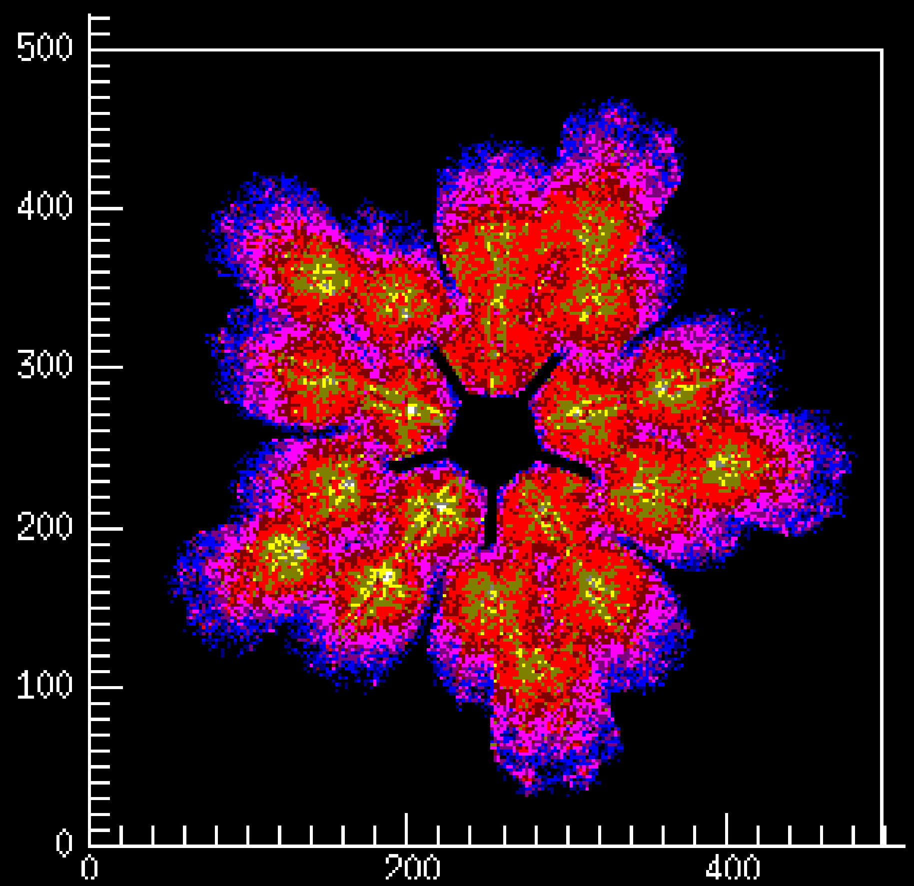
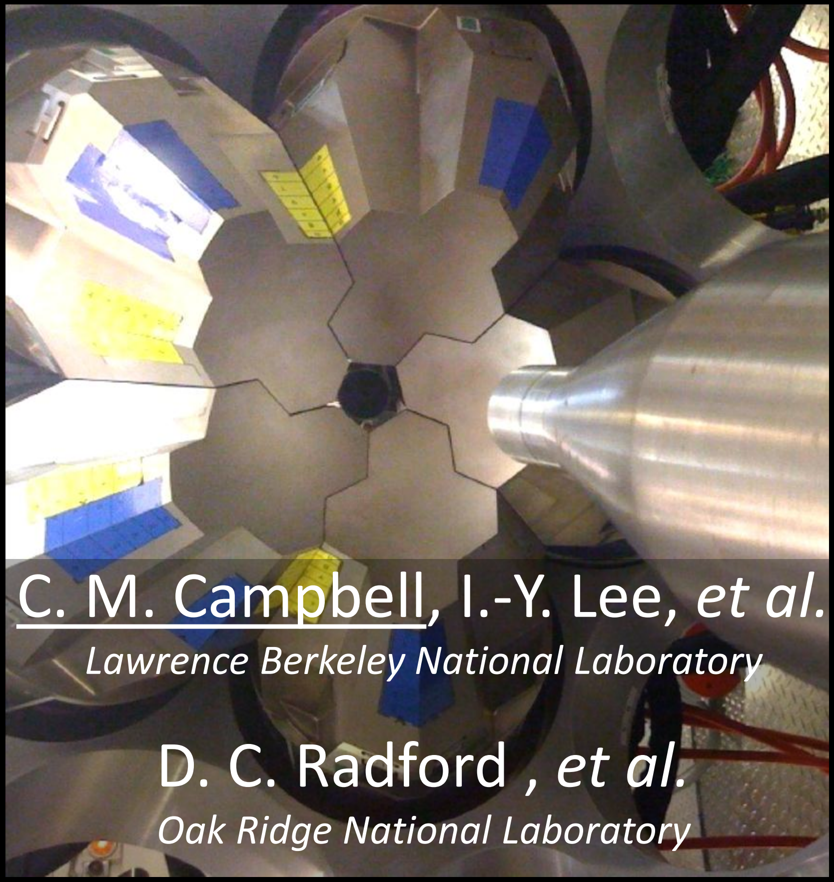
Gamma-Ray Tracking with Gamma Ray Energy Tracking In-beam Nuclear Array (GRETINA)





