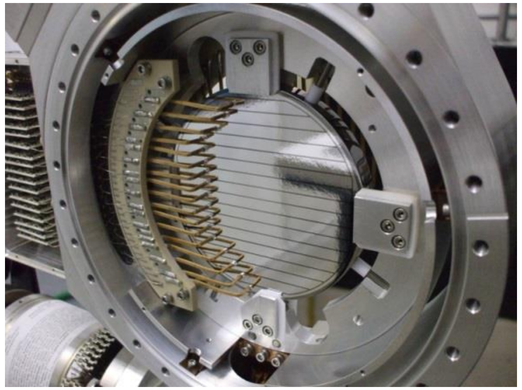
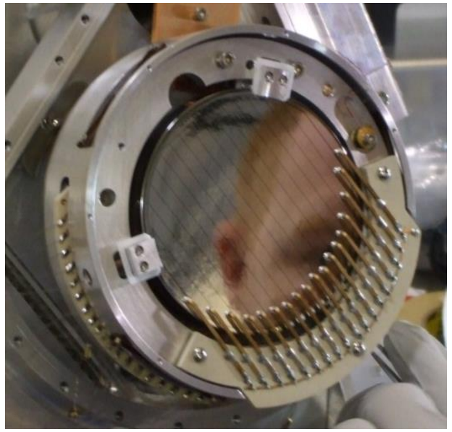
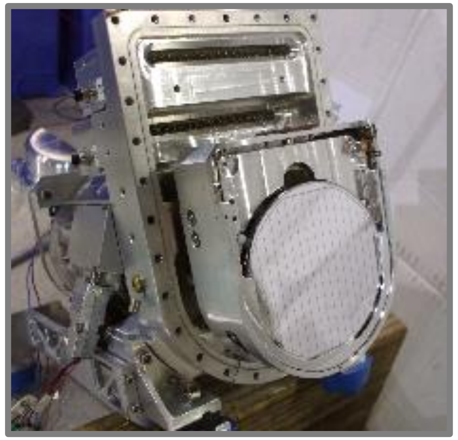
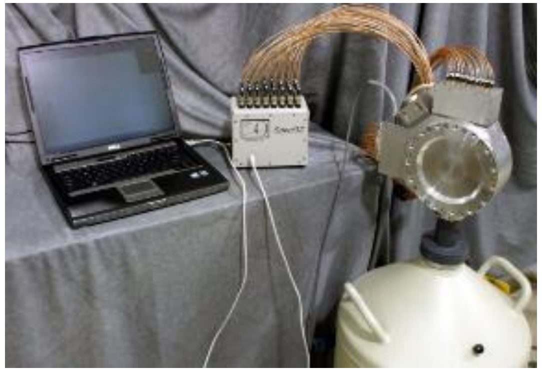


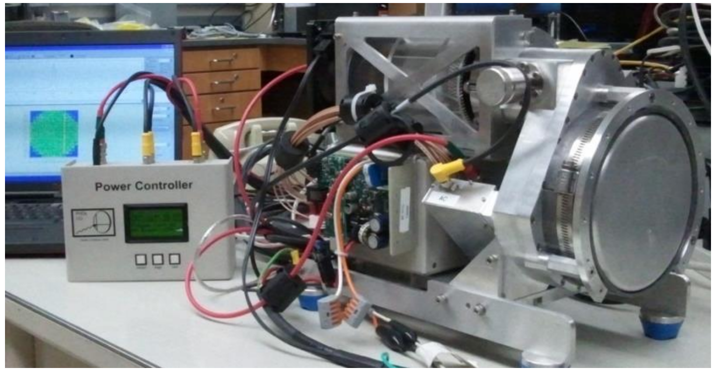


- PMTs coupled to large, continuous NaI(Tl) crystal
- Spatial resolution 3–4 mm FWHM
- Energy resolution 8–10% FWHM
- Large-area, >40cm x 40cm typical

EVOLUTION OF HPGe DSSDS

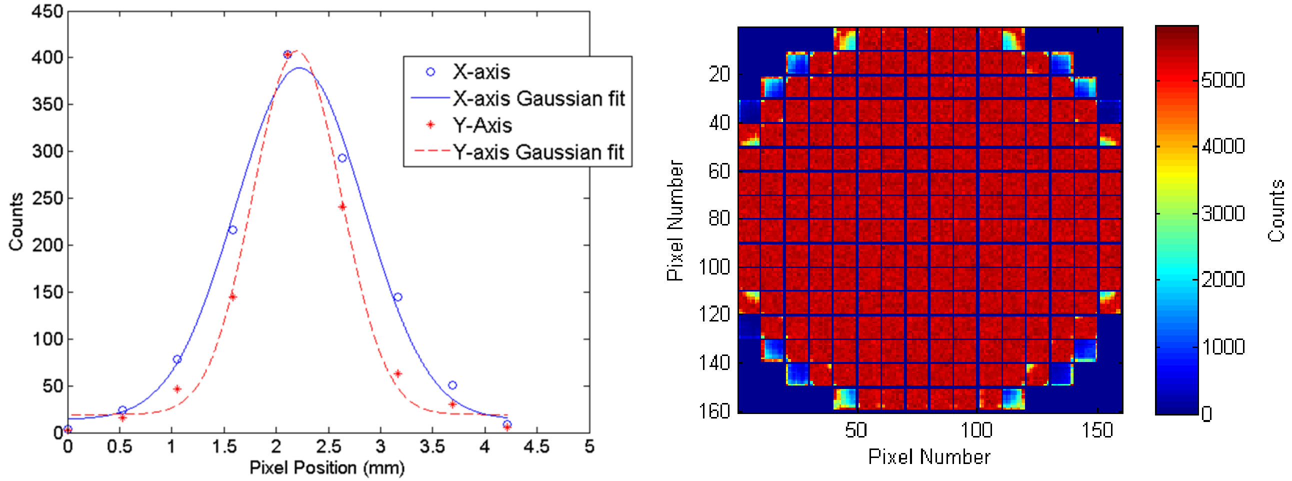
PHDS
Gamma Ray Imaging Detectors



CURRENT HPGe DSSD DESIGN & PERFORMANCE

- 90 mm diameter, 10 mm thick
- 55 cm^2 active area
- 16 x 16 orthogonal strips
- 5 mm strip pitch (0.25 mm gaps)
- Mechanically cooled (75-85 K)
- Position Estimation
  - Sub-Strip interpolation
  - 530 µm x 530 µm pixel size
  - Depth-of-interaction estimation



Detector Property	NaI Camera	HPGe Camera [1]
Intrinsic Efficiency	~90.0%	55.4% (10 mm)
Energy Resolution	~10% @140keV	~1% @140keV
Spatial Resolution	~2-3 mm	<1.5 mm
DOI Estimation	None	~1 mm

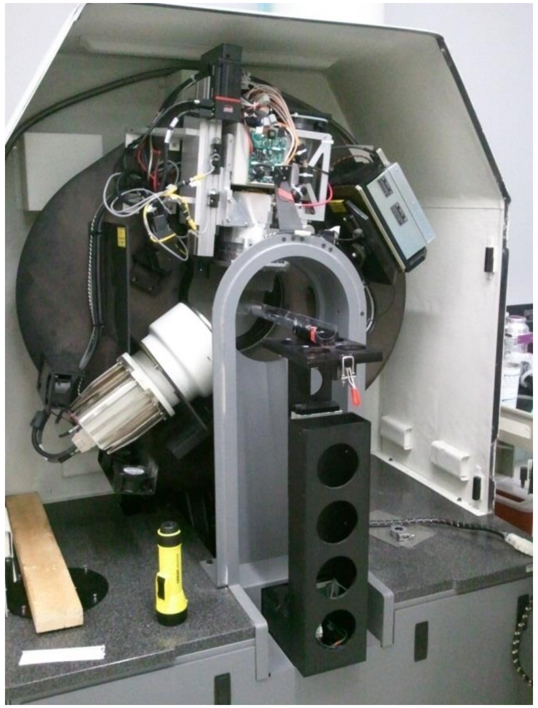
[1] Johnson et al., IEEE Trans Nucl Sci. 62(5), Oct 2015:2036-2042. doi: 10.1109/TNS.2015.2448673.

FIRST HPGe PRECLINICAL SPECT-CT

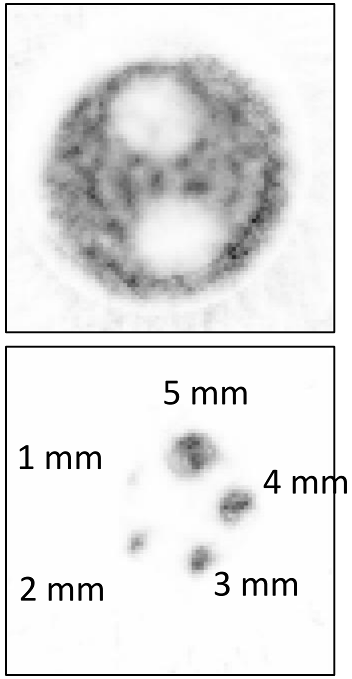
Pinhole Collimator:

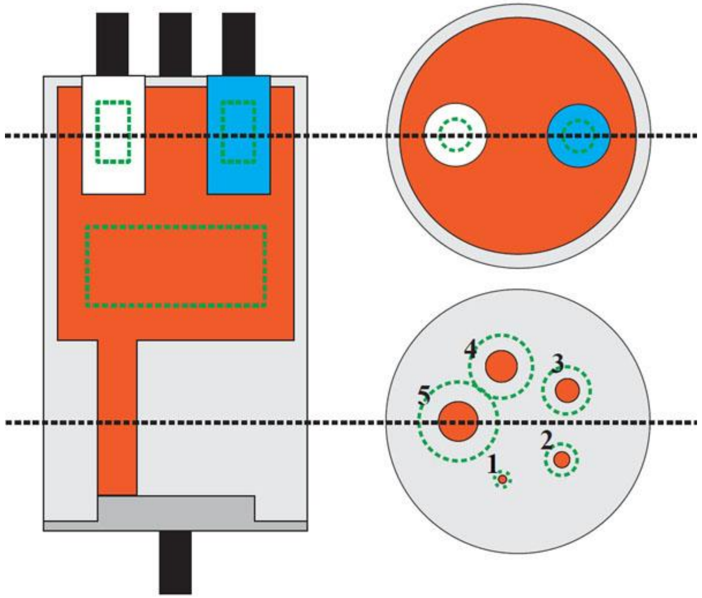
- 1-mm diameter
- Variable focal length: 5.0 – 9.5 cm
- Tungsten polymer composite

