Development of fast 3D gamma-ray imaging technologies for radiation treatment, nuclear physics and nuclear security

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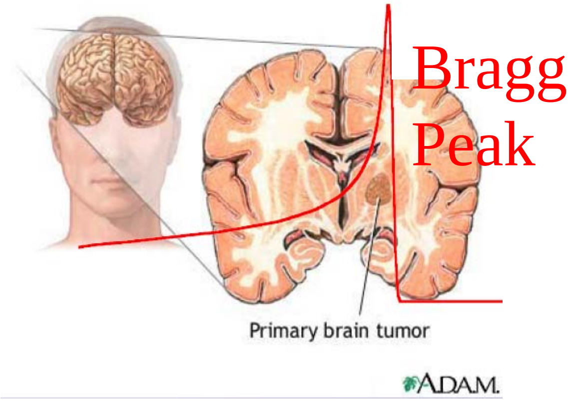
ANS&T Project Overview

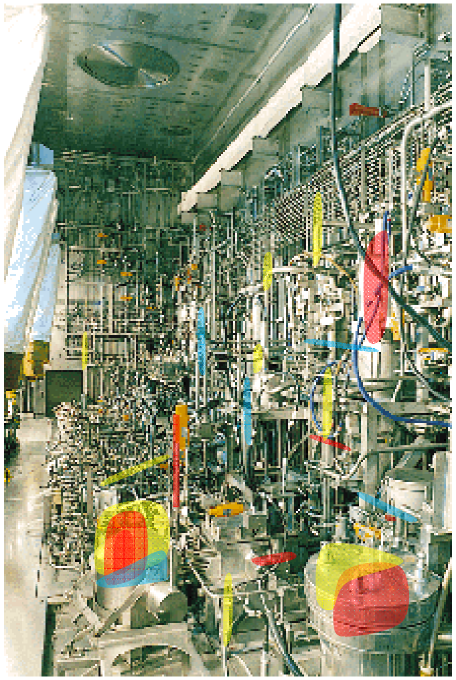
Goal:

- Develop radiation detection technologies and advanced analysis and imaging methods that will enable the introduction of new 3D gamma-ray imaging technologies in various fields, ranging from radiation therapy to nuclear security and fundamental sciences



Objectives:

- Develop fast and efficient data acquisition system for multichannel high resolution detectors (segmented Ge detectors) suitable for imaging.
- Develop data analysis and image reconstruction algorithms to improve detection and imaging performance
- Demonstrate impact of the developed technologies in various fields



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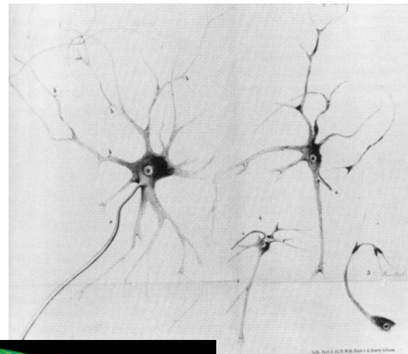
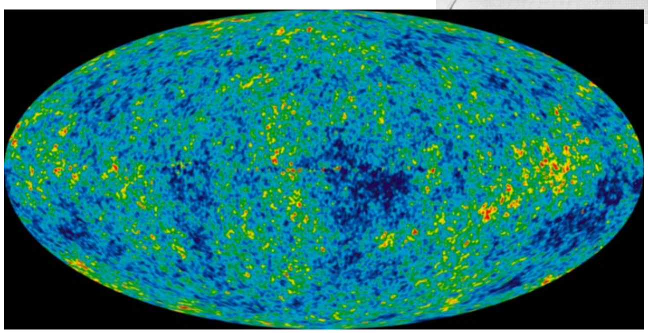
Why Imaging?

Determine Structure

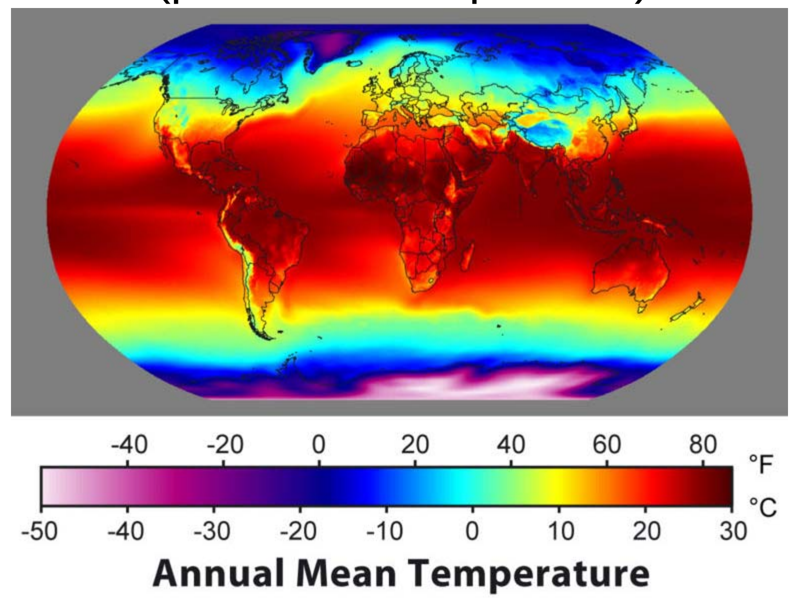


Otto Friedrich Carl Dieters (1834-1863) produced the most accurate description of that time of a nerve cell

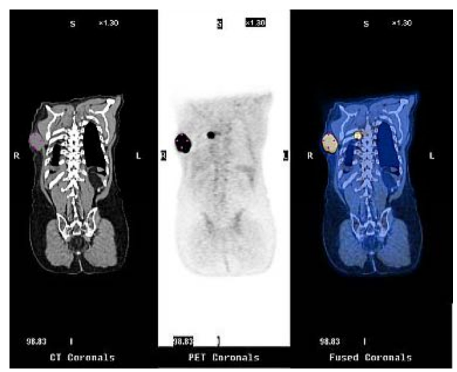


Full-sky image of background cosmic radiation temperature map taken by NASA's Wilkinson Microwave Anisotropy Probe (WMAP) (2010)

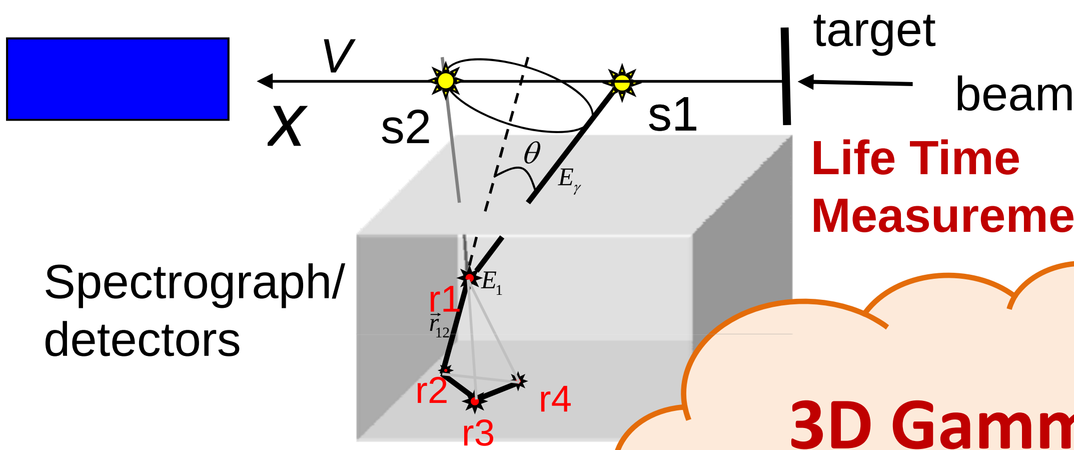
Measure Quantities (parameter amplitudes)



Detect Features (Anomalies)