C. M. Campbell, I.-Y. Lee, *et al.*
Lawrence Berkeley National Laboratory

D. C. Radford , *et al.*
Oak Ridge National Laboratory

Gamma-Ray Tracking

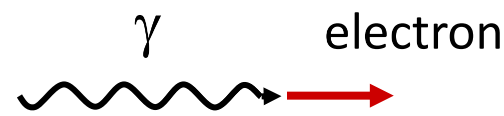
- What is it?
- Why do we need it?
- How do we do it?

What is gamma-ray tracking?

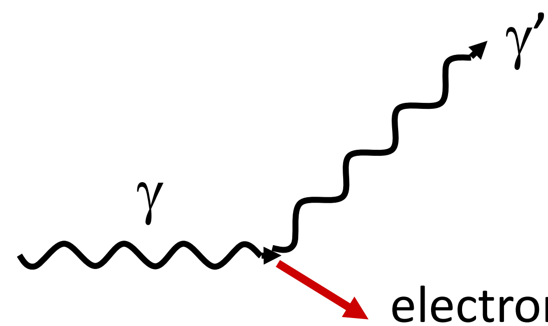
- Goal: extract more information using knowledge of γ interactions with detector.
- Similar to charged particle tracking
  - measure energy deposited by electrons
- Different
  - Energy deposited in one or more large chunks
  - Photon tracks often change angle, and may split
  - Governed by probability
- Two steps
  - Find interaction positions and energies
  - Reconstruct the photon(s) path (track)