Integrated HPGe camera with MicroCAT II CT scanner



Johnson et al., *IEEE TNS* 62(5) (2015)

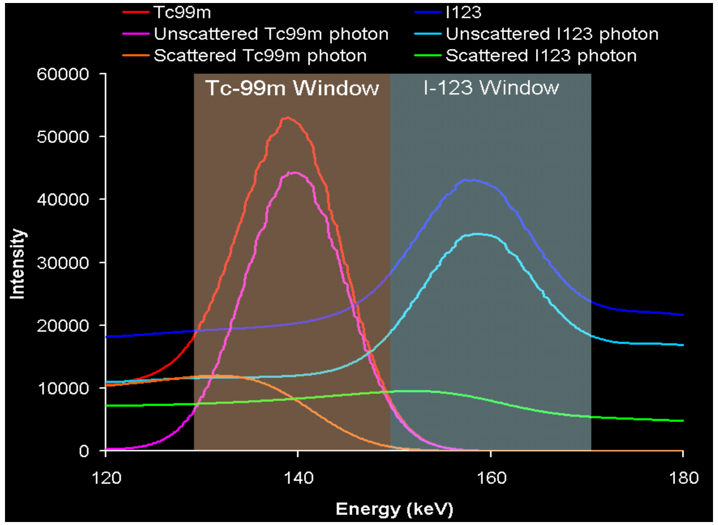


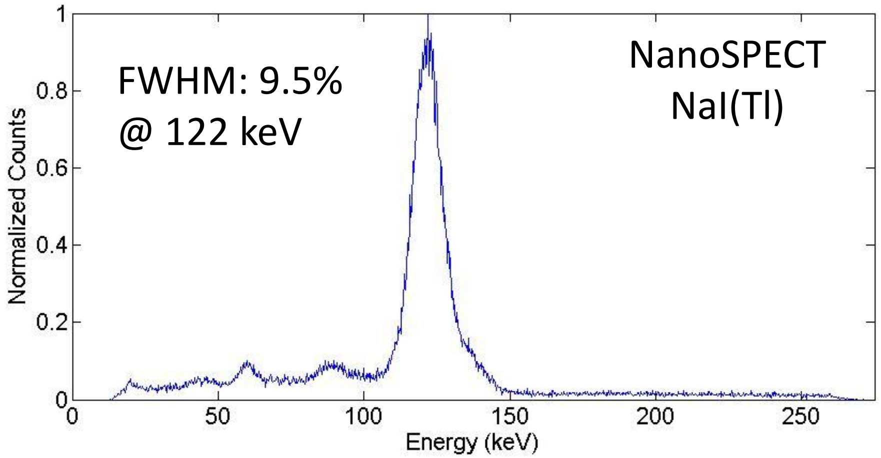


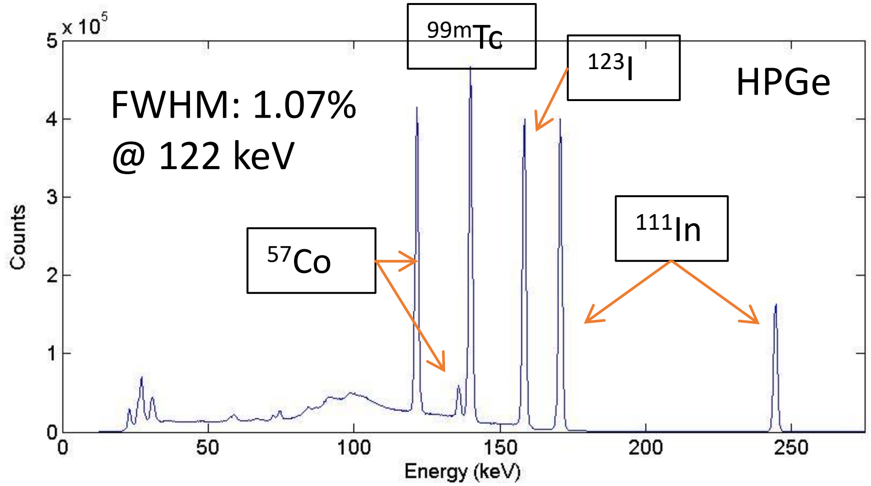
NEMA NU-4 2008 Small-animal IQ Phantom

- Helical acquisition
- 64 projections

ENERGY RESOLUTION



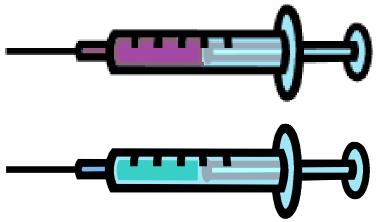




- Brain Imaging – simultaneous imaging of dopamine transporters (^{99m}Tc-TRODAT) and receptors (^{123}I-IBZM) or perfusion (^{99m}Tc-HMPAO) and receptors
- Cardiac Imaging – simultaneous perfusion (^{99m}Tc-MIBI) and innervation (^{123}I-MIBG)
- Cancer Imaging – “multi-spectral” imaging of biologicals (antibodies, peptides, etc.)

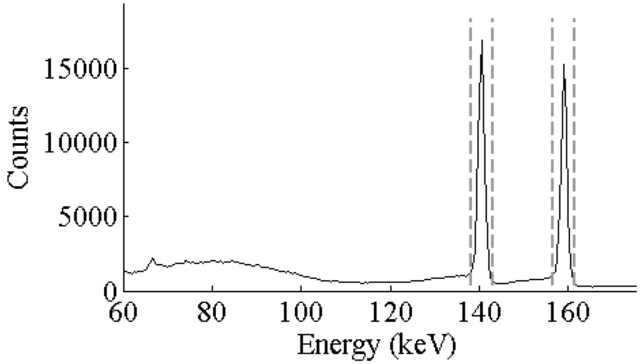
DUAL-ISOTOPE EXPERIMENT

- Compare Germanium camera to BioScan NanoSPECT (NaI)



Energy Windows	NanoSPECT	Ge-SPECT
^{99m}Tc (140 keV)	122.5 – 149.5	137.5 – 142.5
^{123}I (159 keV)	150.5 – 171.5	156.5 – 161.5

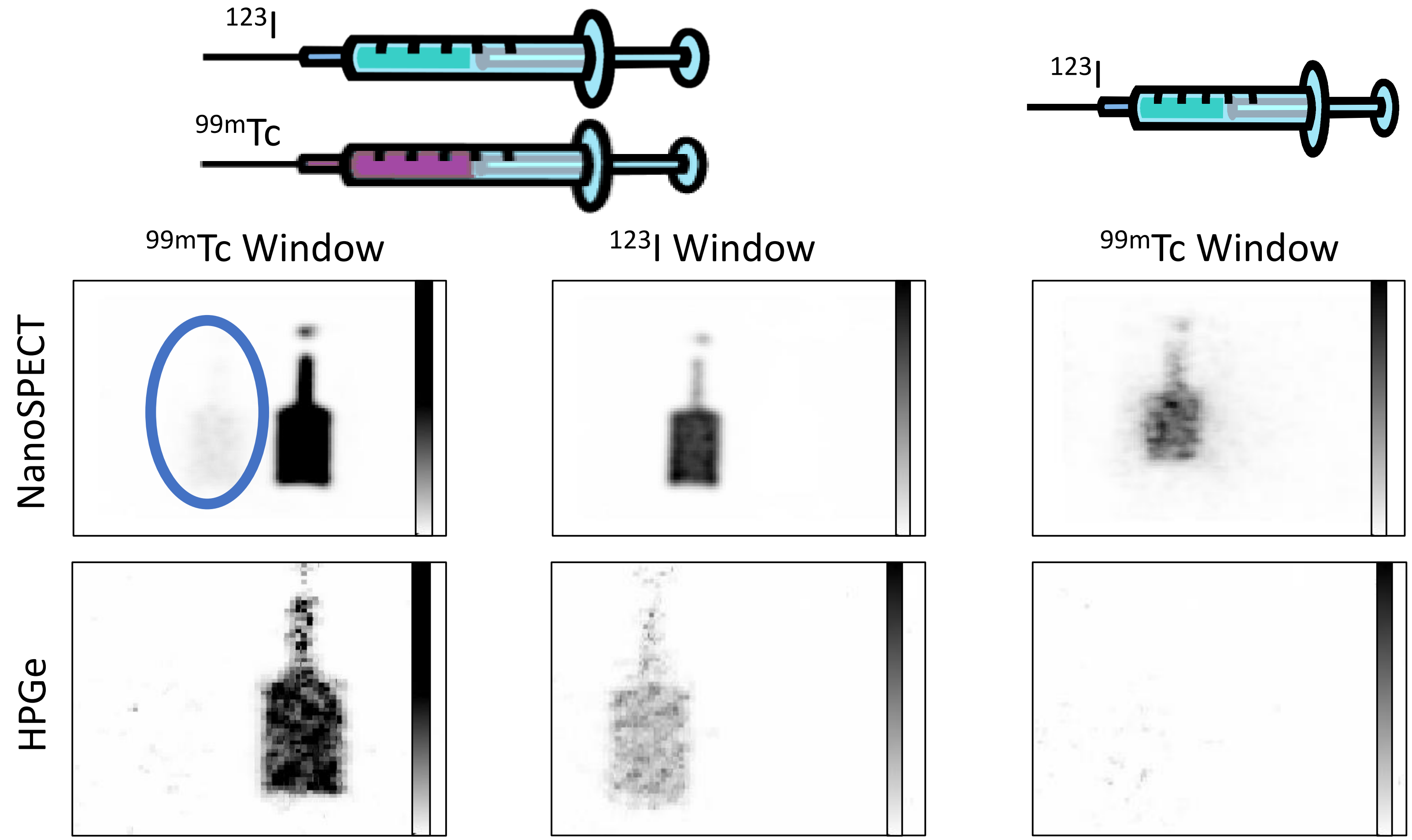
- Cross-Talk Ratios from single-isotope projections:



Cross Talk Ratios	NanoSPECT	Ge-SPECT
^{99m}Tc into ^{123}I Window	5.3%	0.31%
^{123}I into ^{99m}Tc Window	16.4%	6.71%

- Acquired SPECT images with all syringe combinations on both systems
- Utilized NanoSPECT's software to implement cross-talk correction

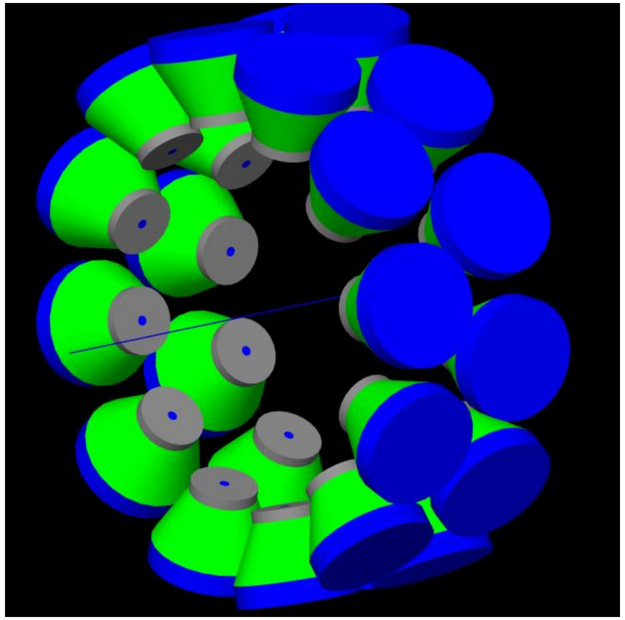
DUAL-ISOTOPE EXPERIMENT



PRELIMINARY BRAIN SPECT SYSTEM DESIGN

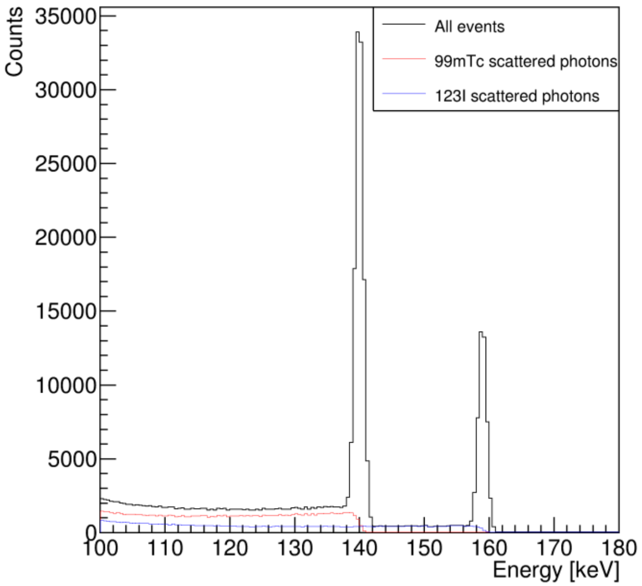
- Single-pinhole collimation
- Fix analytic resolution at CFOV to 7 mm
- Vary pinhole diam., focal length, & # detectors as function of system radius
- Initial simulation study: 24-detector, cylindrical 2-ring system
- Sensitivity: 106 cps/MBq @CFOV

[1] Zubal et al., Medical Physics 21(2), Feb 1994:299-302.
[2] Du and Frey, Medical Physics 36, June 2009:2021-2033. doi:10.1118/1.3120411.

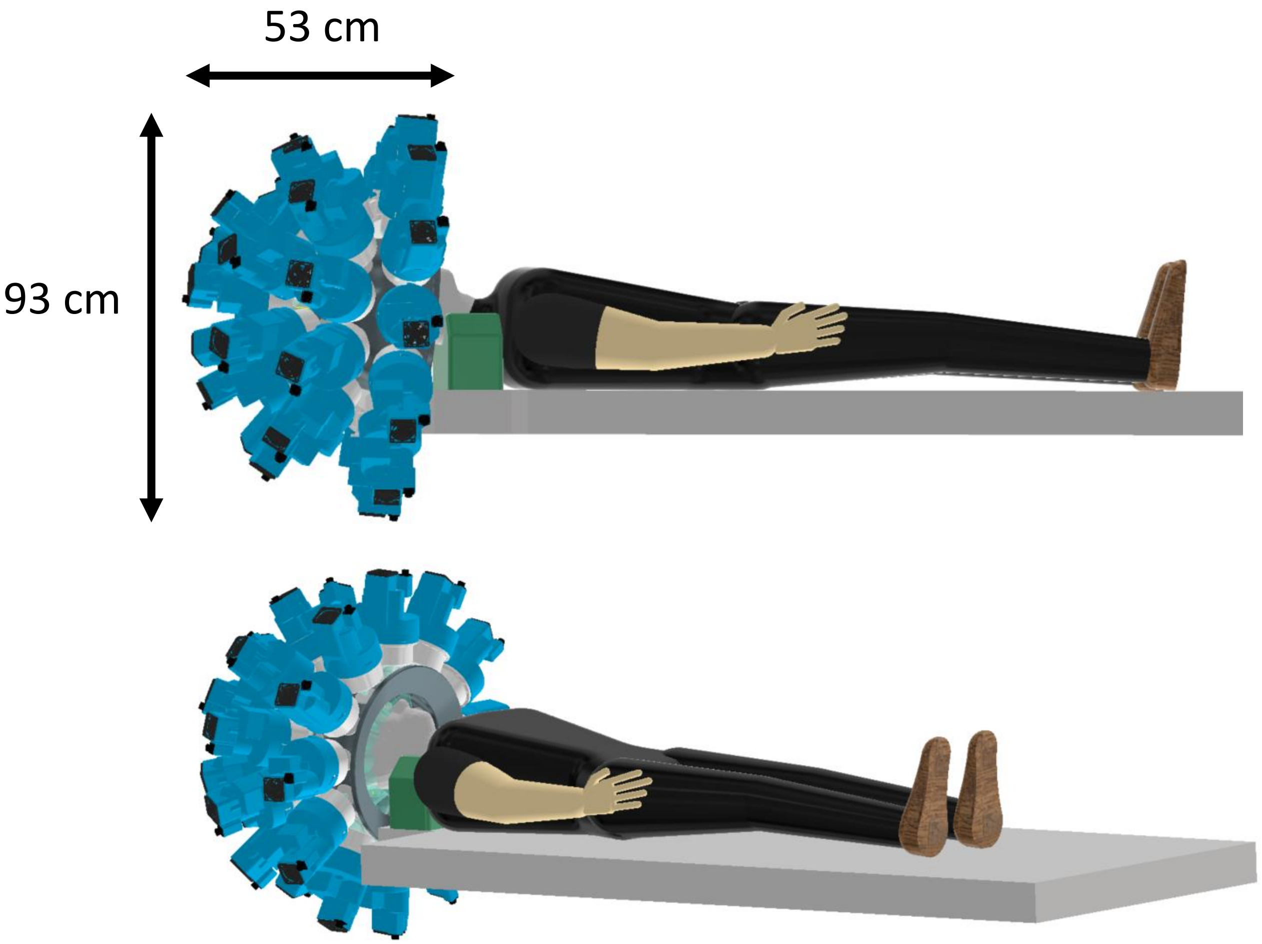


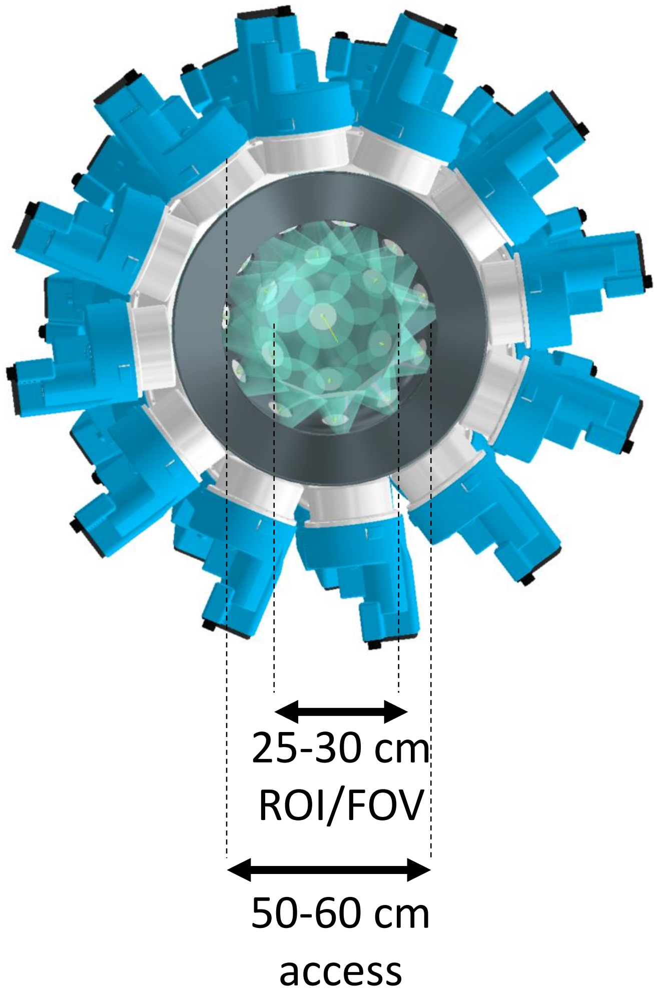
GATE Simulation:

- Zubal phantom [1]
- Striatum:Background ratios 5:1 for both ^{99m}Tc & ^{123}I with 2:1 ^{99m}Tc :^{123}I ratios [2]
- Energy windows: 138-142 keV & 156.5-161.5 keV
- Downscatter from ^{123}I into ^{99m}Tc window was 2.8% of total
- Scatter within own windows <5%
- Compared to ~60% downscatter and ~11% self-scatter for NaI simulation [2]