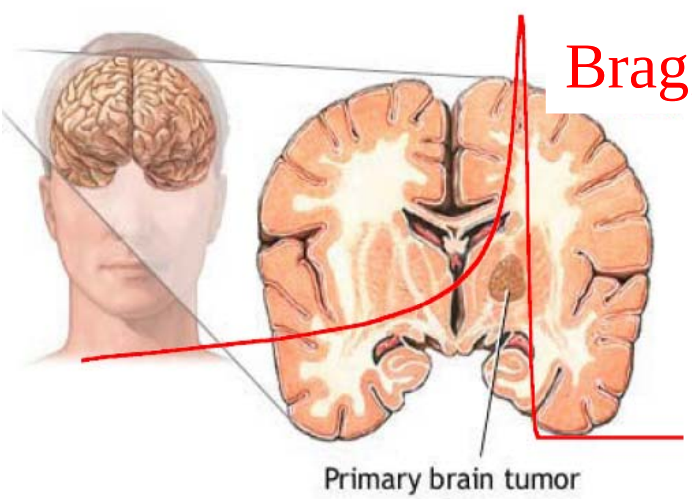


Overview of 3D Gamma-Ray Imaging Applications

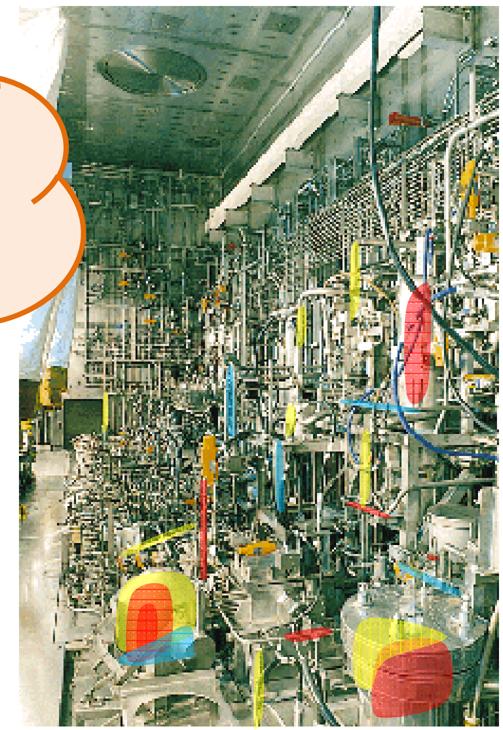


Life Time Measurements

3D Gamma-Ray Imaging

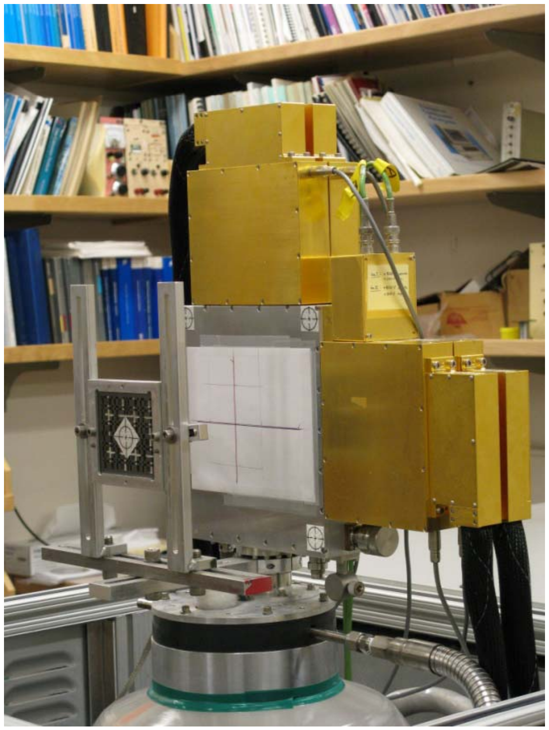


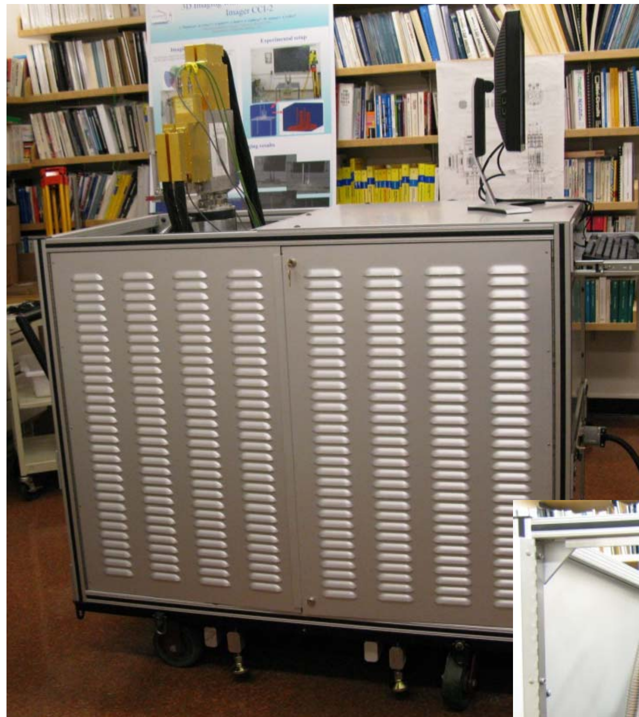
Hadron Therapy Verification

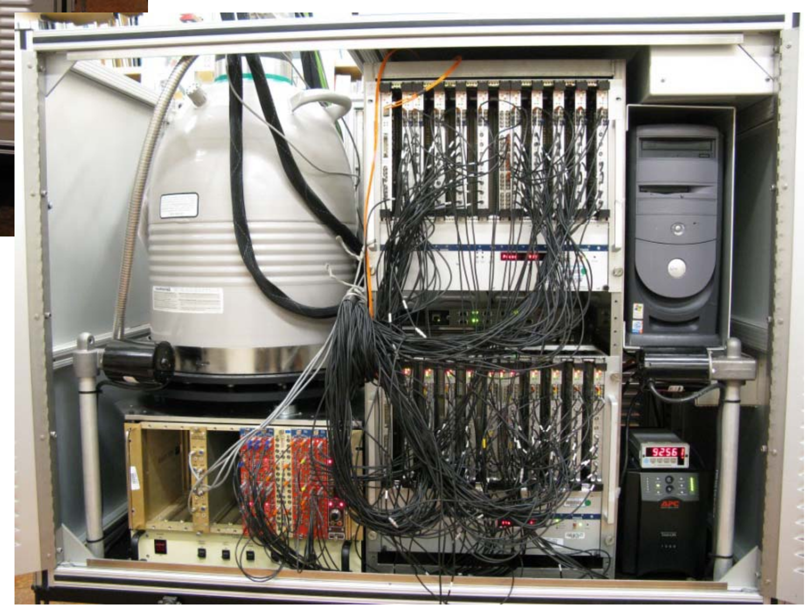


Nuclear Safeguards: Verification of Nuclear Facilities

Compact Compton Imager: CCI-2





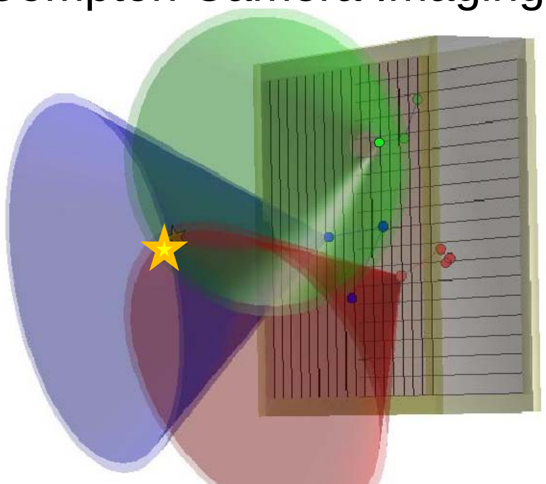


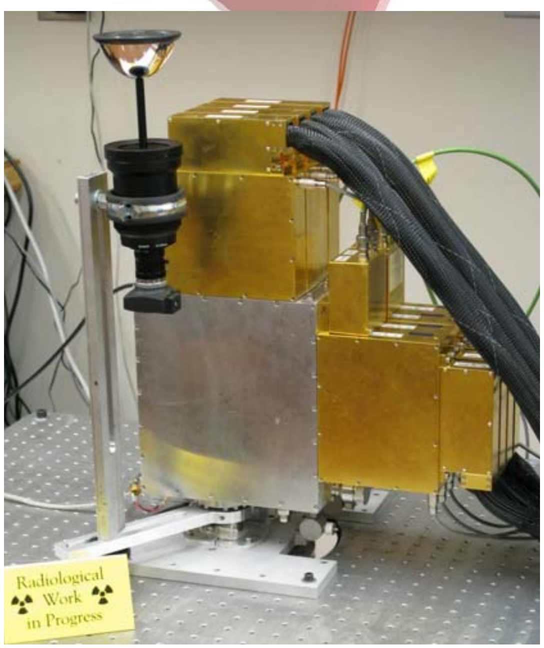
- 2 HPGe large DSSD detectors in two cryostats & 2nd generation digital DAQ
- Each 37+37 strips w/ 2 mm pitch size; 15 mm thickness; 1.7 keV at 60 keV

Ge Detectors by Mark Amman

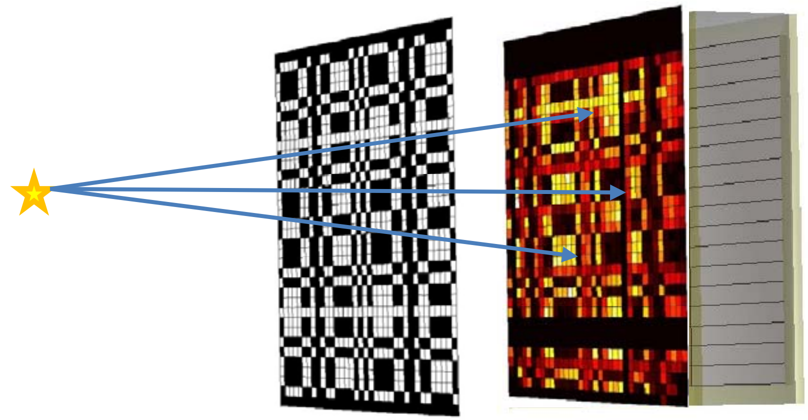
CCI-2: Imaging modalities

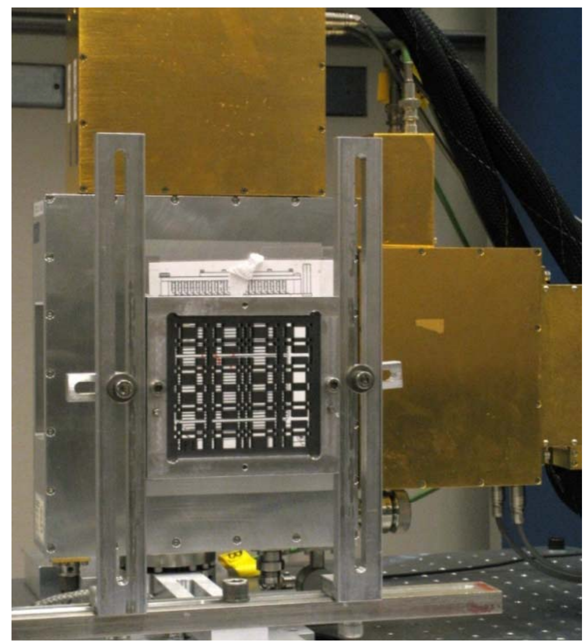
Compton Camera Imaging





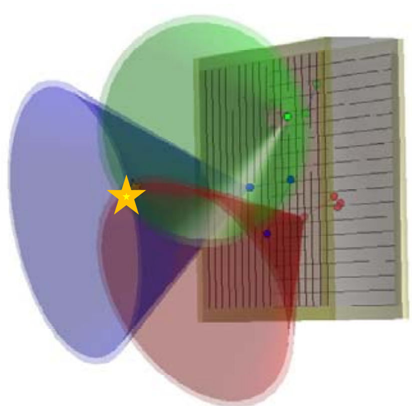
Coded Aperture Imaging

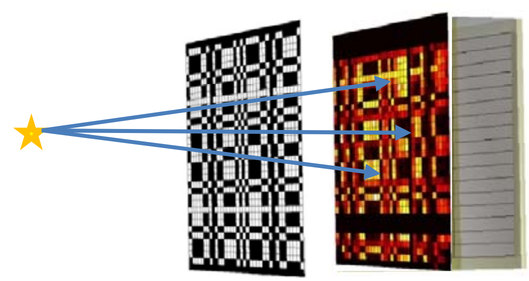




Present imaging performance with CCI-2

Metric	Compton Camera	Coded Aperture
Angular resolution	1-2 degrees	23 arcmin
Energy resolution	2 keV	2 keV
Imaging sensitivity	150 keV – 4 MeV	20 keV – 500 keV
Field-of-view	4π	$0.05\pi – 0.25\pi$



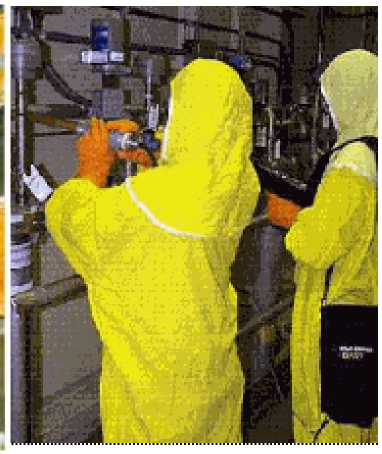


3D Gamma-Ray Imaging for Nuclear Safeguards

Safeguards Application

Current technology

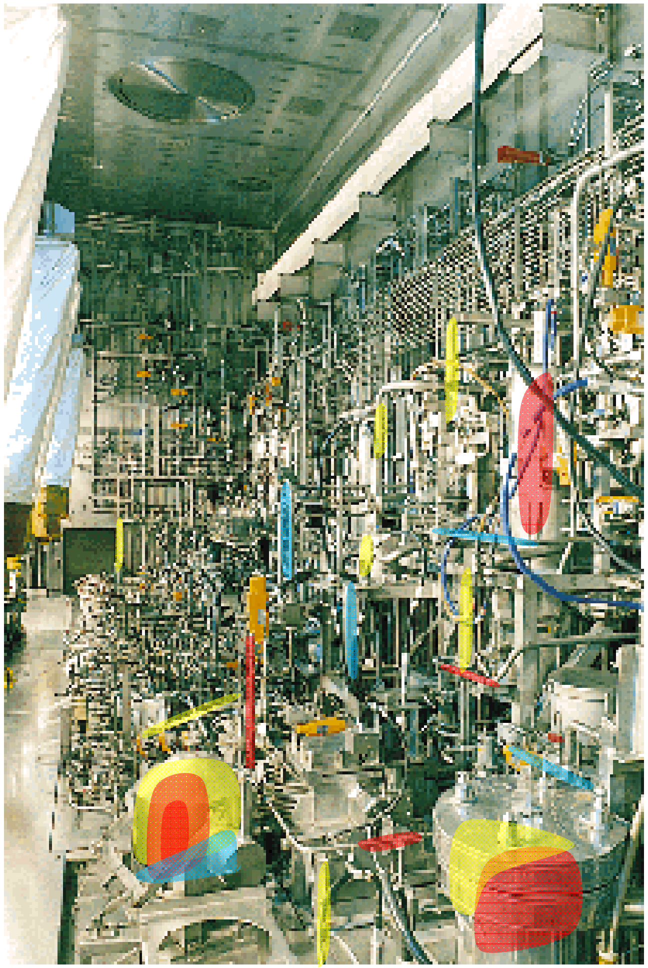
Measurement of Holdup at the Rocky Flats Site