Interaction of γ-rays with Matter

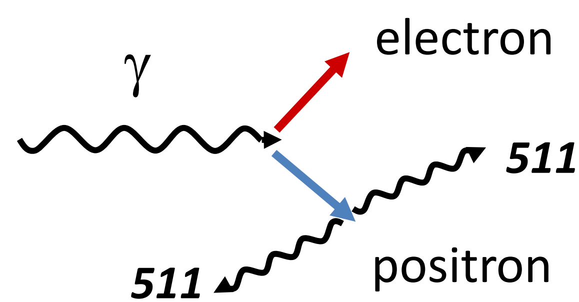
- Photo electric



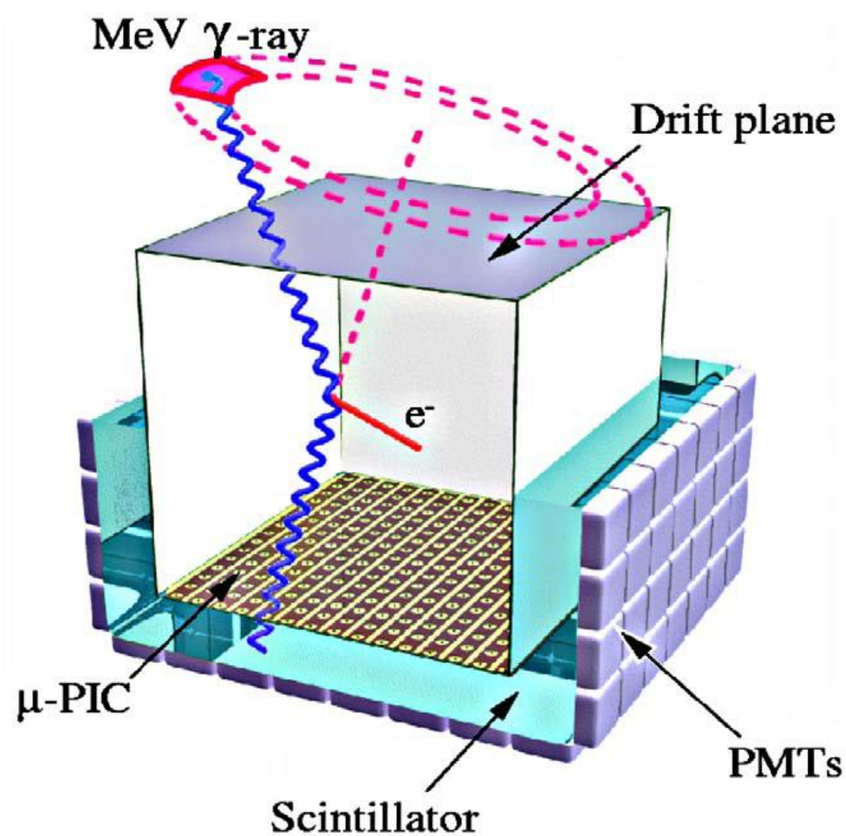
- Compton scattering
  - Likely 150keV - 8MeV
  - (most nuclear transitions)



- Pair production



Can we use the electron angle?



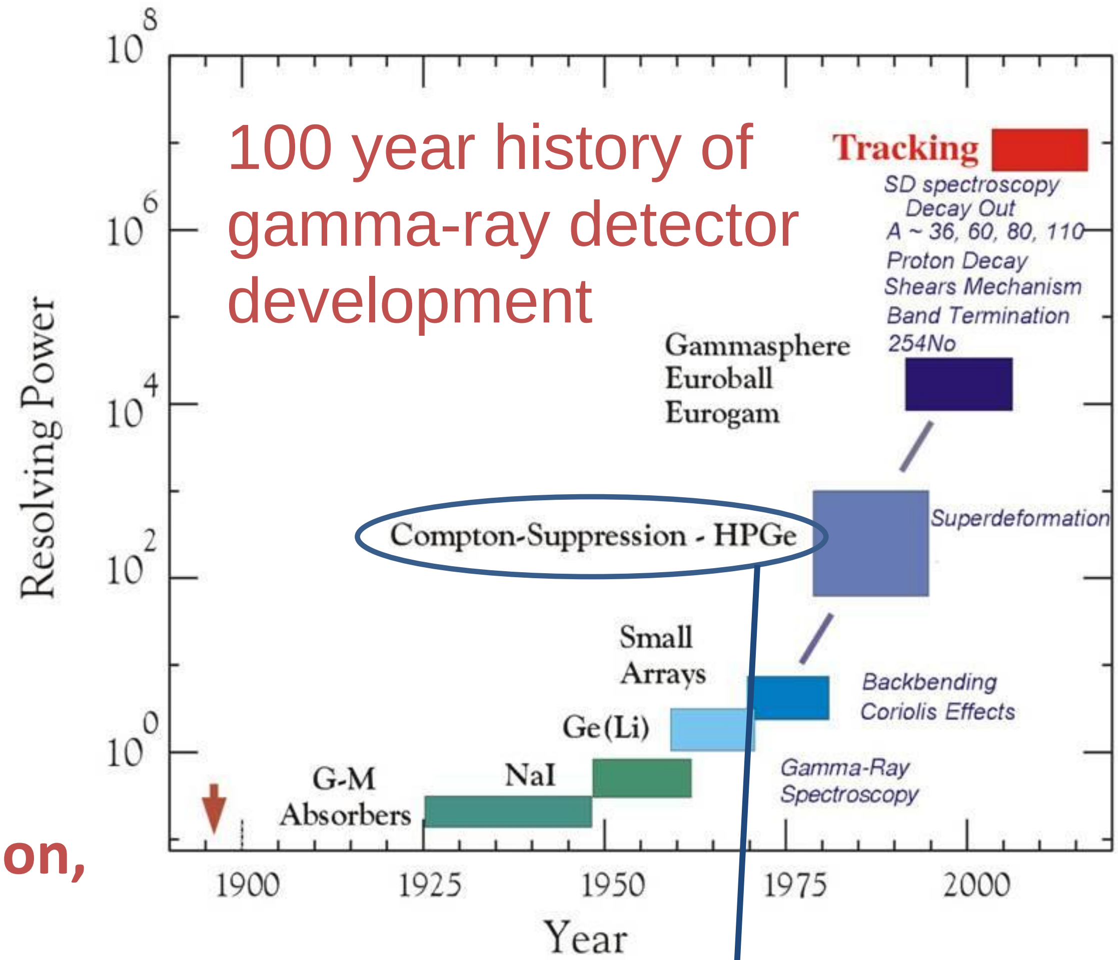
Electron-Tracking Compton Camera (ETCC)
Kyoto University