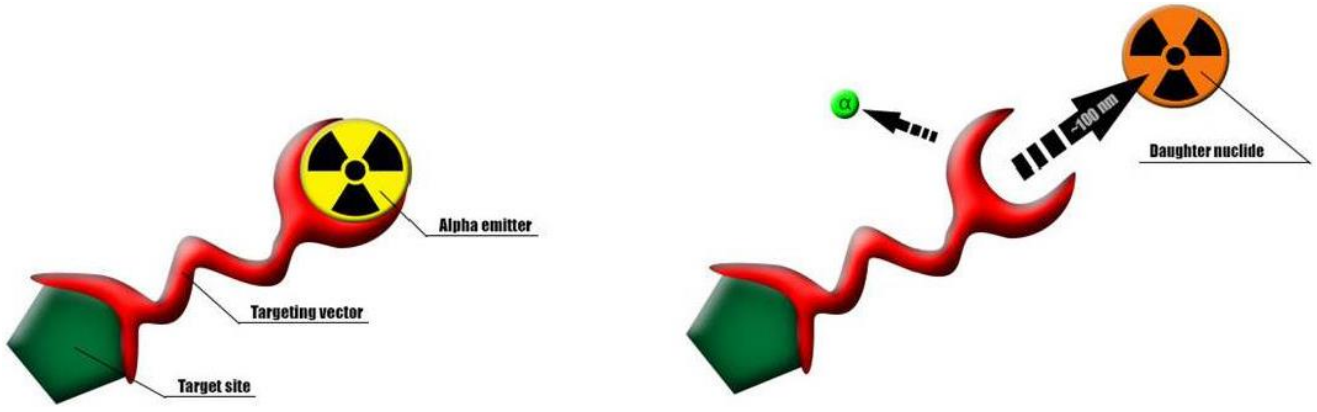
HPGe Brain SPECT – DESIGN CONCEPT



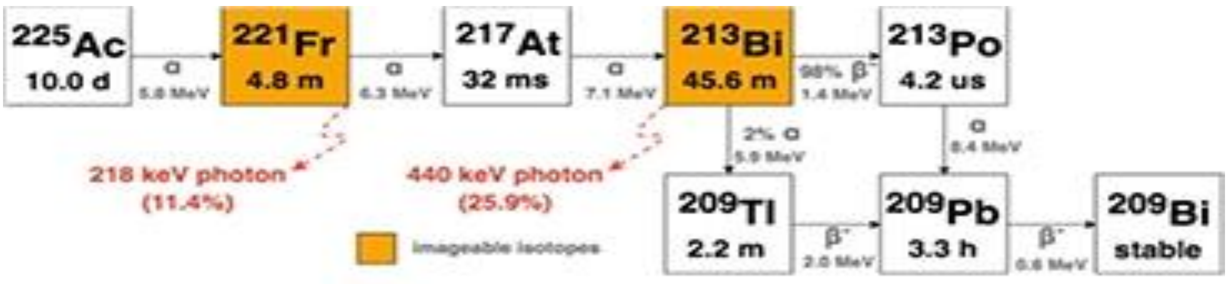


30 detectors: Rings of 12, 11, 6, 1

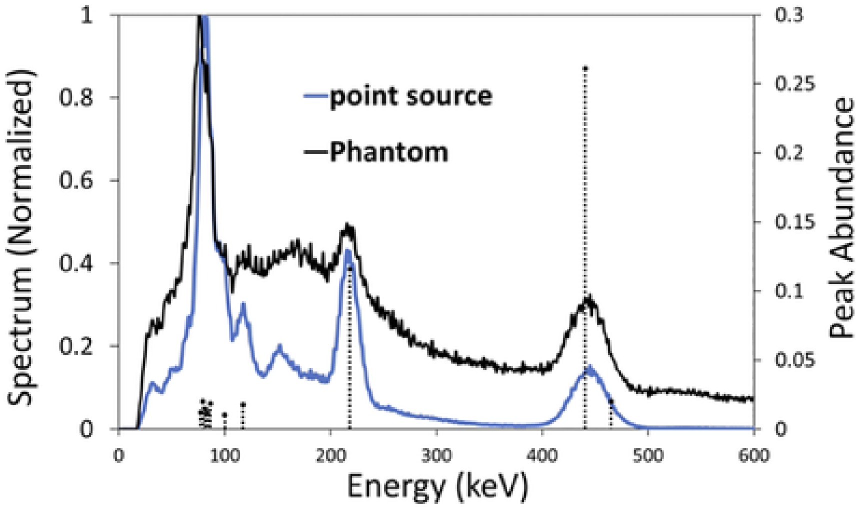
TARGETED ALPHA THERAPY IMAGING



De Kruijff et al. 2015 Pharmaceuticals 8(2)



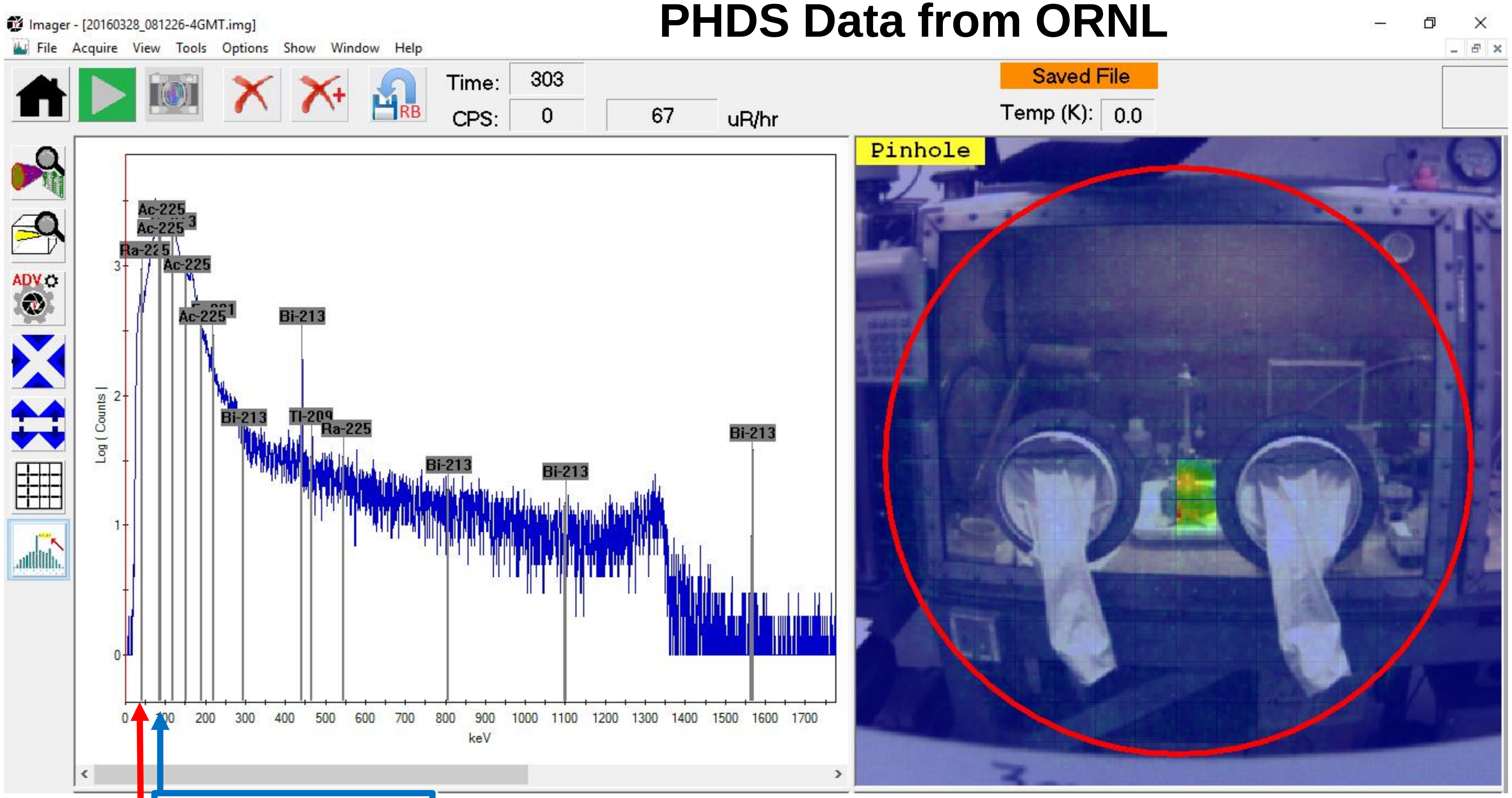
Robertson et al 2017 Phys. Med. Biol. 62 4406
doi:10.1088/1361-6560/aa6a99