Determination of changes in holdup inventories in process plants

Applications of new 3D gamma-ray imaging system:

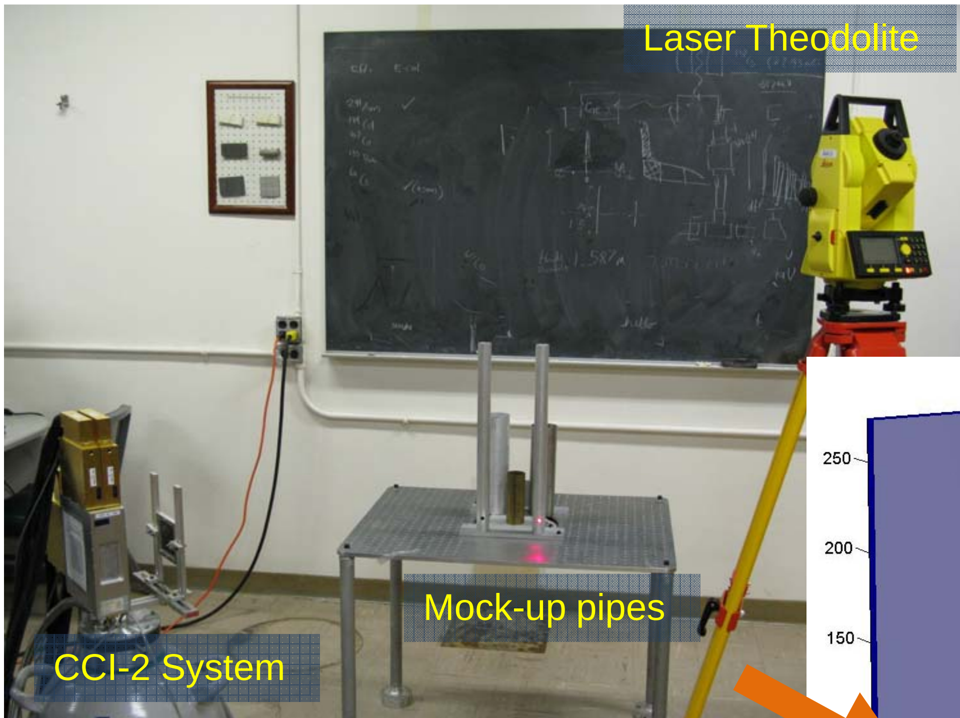
- Timely detection of highly-enriched uranium production in a modern uranium enrichment plant,
- Timely detection of undeclared traces of gamma-emitting isotopes, indicating undeclared enrichment or spent fuel reprocessing,
- Detection of concealed or buried nuclear/chemical process vessels or piping during facility design information verification (DIV).



Process test bench for reprocessing study in the Nuclear Fuel Cycle Safety Engineering Research Facility (NUCEF) -JAEA

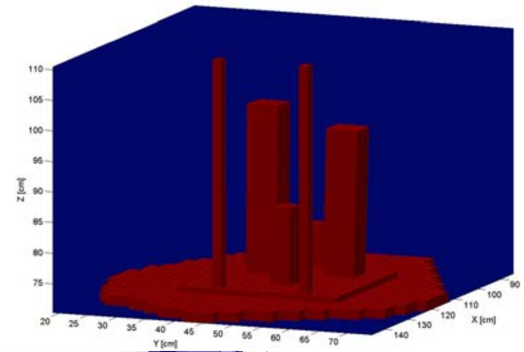
Stand-Off 3D Imaging

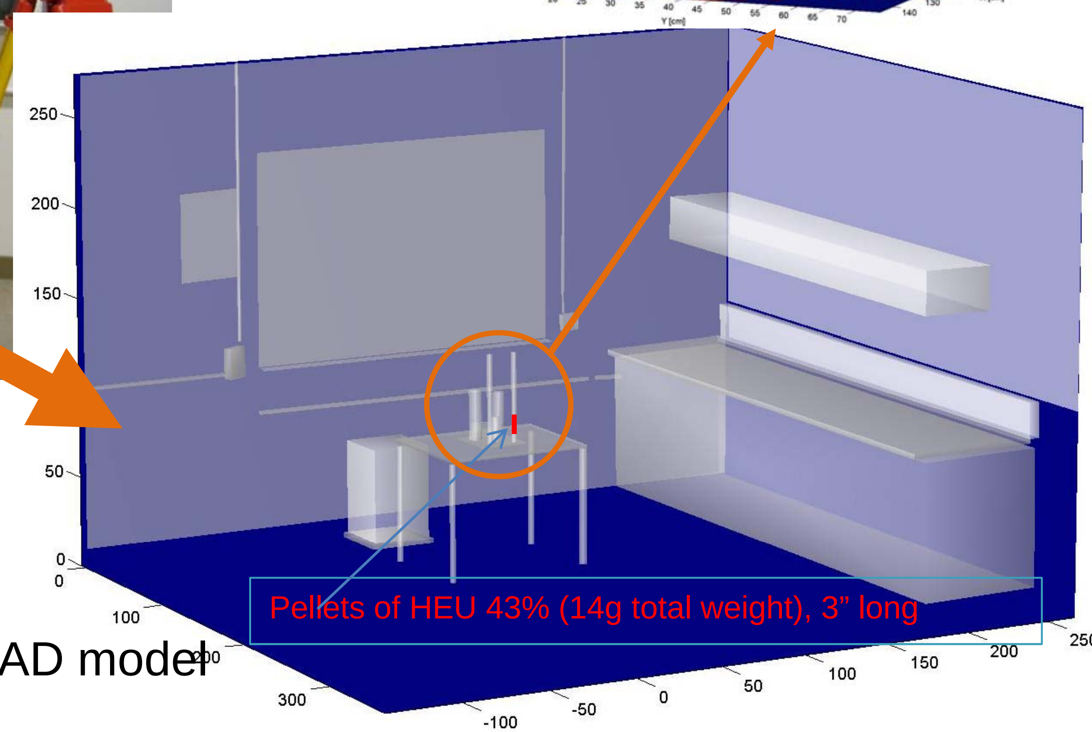
3D gamma-ray imaging demonstration measurement