- In principle? Yes.
- In practice, in a gas? Yes.
- In practice, for all events, with high-efficiency? No …

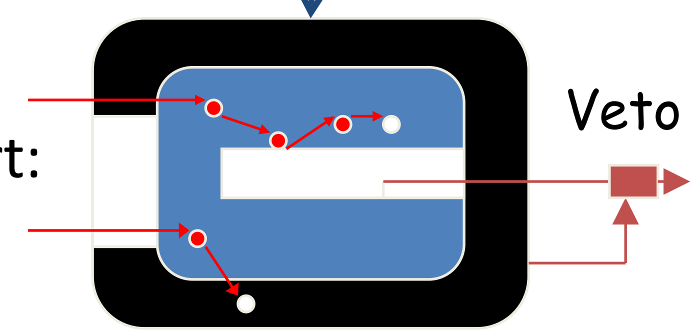
- Research by the Applied Nuclear Physics group at Berkeley shows it may be very useful in a next-generation Compton Camera

Why a Tracking Array?

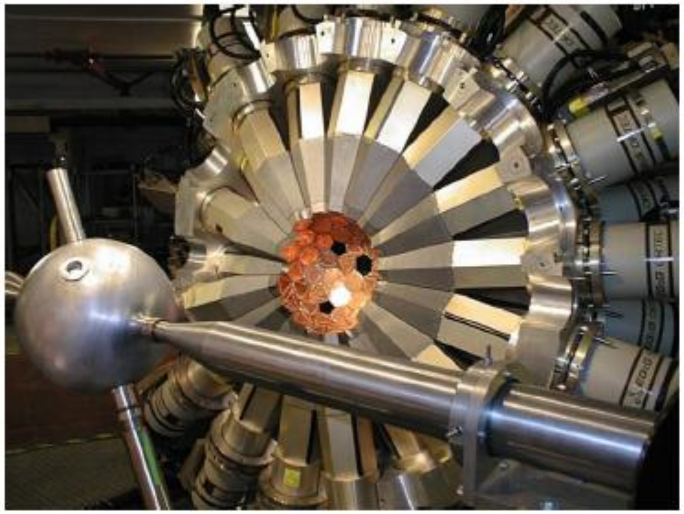
- *Challenge*
  - ***Requirement***
- Low beam rate /cross-section
  - **High efficiency**
- Large recoil velocity
  - **High position resolution, Doppler correction**
- High beam-related background
  - **High Peak-to-Total**
  - **High counting rate**