Du et al. 2022 PLOS ONE 17(1)
Doi:10.1371/journal.pone.0261982

PLANAR IMAGING OF THERAPEUTIC RADIONUCLIDES

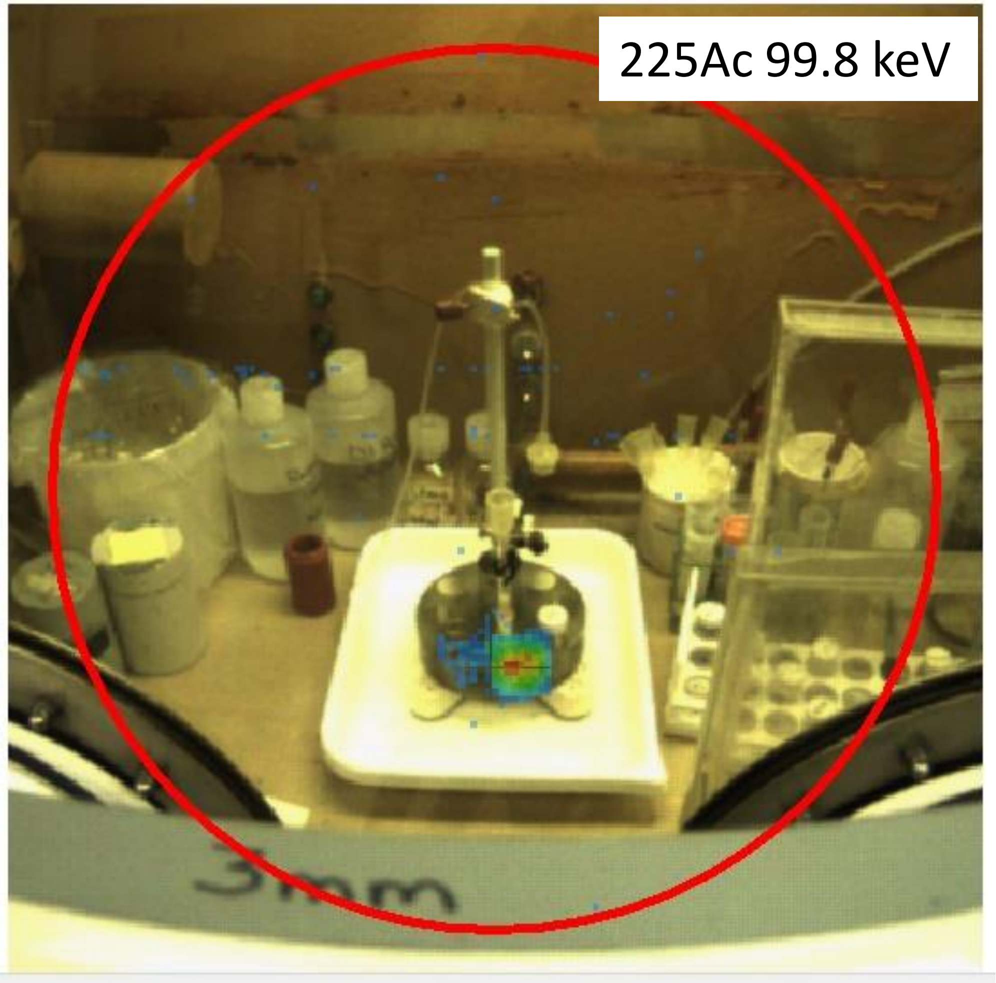
PHDS Data from ORNL

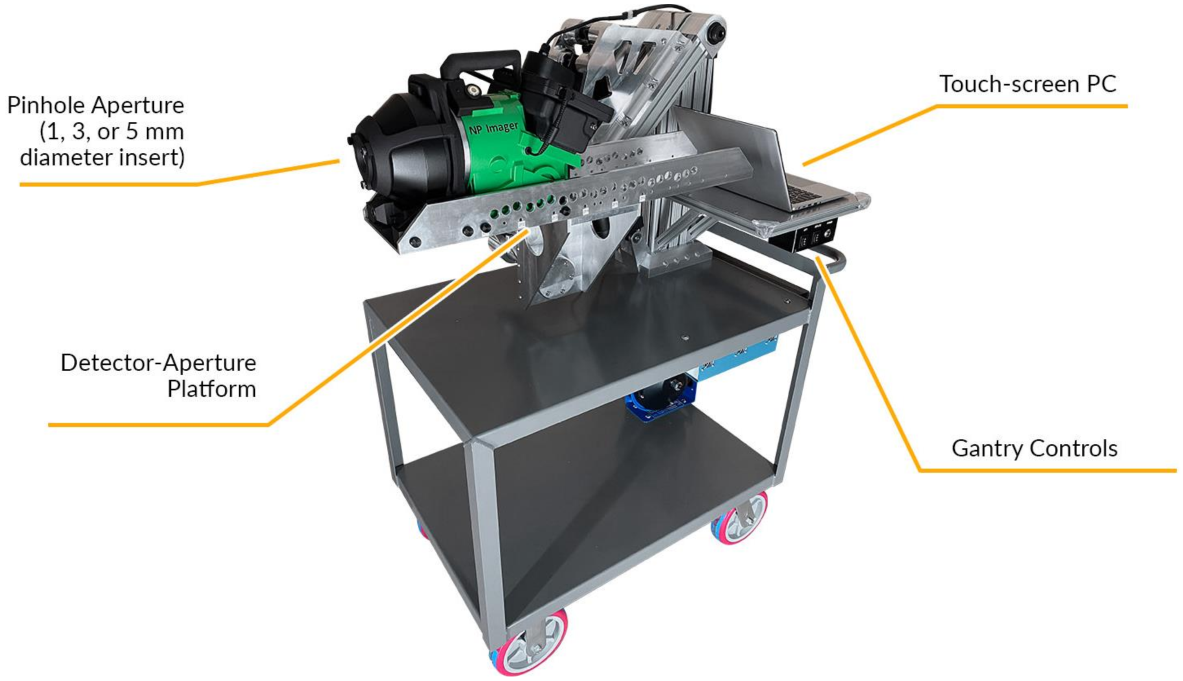


99.8 keV ^{225}Ac

40 keV ^{225}Ra

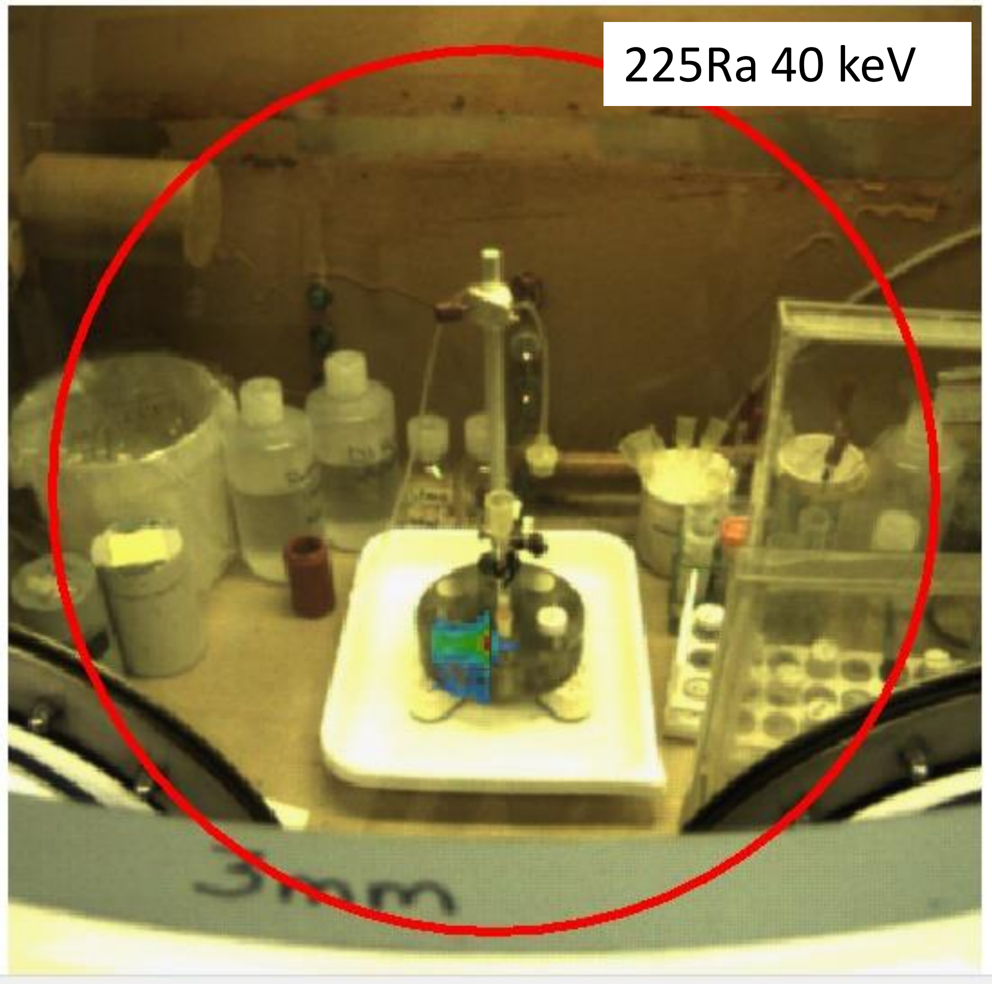
COLLECTION CAROUSEL IMAGES