Experimental setup

Voxelized model

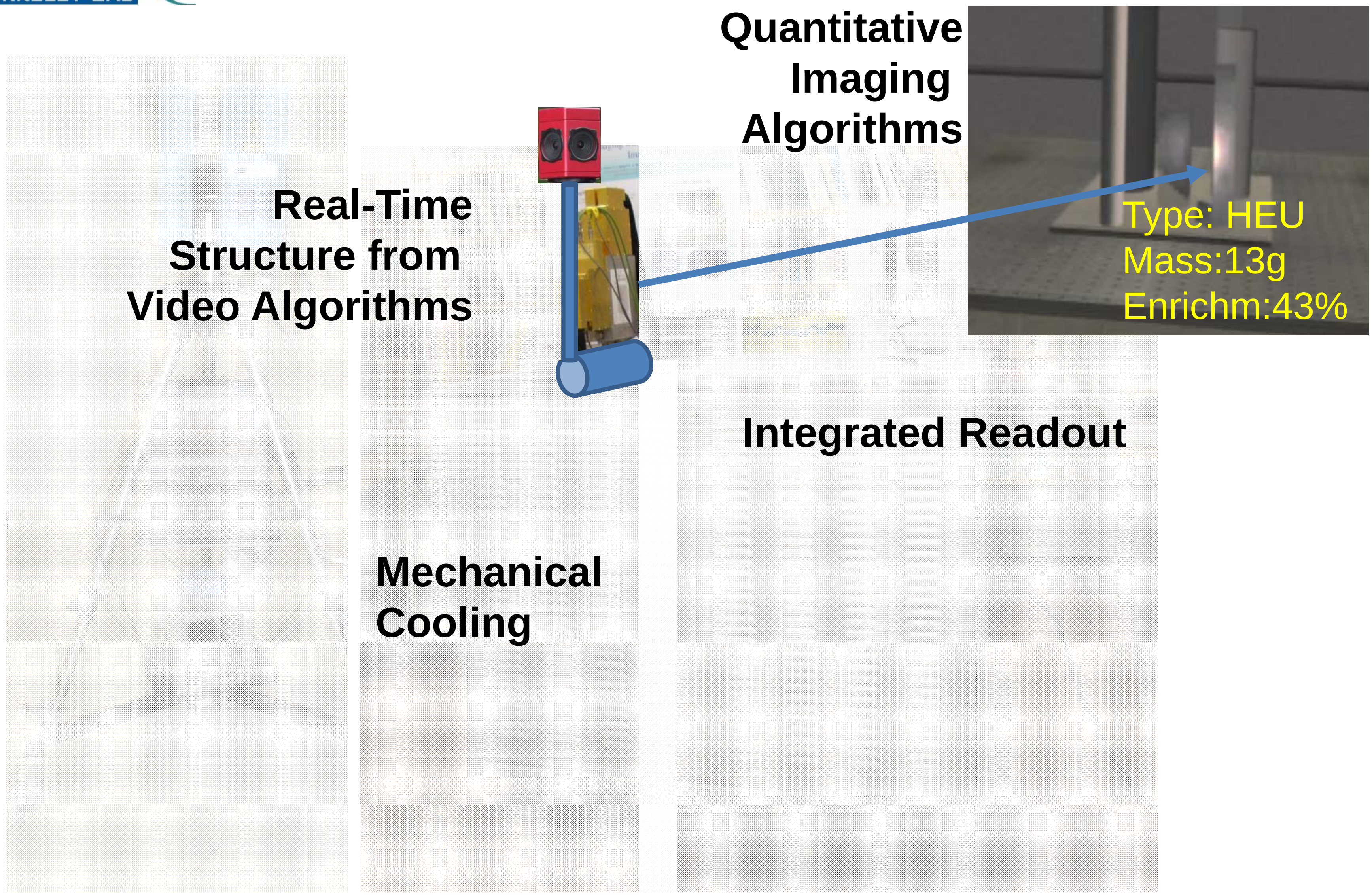




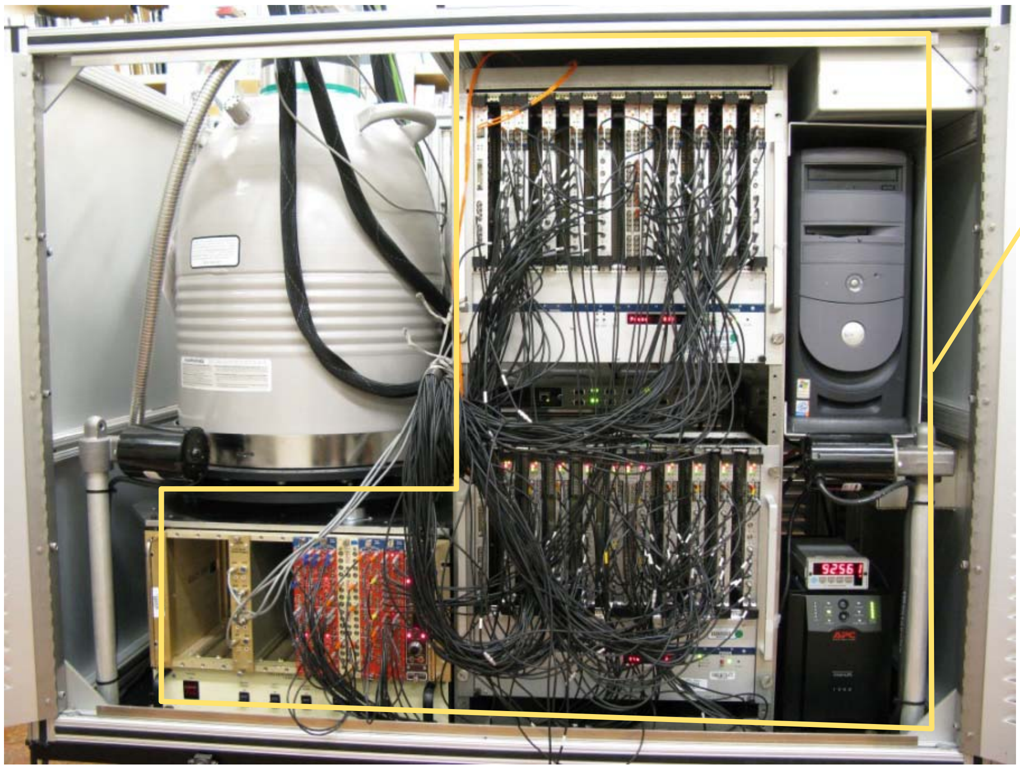
CAD model

3D gamma-ray imaging demonstration measurement

Bringing systems from the lab to the field

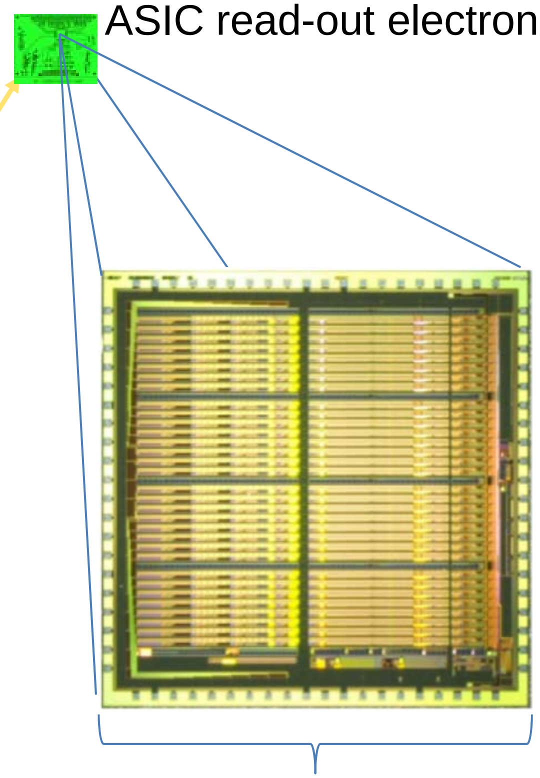


Development of high resolution, low power integrated read-out



Current segmented Ge detection systems require expensive, bulky, power hungry electronics

Signal filtering and data acquisition will be done on ASIC read-out electronics

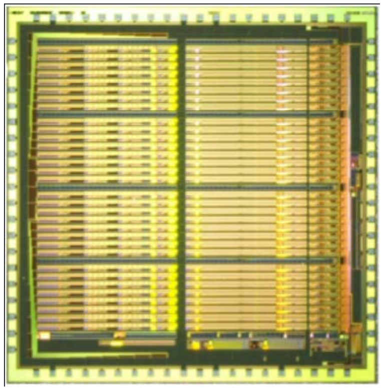


5mm

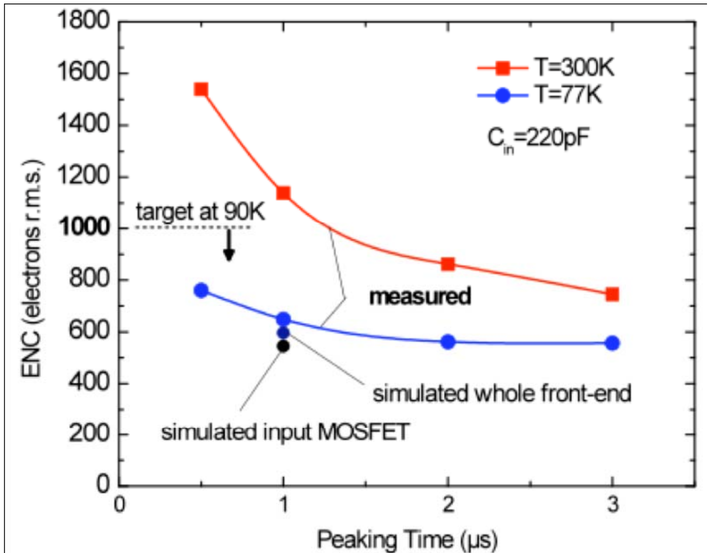
Die picture of NCI ASIC
(5 mm x 5 mm)

ASIC design by Gianluigi De Geronimo (BNL)