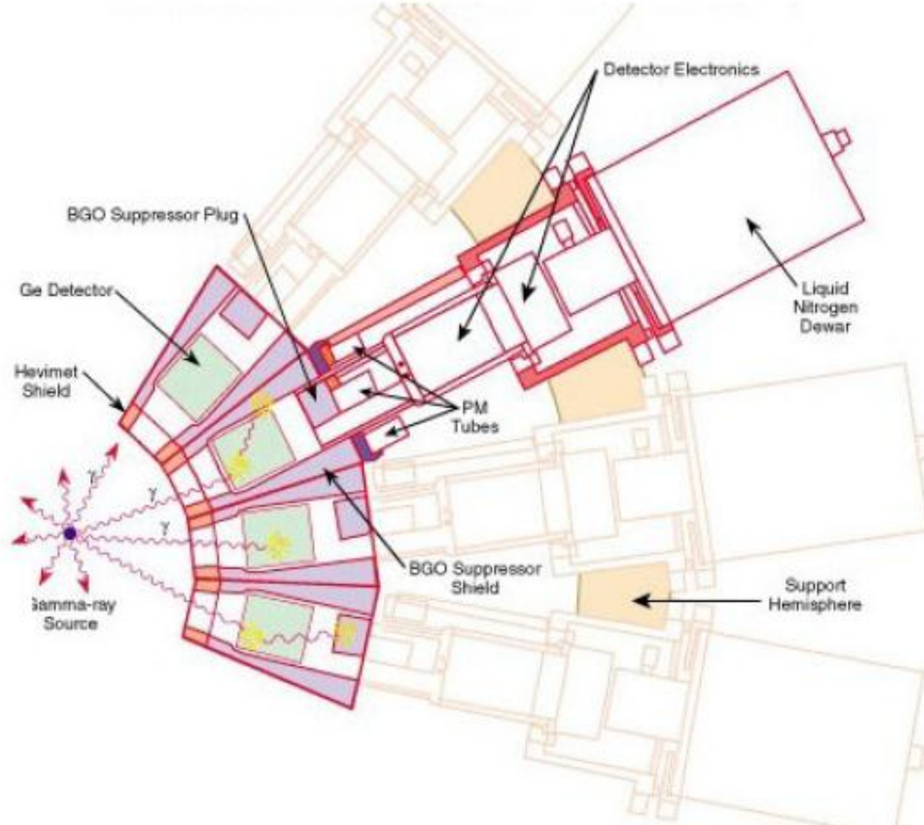


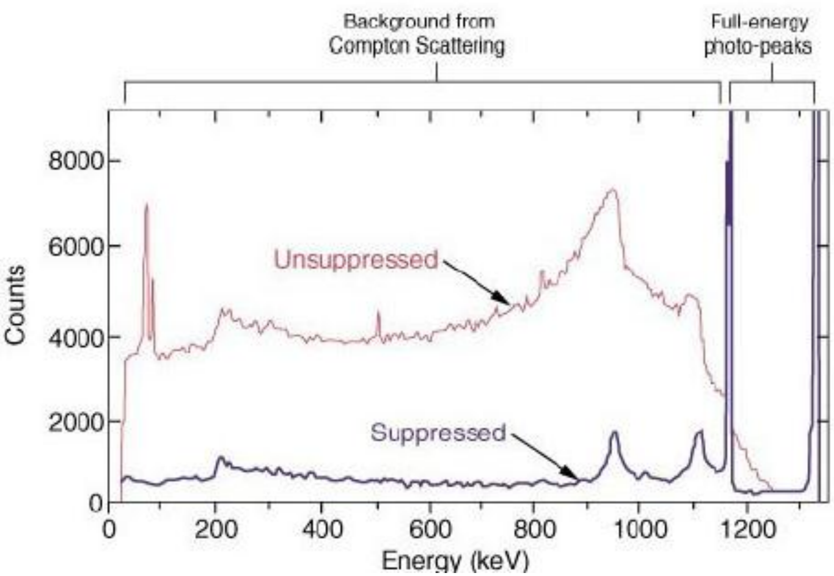
1990's
State of the art:



Compton Suppression
– improving the peak-to-background ratio



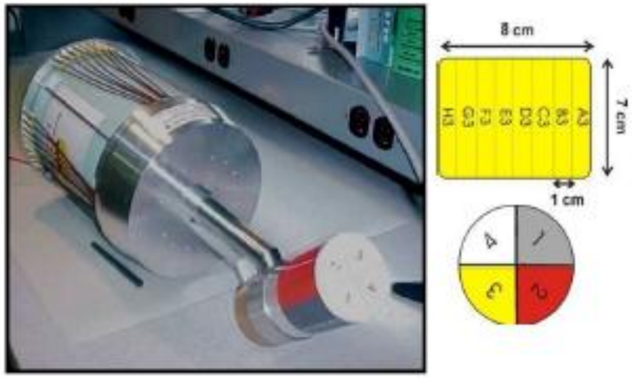




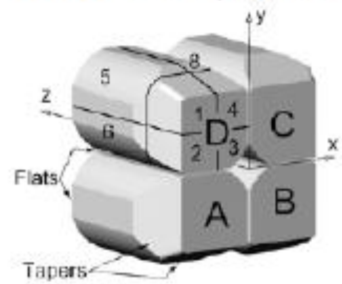
Gammasphere – the most sensitive of the current generation of gamma detector arrays

Segmented HPGe detetctors

SeGA (NSCL)