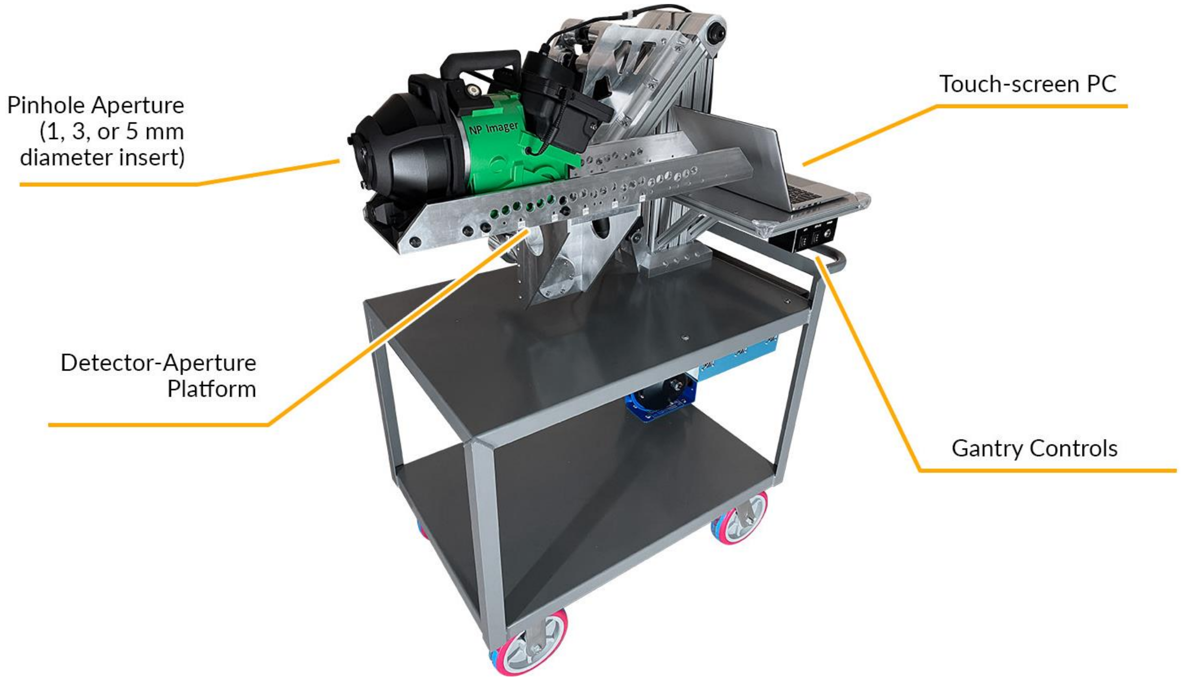




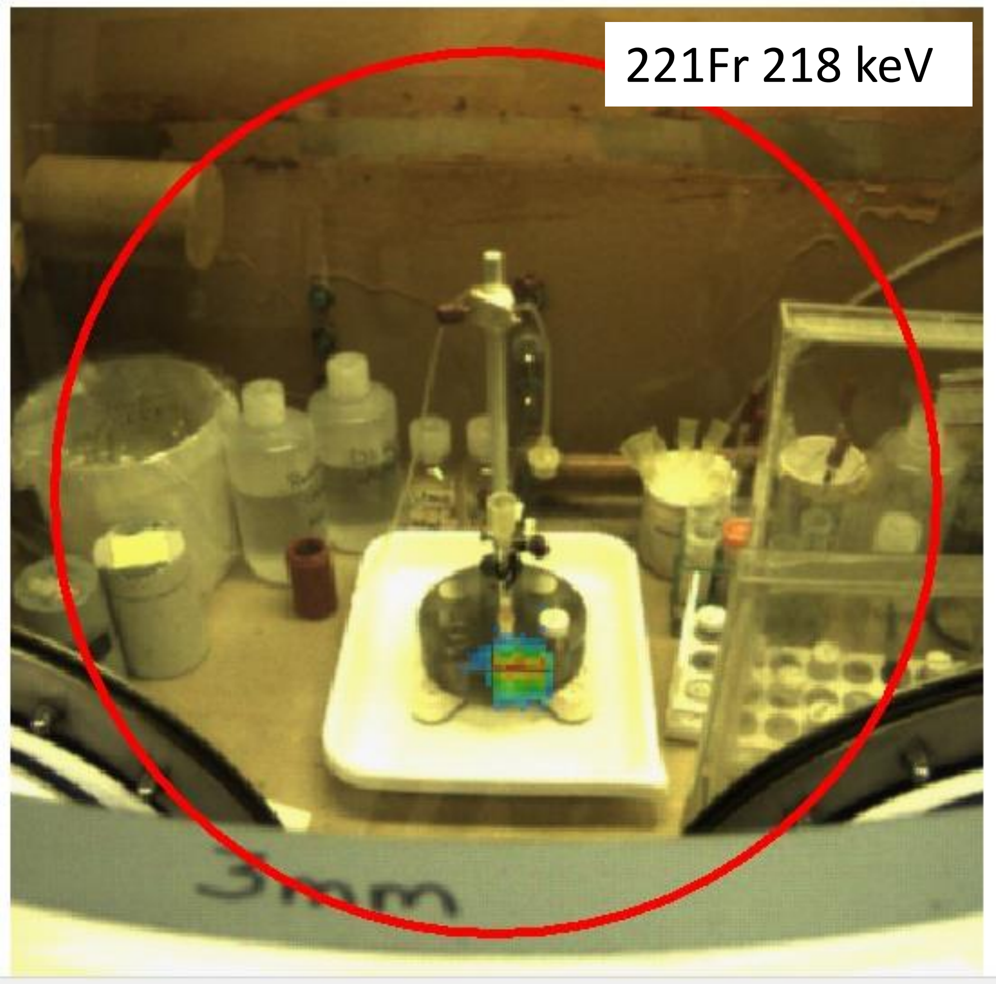
COLLECTION CAROUSEL IMAGES

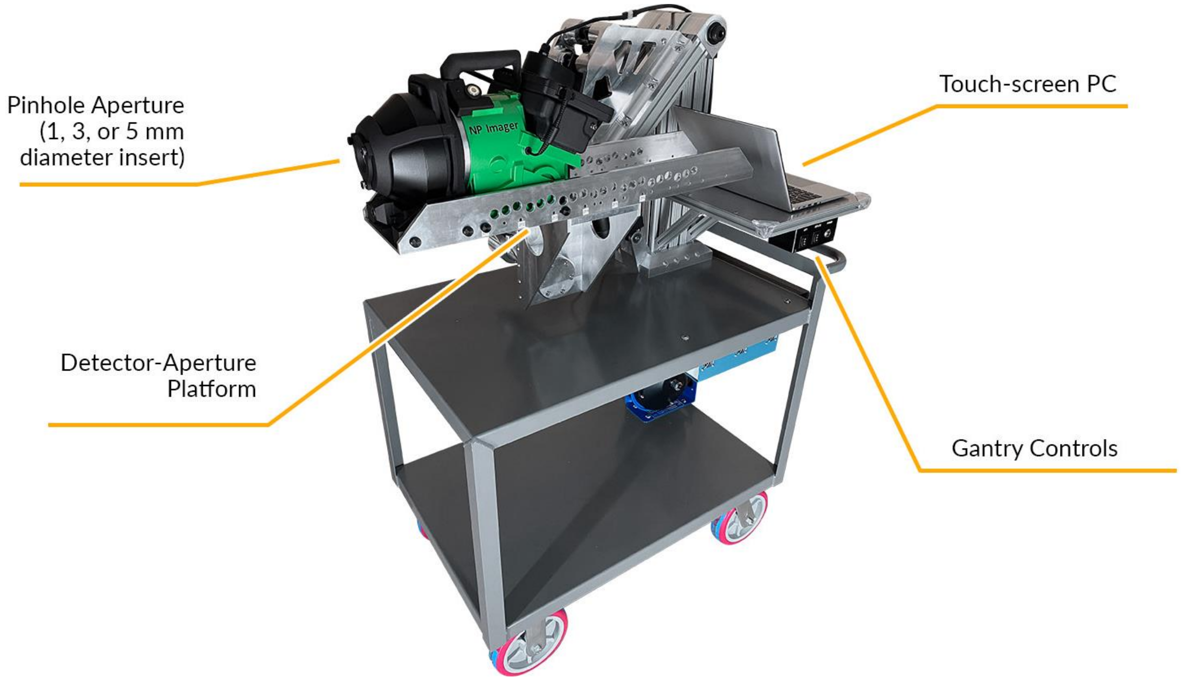
Gamma Ray Imaging Detectors





COLLECTION CAROUSEL IMAGES





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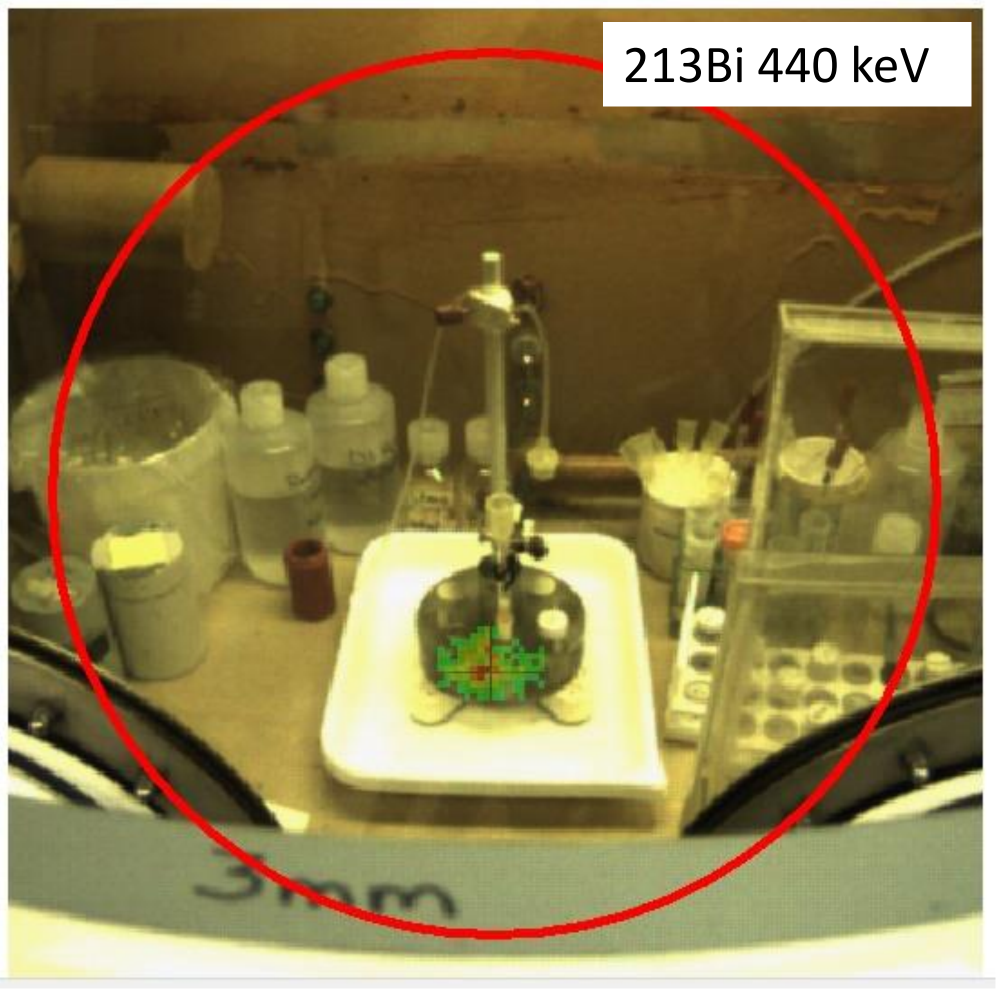