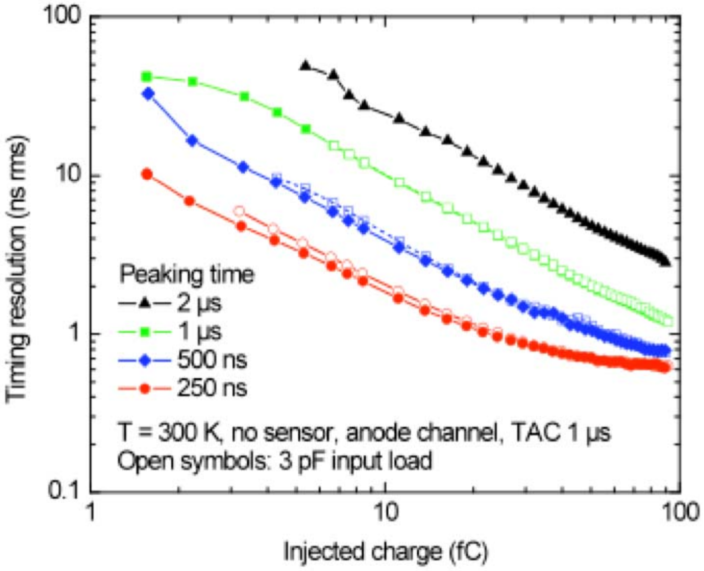
The BNL NCI ASIC

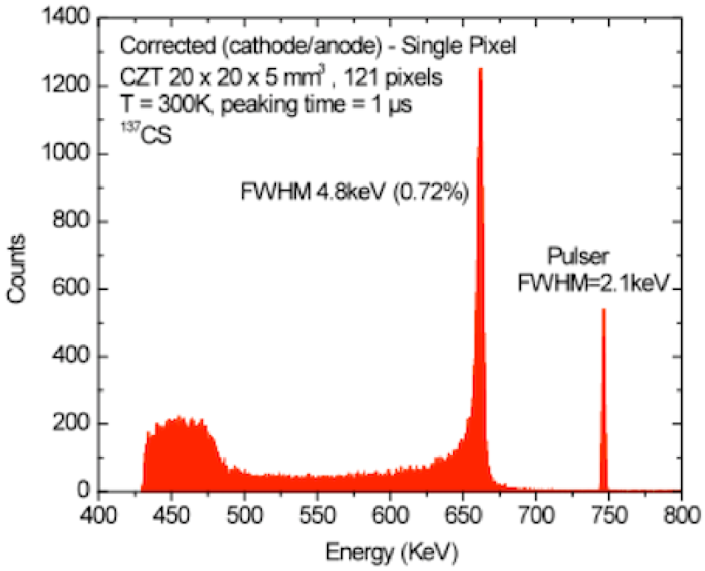


Die picture of the NCI ASIC

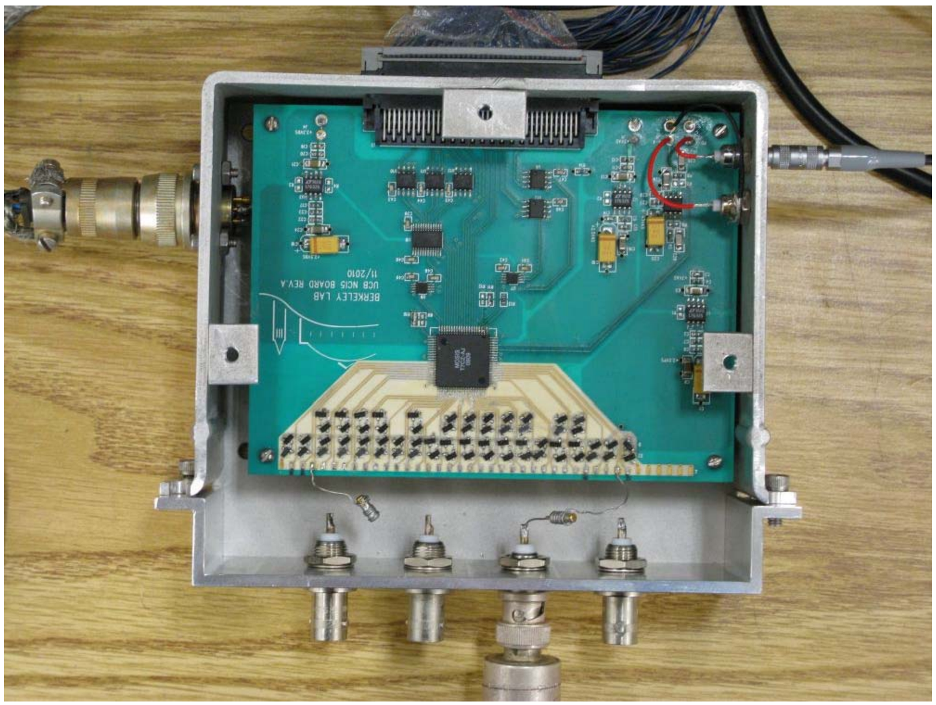


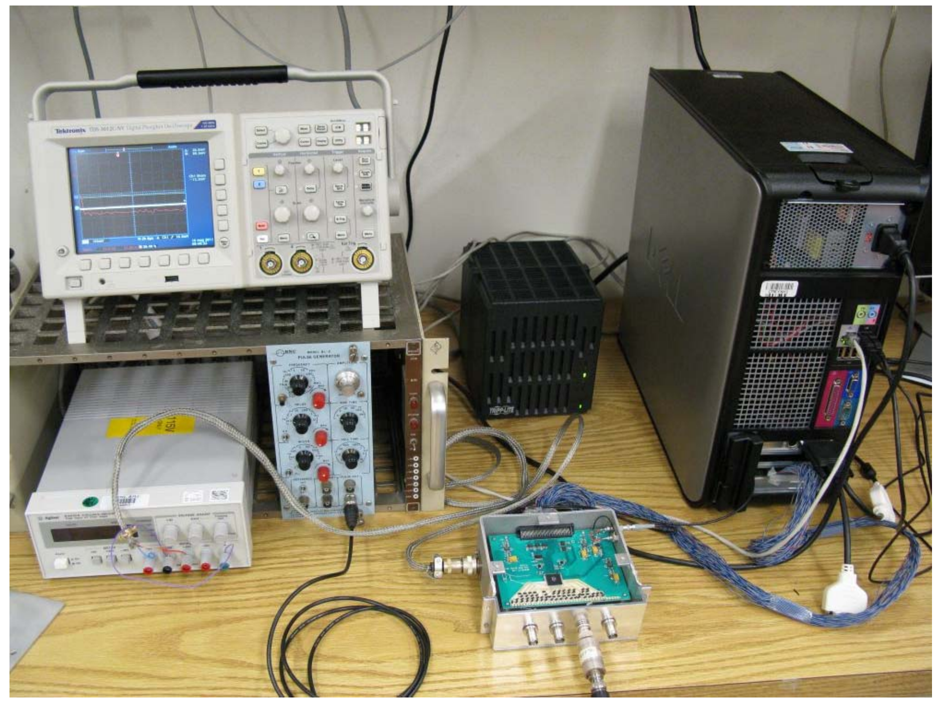
Measured ENC for the NCI ASIC





Development of high resolution, low power integrated read-out

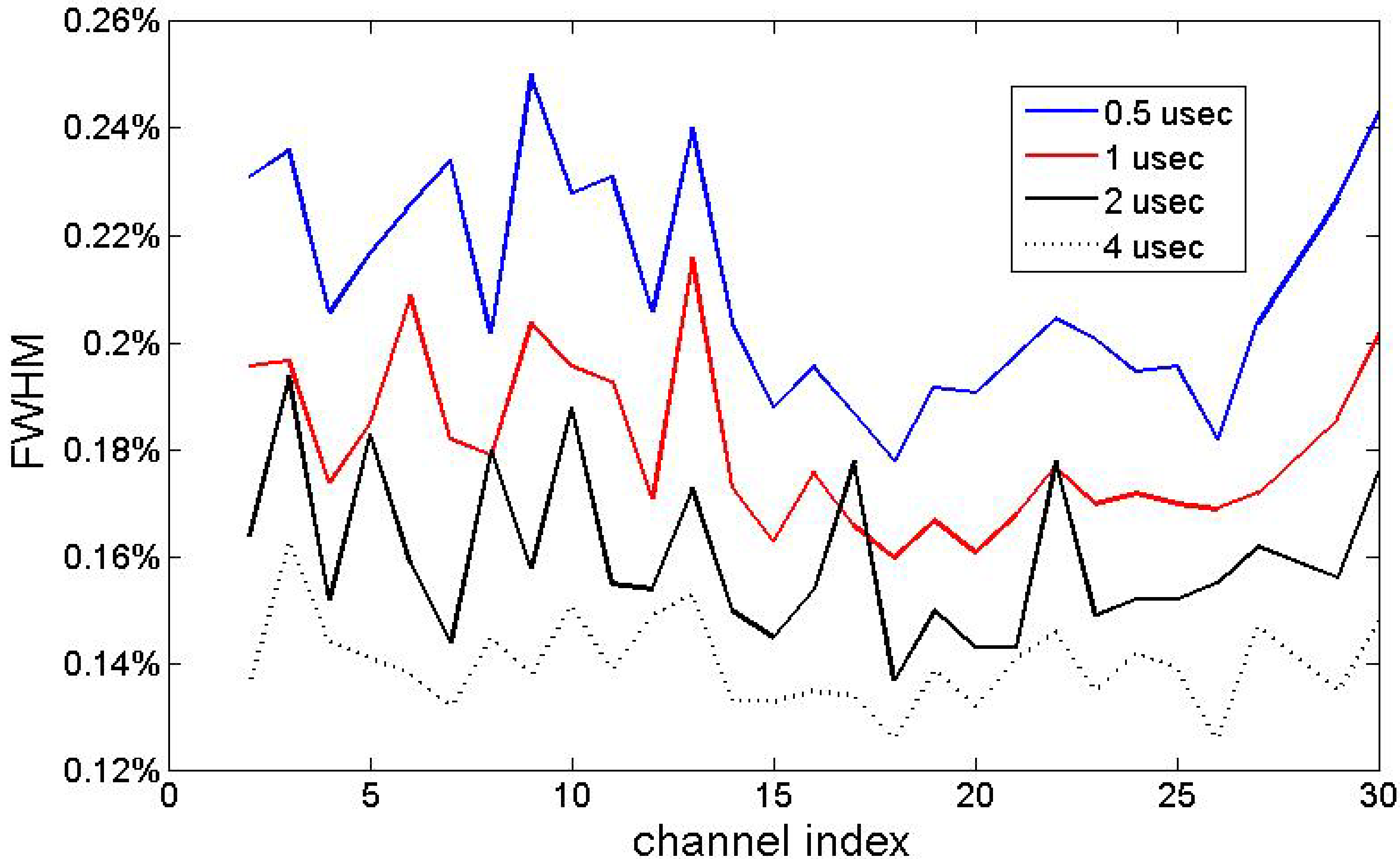




ASIC board design by Jane Hoberman (UCB/SSL)

Test measurements by Cameron Bates

Measured performance of the BNL NCI ASIC



In-Beam Gamma-Ray Imaging for Ion Cancer Therapy Verification

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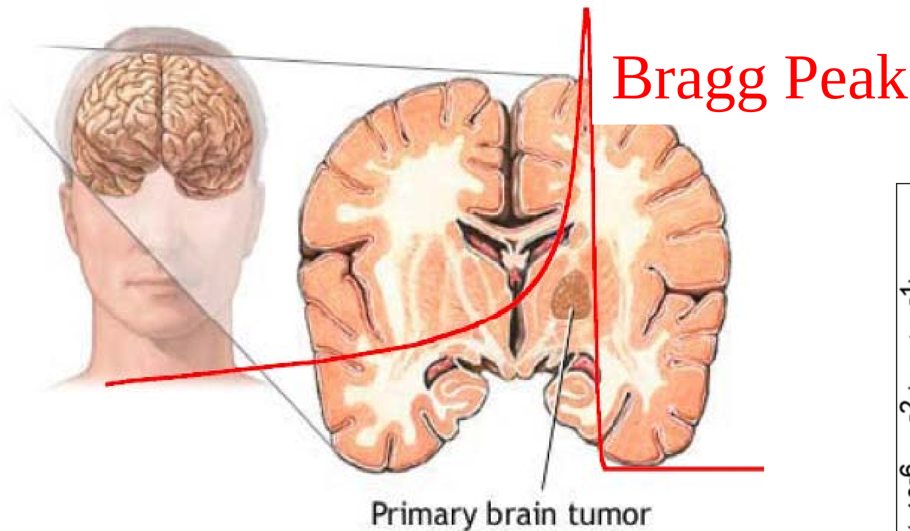
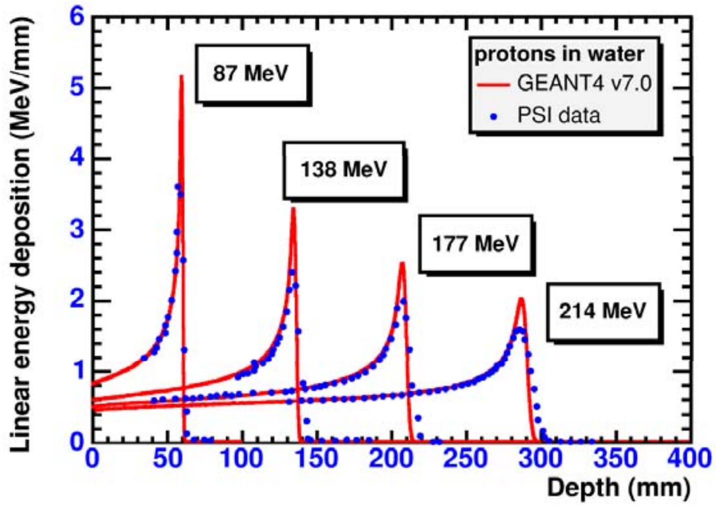
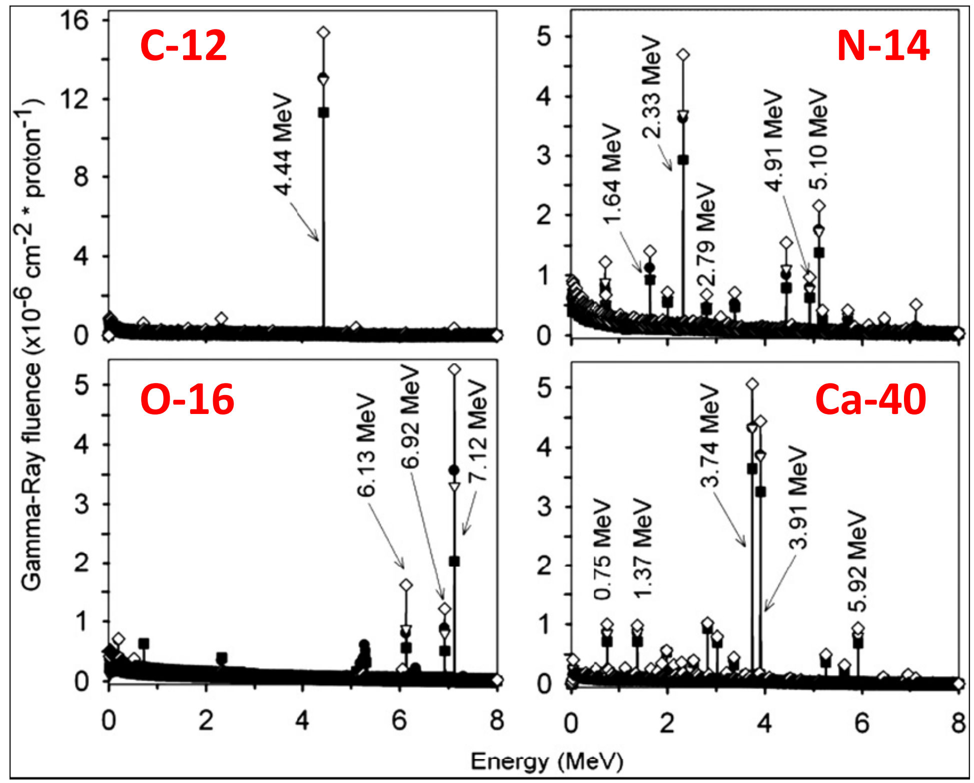
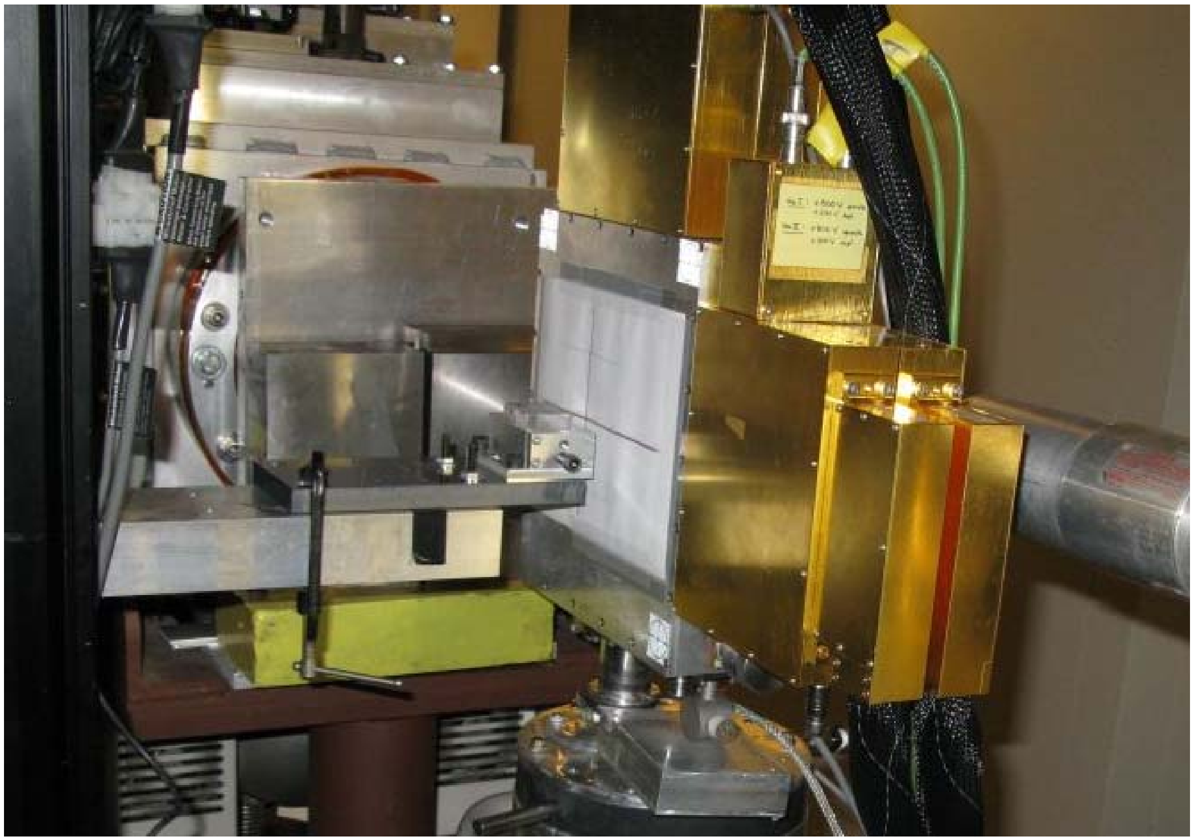