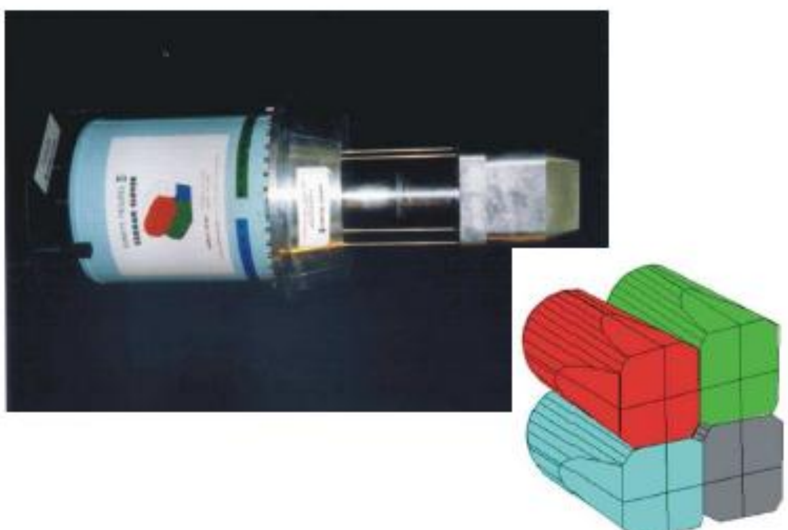


TIGRESS (TRIUMF)

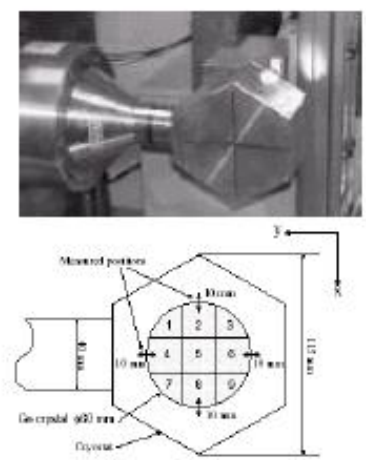


MINIBALL (CERN)

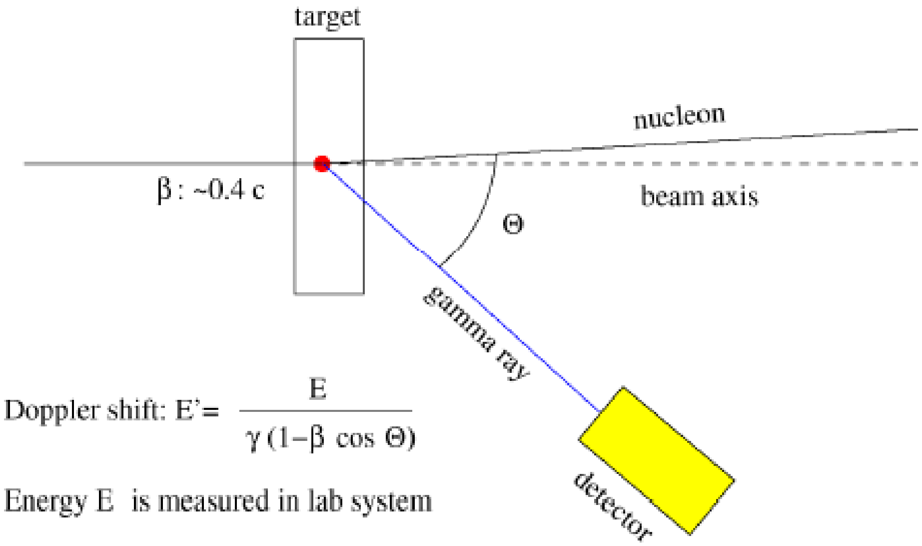
EXOGAM (GANIL)



GRAPE (RIKEN)