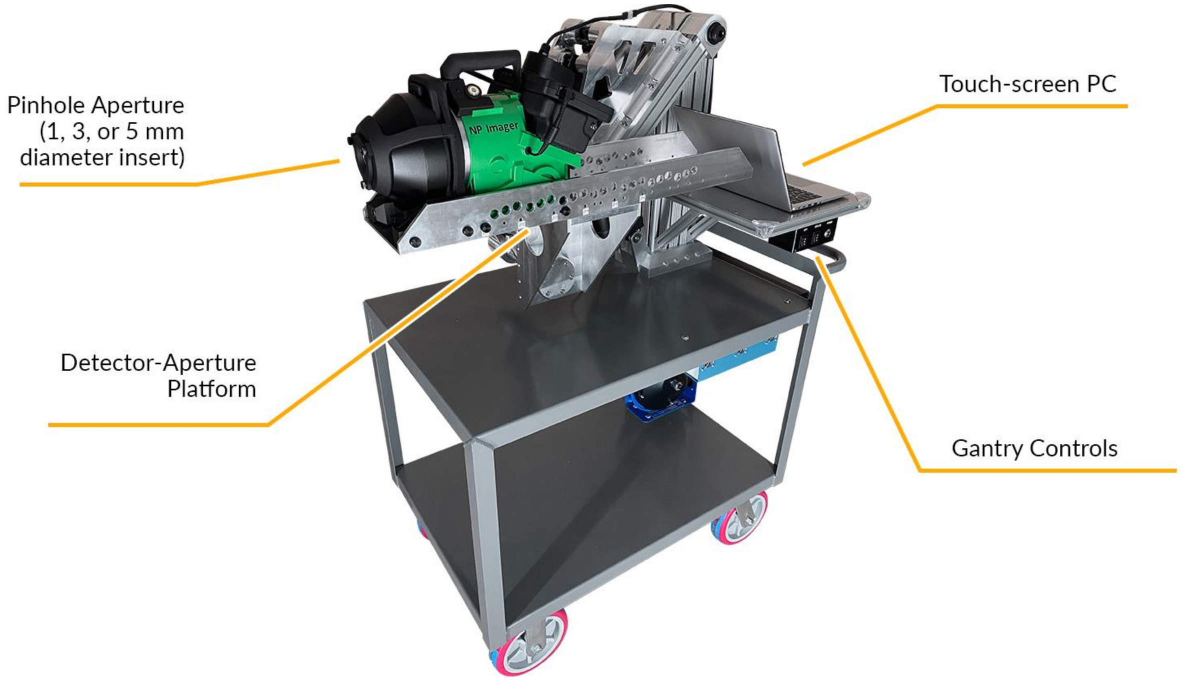

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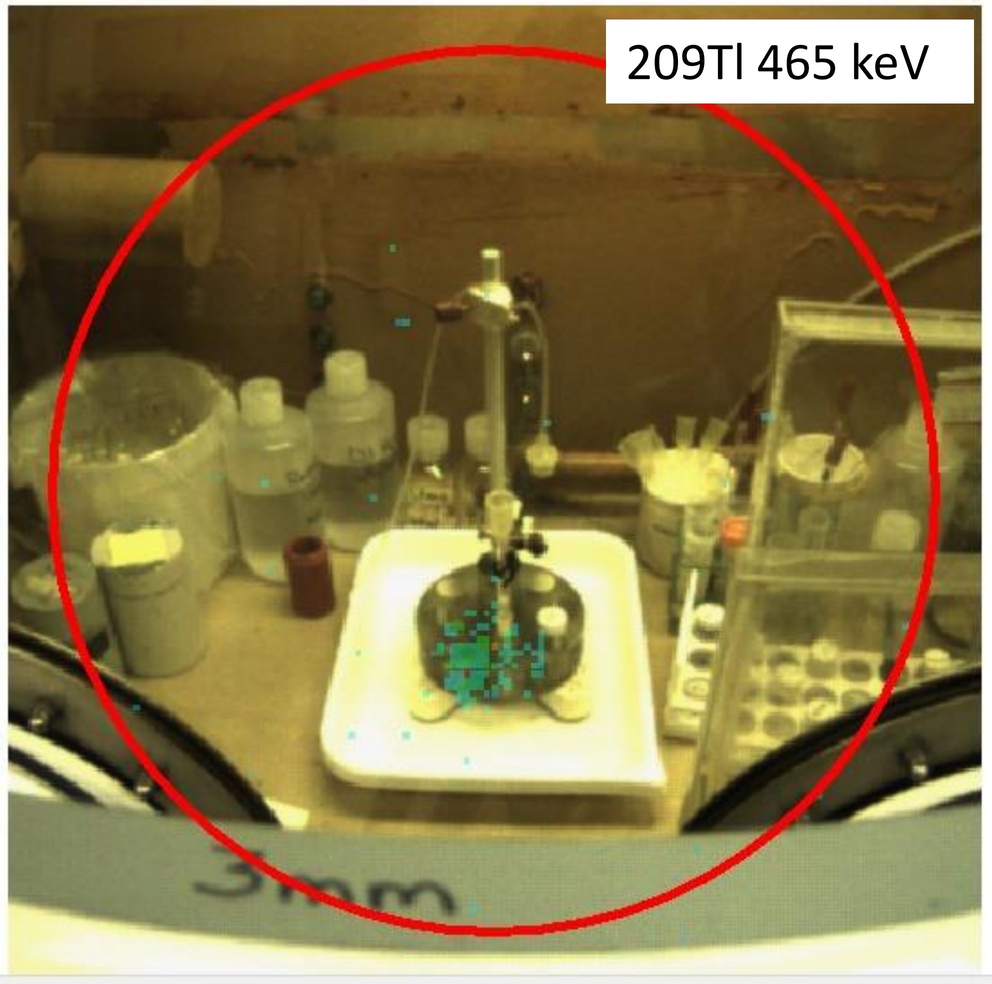
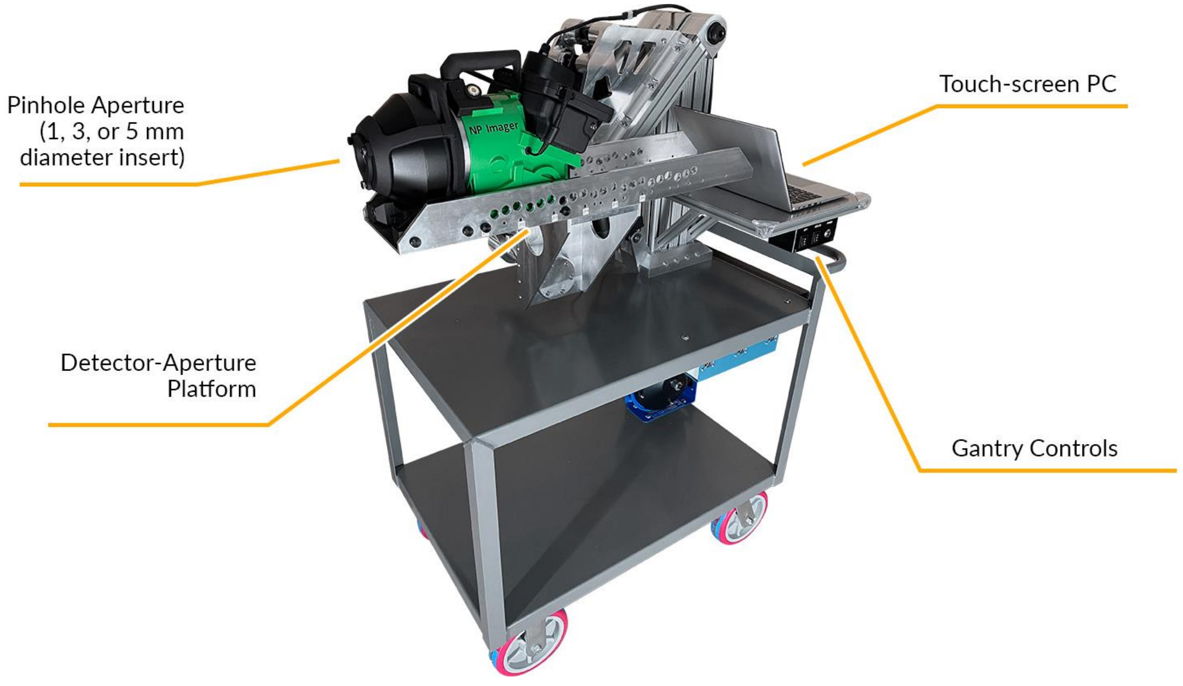


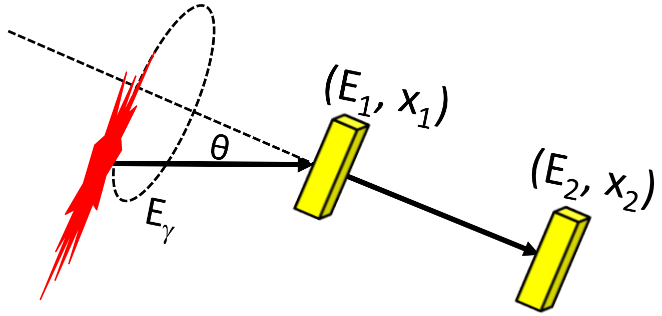


CHALLENGES IMAGING THERAPEUTIC RADIONUCLIDES

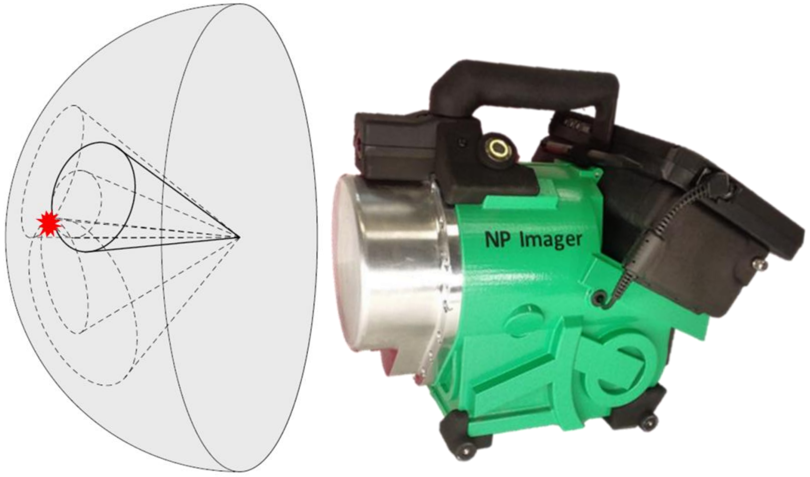
- **Sensitivity**
  - Administered doses often <2 mCi
  - Branching ratios not large
- **Energy range** – many emissions above ~300 keV
  - Collimation challenging
  - Detection efficiency decreases
  - Compton scattering dominates

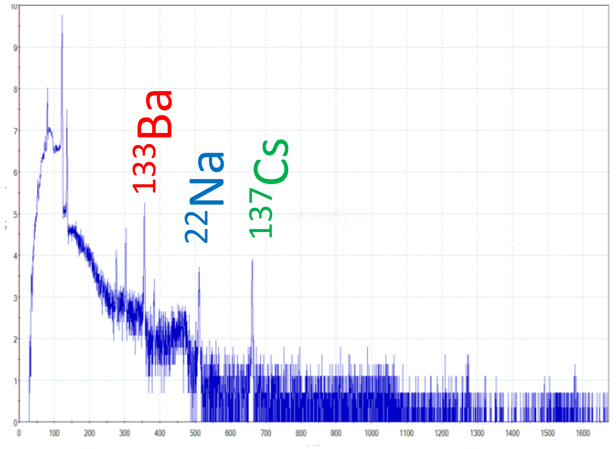
→ Consider Compton Camera or Compton-enhanced imaging