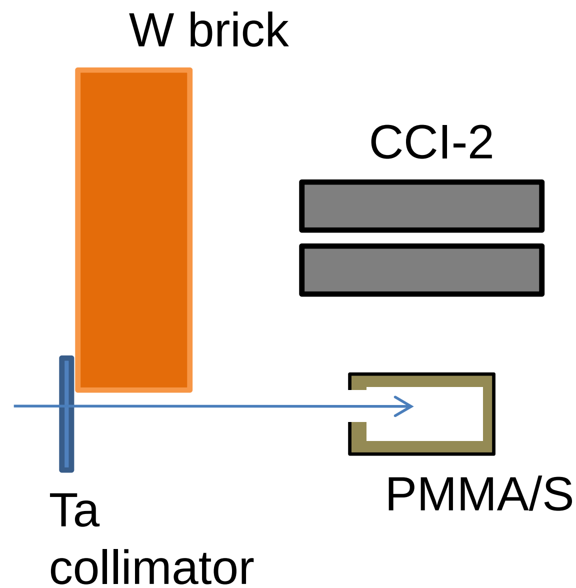




JC Polf et al. Phys. Med. Biol. 54 (2009) 731–743

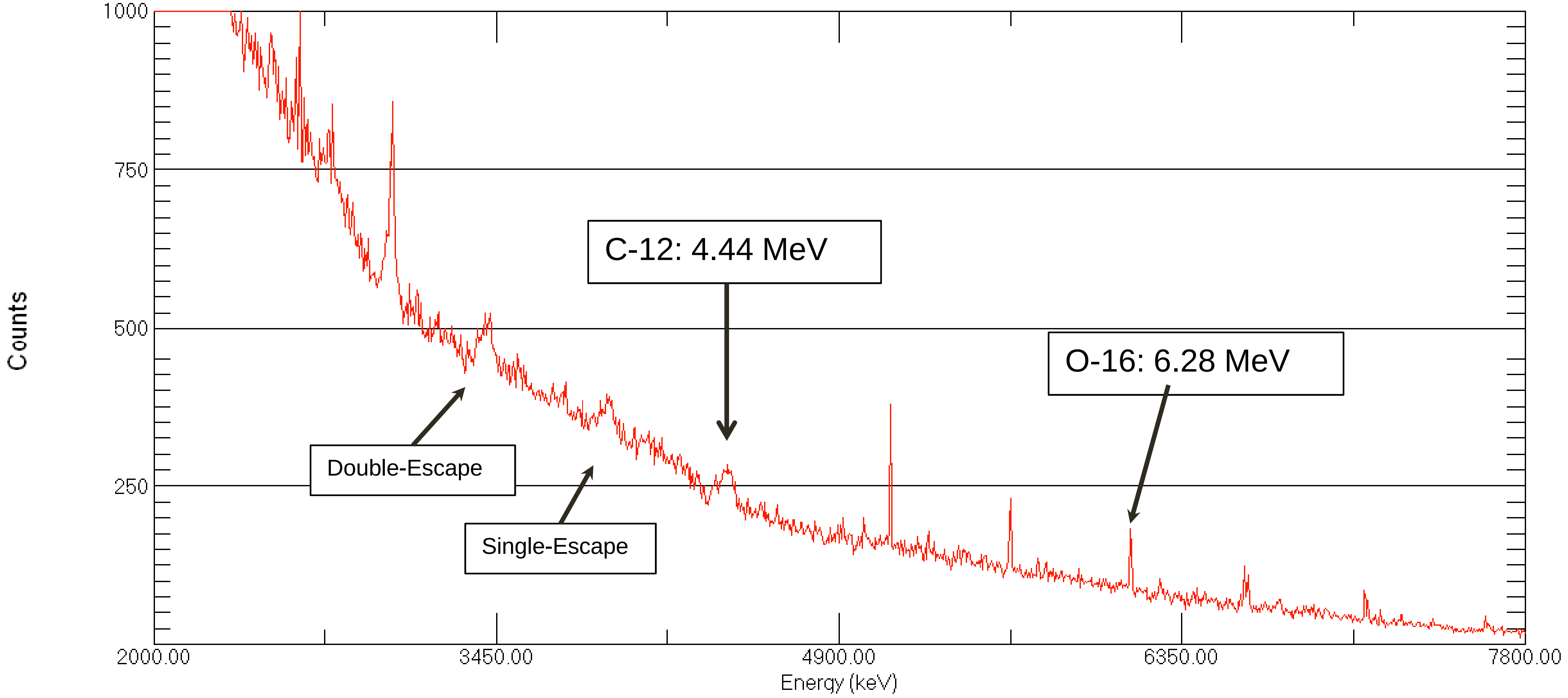
Preliminary test of In-Beam Gamma-Ray Imaging for Ion Cancer Therapy Verification

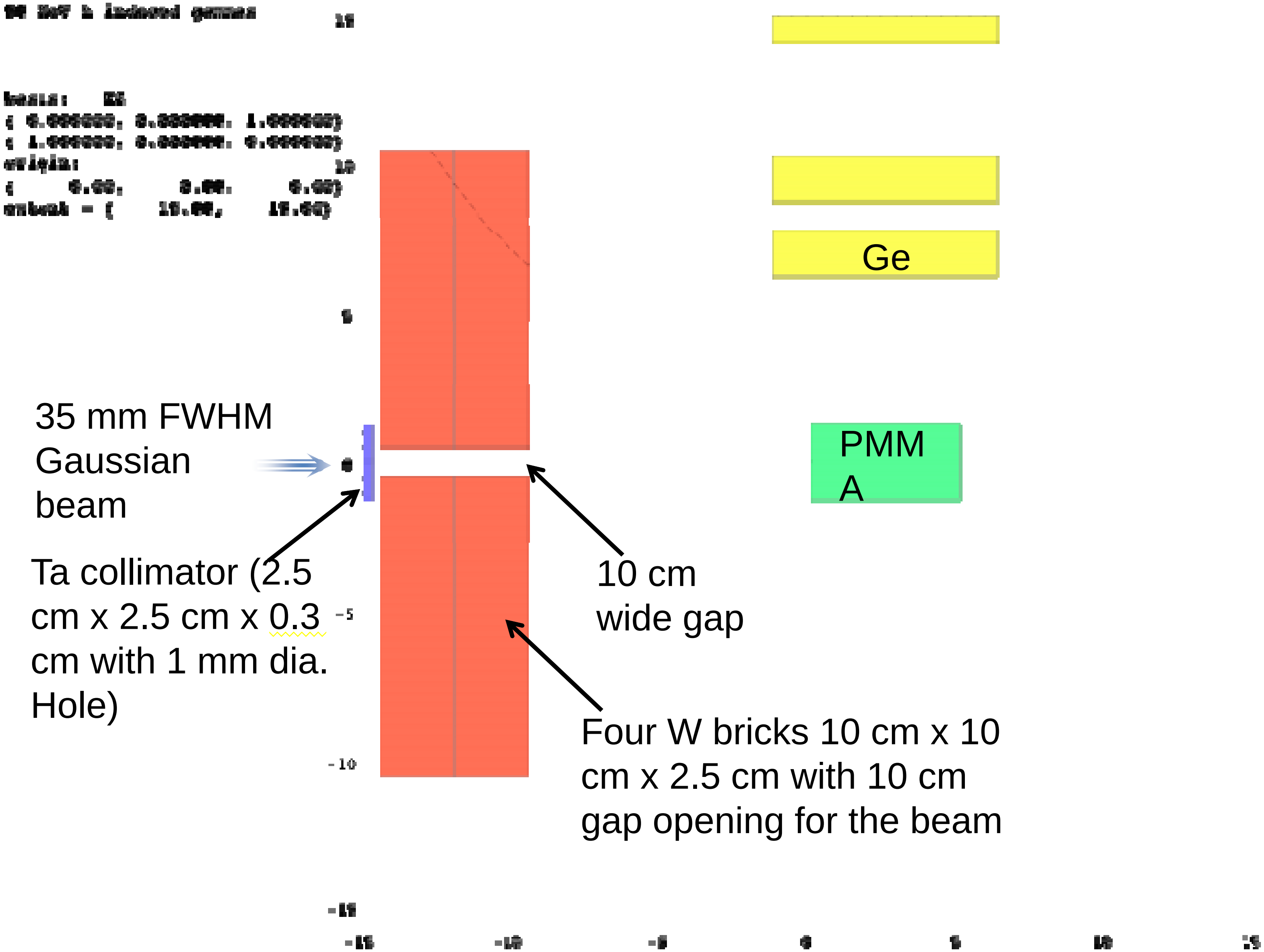




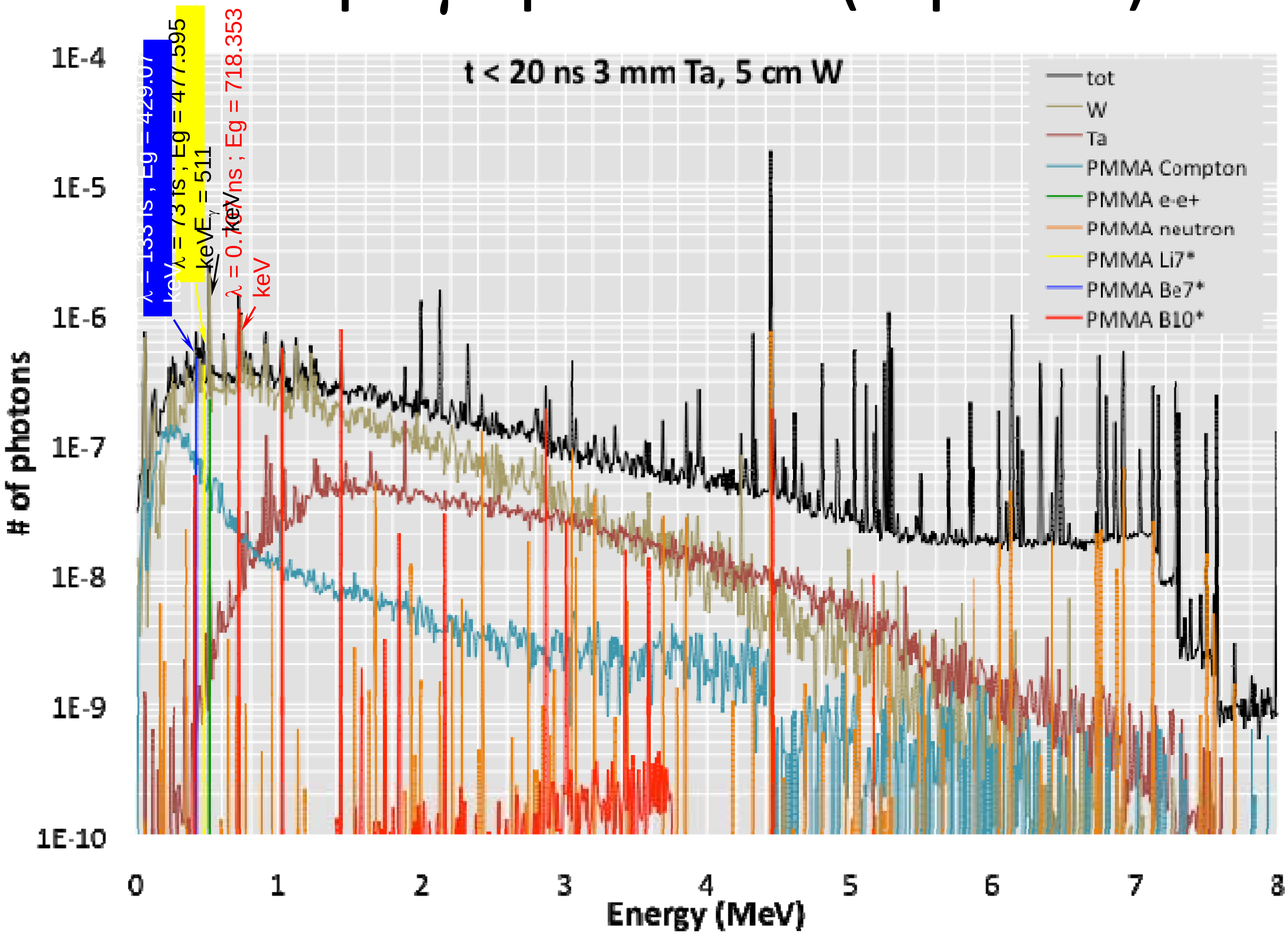
Measurements performed at the 88" cyclotron

Measured Spectra
E_p=50MeV

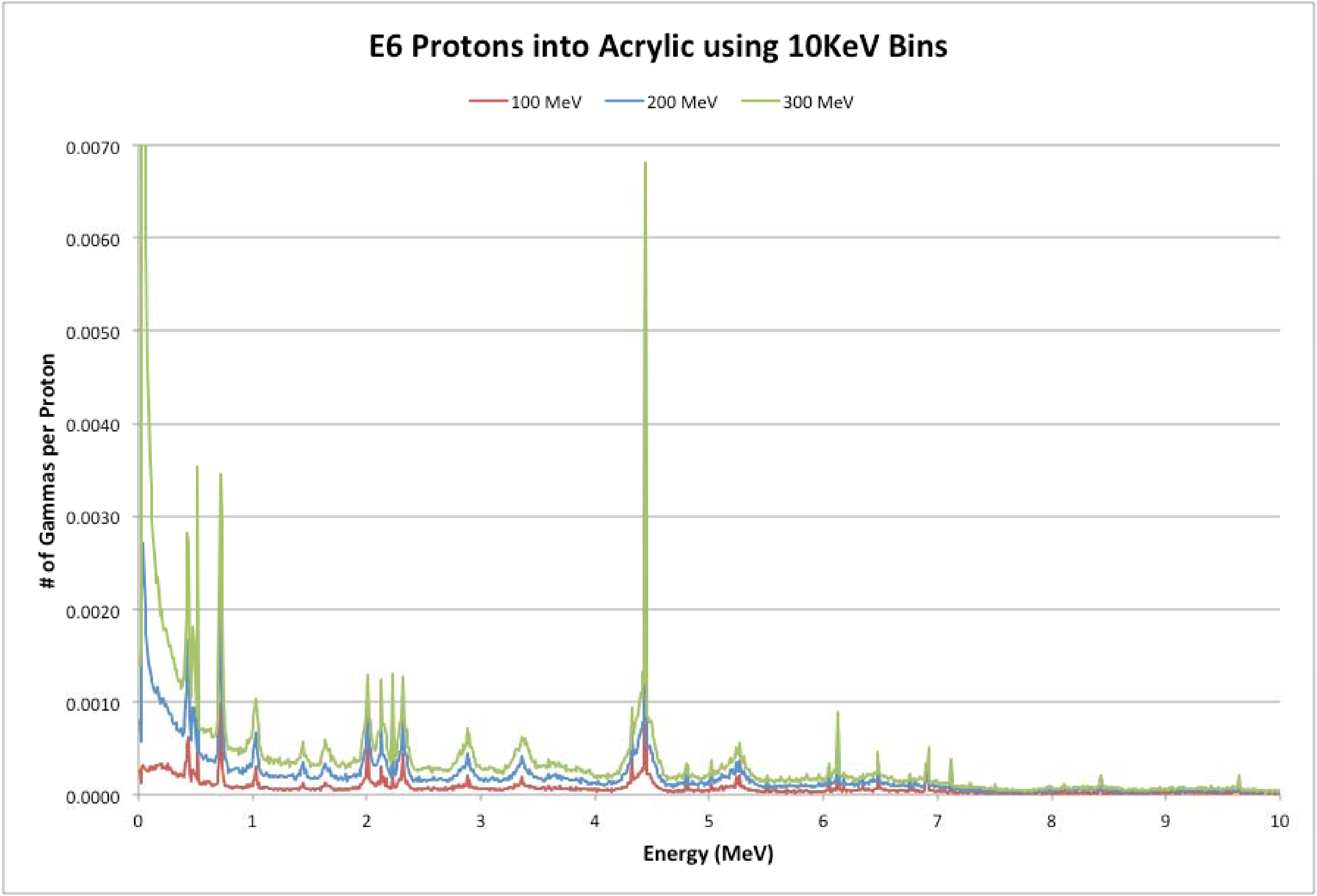



Ge
PMM
A
35 mm FWHM
Gaussian
beam
Ta collimator (2.5 cm x 2.5 cm x 0.3 cm with 1 mm dia. Hole)
10 cm
wide gap
Four W bricks 10 cm x 10 cm x 2.5 cm with 10 cm gap opening for the beam

Prompt γ spectrum (inp.014)



Geant-4 Gammas from Acrylic



Simulations by Joe Miller and Daniel Bond

Nuclear Life-Time Measurements using Compton Back-Projection

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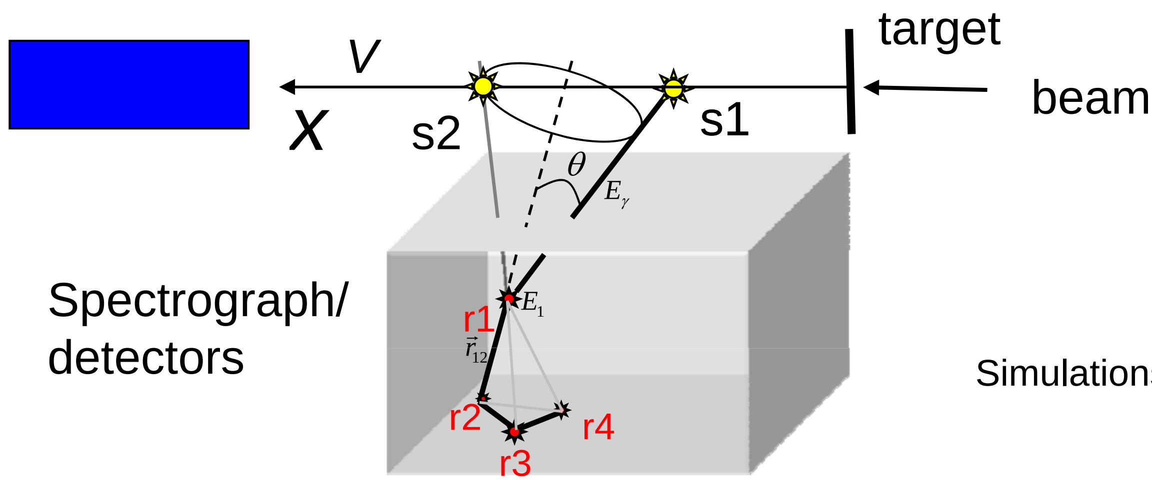
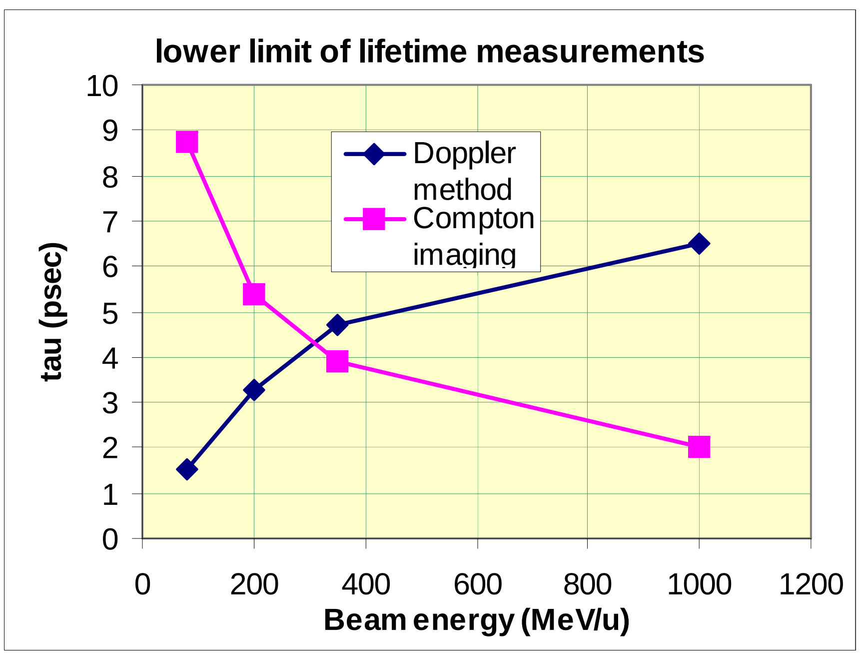
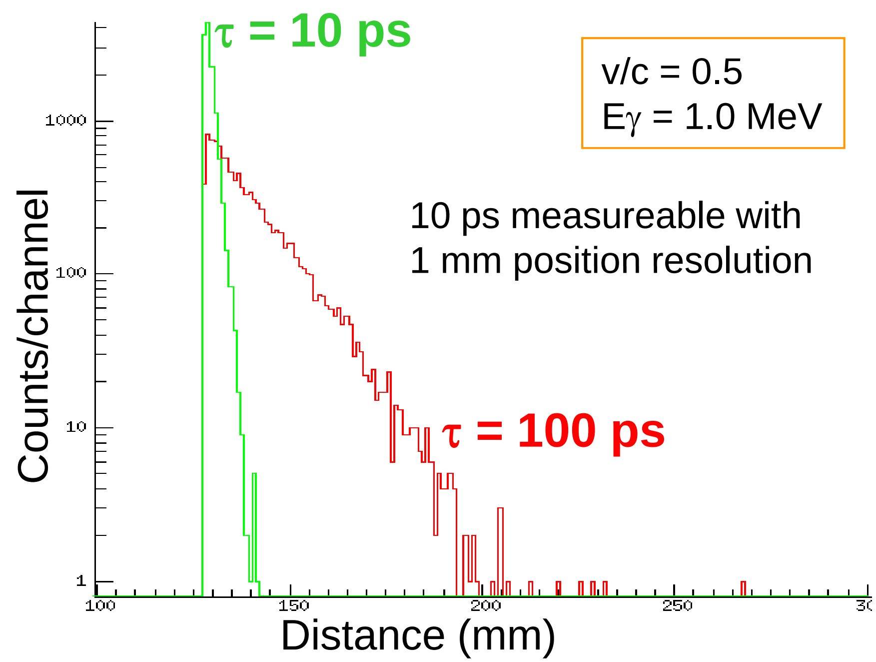


Simulations by I-Yang Lee





10 ps measureable with
1 mm position resolution

Further Work

- Test NCI ASIC with DSSD Ge detectors
- Develop a new ASIC optimized for Ge detectors
- Develop 3D image reconstruction algorithms
- Perform modeling to estimate best gamma-ray signatures and evaluate gamma-ray to dose correlations
- Perform p therapy verification test measurements using a 50 MeV proton beam on PMMA at the 88" cyclotron
    - Benchmark simulation
    - Identify most relevant imaging signatures
    - Demonstrate 3D imaging of p-beam
- Continue modeling and perform tests to demonstrate capability for life-time measurements

Team

LBNL: Lucian Mihailescu, Kai Vetter, Donald Gunter, Mark Amman, Paul Barton, Cameron Bates, Robert Crabbs, Matthew Pistone, Lazar Supic, Julien Rohel, I-Yang Lee, Jonathan Maltz, Grant Gullberg, Joe Wallig, Tim Loew

UCB: Dan Chivers, Mark Bandstra, Tim Aucott, Christina Moore, Joe Miller, Daniel Bond, Amy Coffer, Andrew Haefner, Sebastian Dionisio, Joe Curtis, Micah Folsom

UCSF: Martina Descovich, Sebastien Gros

BNL: Gianluigi De Geronimo, Jack Fried,

UCB/SSL: Steve Boggs, Jane Hoberman, Steve McBride

Questions?