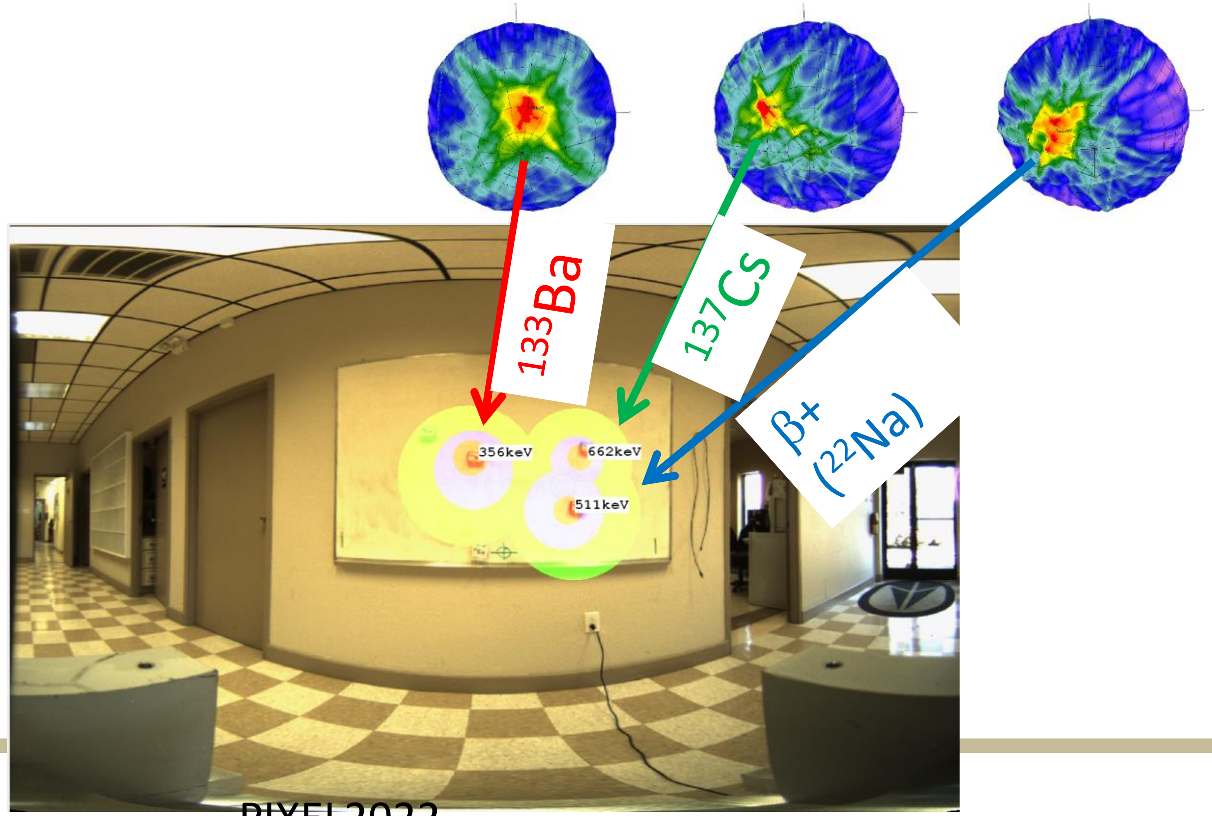
HPGe COMPTON CAMERA



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







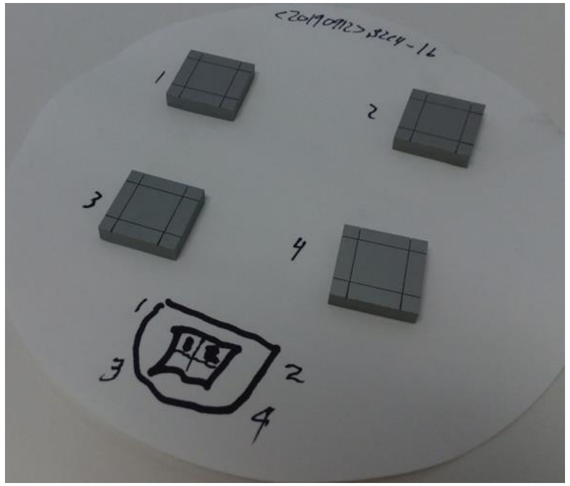
DETECTOR INVESTIGATIONS

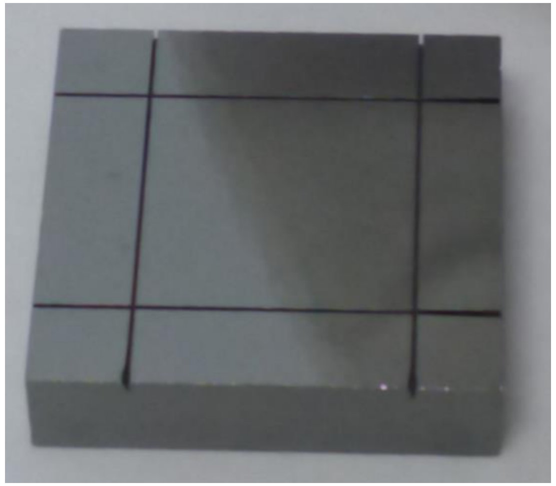
Increasing operating temperature:

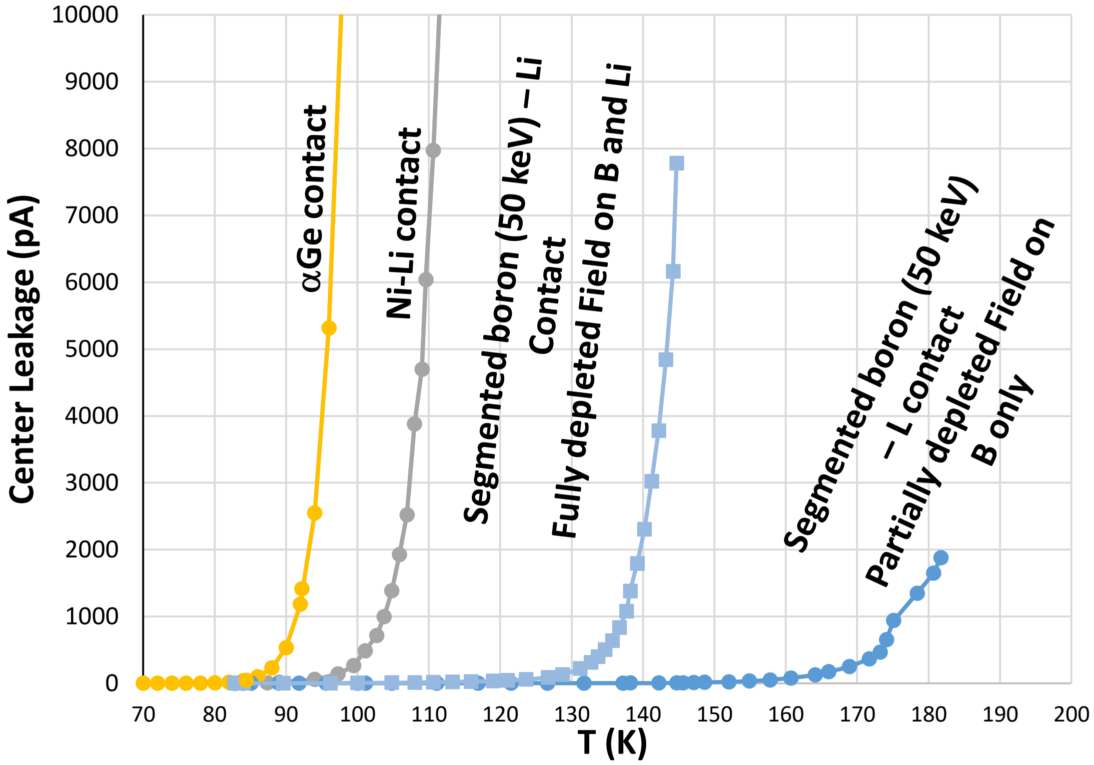
- Reduces power consumption
- Slows charge collection → improved spatial resolution?

G551 – Test detector:

- 16x16 strips with amorphous Ge contacts
- Charge collection times (Temp): 100 ns (85 K) to 120 ns (105 K)

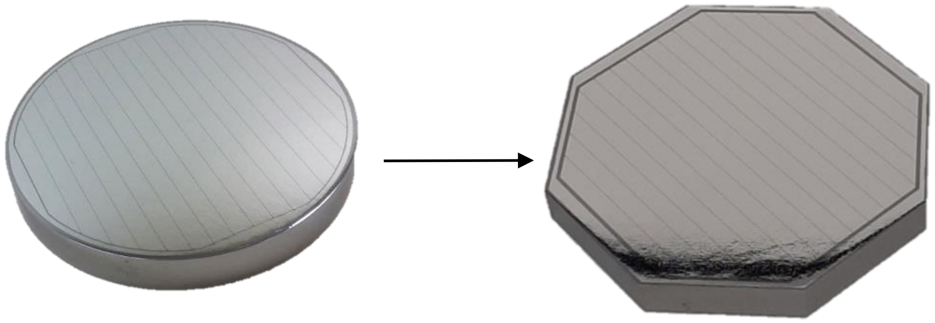






ONGOING DEVELOPMENTS

- Improving fabrication
  - Flat cuts
    - Higher fabrication yield
    - Better temperature tolerance
  - Larger-diameter detectors
- Signal processing – improve spatial resolution
- Alternative electrode configurations



56.4 cm² ***61.3 cm²***

→ HPGe detectors are a promising technology for enabling multi-tracer SPECT, but much work remains to be done

ACKNOWLEDGMENTS

- Funding:
  - NIH:
    - R25 CA136440
    - R44 RR031937
    - R01 EB013677
    - R01 EB026991
    - F31 EB022422-02
  - US Department of Energy BER
  - SREB
- Ethan Hull, Matthew Kiser, Jim Lathrop

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