“The real voyage of discovery consists not in seeking new landscapes but in having new eyes”

--Marcel Proust

Imaging Tasks

$$\mathbf{g} = \mathrm{A}\mathbf{f} + \mathbf{n}$$

Signal Detection

Check hypotheses:

1. signal present H1
2. signal absent H0

$$H_1 : \mathbf{g} = \mathrm{A}(\mathbf{f}_s + \mathbf{f}_b) + \mathbf{n}$$

$$H_0 : \mathbf{g} = \mathrm{A}(\mathbf{f}_b) + \mathbf{n}$$

The Ideal Observer is the likelihood ratio:

$$\Lambda(\mathbf{g}) = \frac{p\left(\mathbf{g} \mid H_1\right)}{p\left(\mathbf{g} \mid H_0\right)}$$

Signal Estimation (amplitude, position).

Find $\hat{f}_i$, best estimate of f_i

Minimize the mean square error:

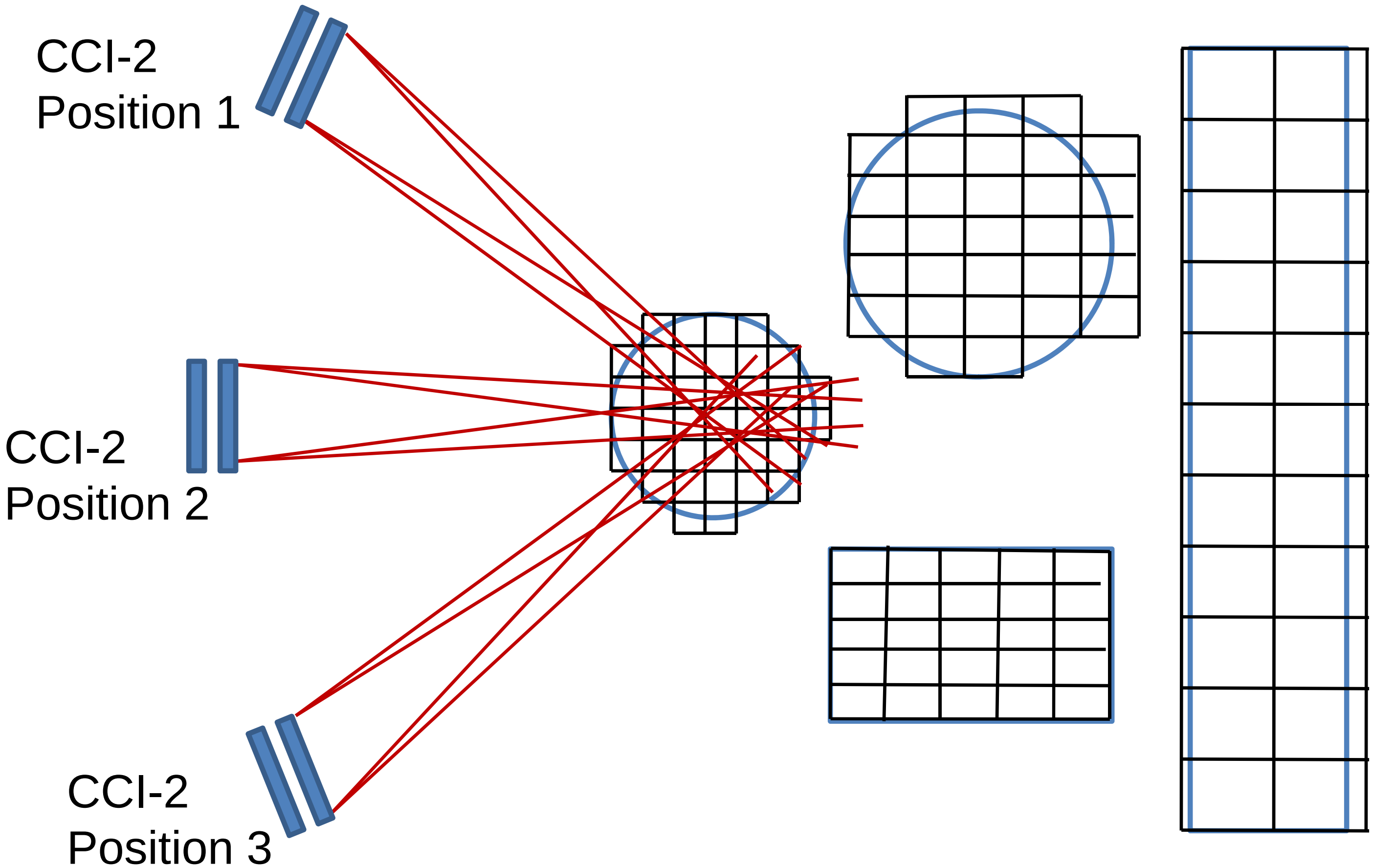
$$MSE(\hat{f}_i) = E\left[(\hat{f}_i - f_i)^2\right]$$

$$E[\hat{f}_i] = \int_{-\infty}^{\infty} \hat{f}_i p(\hat{f}_i) d\hat{f}_i$$ is the expected value

$$MSE(\hat{f}_i) = \underbrace{\left(E[\hat{f}_i^2] - E^2[\hat{f}_i]\right)}_{\sigma^2(\hat{f}_i)} + \underbrace{\left(E^2[\hat{f}_i] - f_i\right)^2}_{b^2(\hat{f}_i)}$$

Variance bias

Dynamic voxelization for 3D imaging



Data Analysis for Compton Imaging: Overview

Signal waveforms

Signal Feature Extraction

List of firing segments (E_i, t_i, a_i)

Event Selection | **Signal Decomposition**

List of interactions, (E_i, r_i)

Gamma-ray Tracking

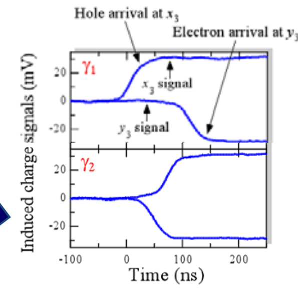
Scattering angle θ, scattering direction s, position r, total energy E

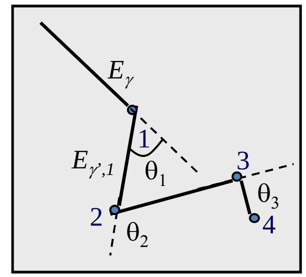
Image Reconstruction

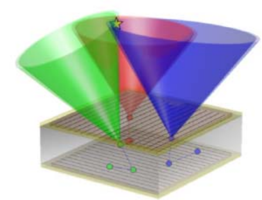
Image

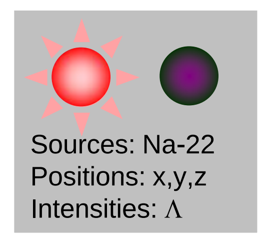
Image-Spectral Analysis

Threat identification, Diagnostics



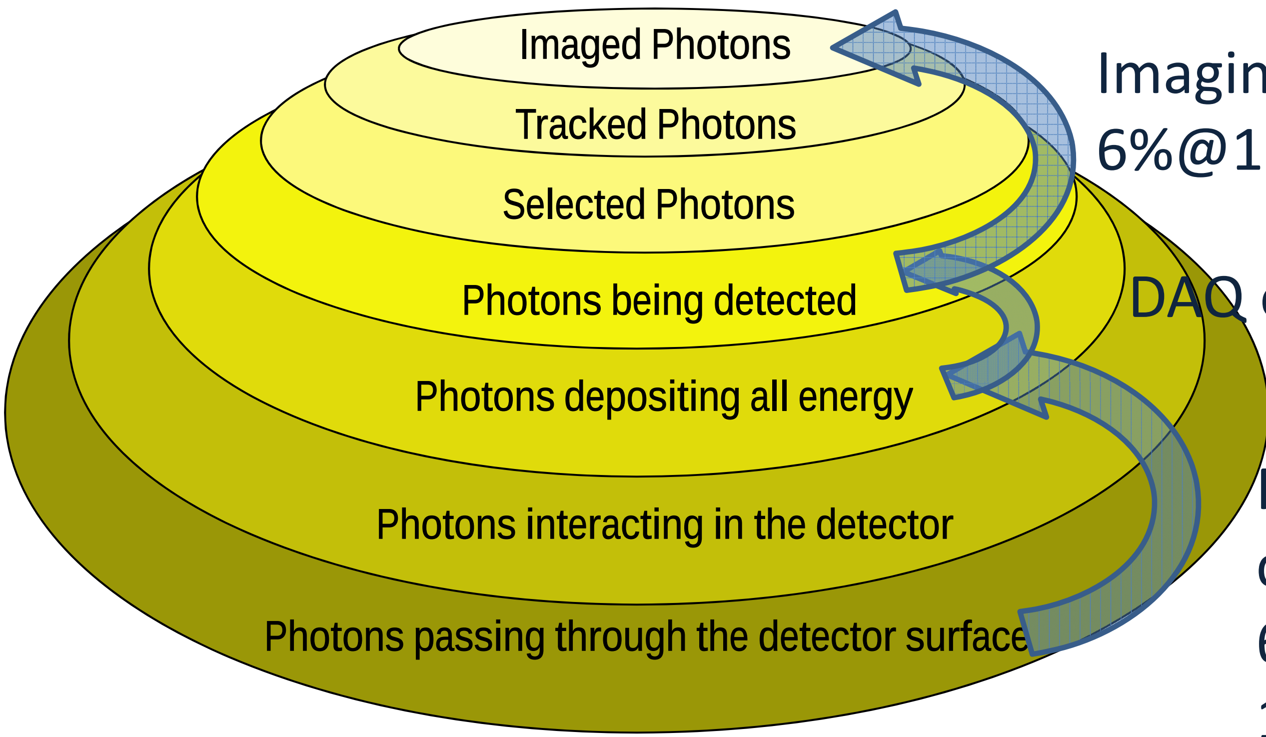






Detection and imaging efficiency

Photon statistics



Imaging efficiency
6%@186keV- 18%@1MeV

DAQ efficiency
75% @2kHz

Full energy deposition efficiency
60%@186keV-
15%@1MeV

Currently, CCI-2 has a total imaging efficiency of 2-4%