Fast beam experiments: Doppler shift



Doppler shift: $E' = \frac{E}{\gamma(1-\beta\cos\Theta)}$

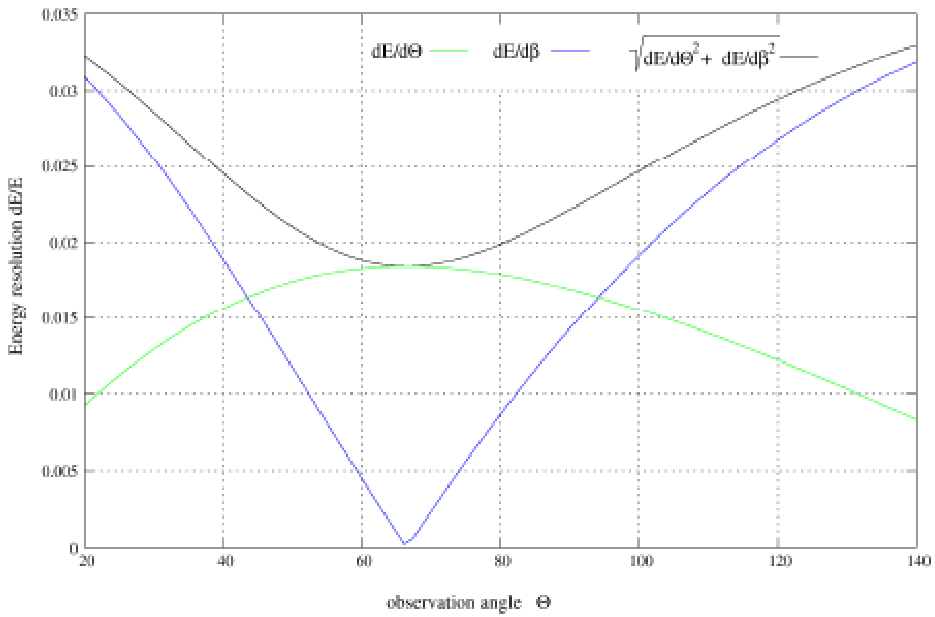
Energy E is measured in lab system

Uncertainties:

ΔΘ: opening angle detector, trajectory of nucleon

Δβ: velocity change in target (unknown interaction depth), momentum spread

→**Doppler broadening**
(i.e. peak in spectrum becomes wider)



Doppler broadening dE/E at v=0.4c for
$\Delta\Theta = 2.4^\circ$ (SeGA classic)
$\Delta\beta = 0.03$
(recall: HPGe FWHM 0.002)

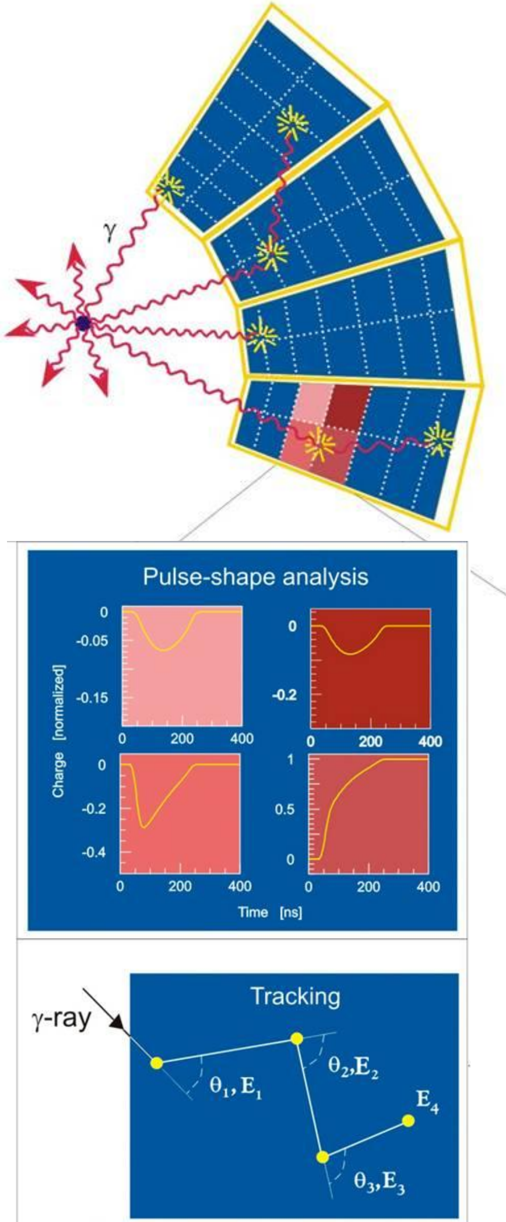
Another important effect: **Lorentz boost**
Forward focusing of gamma-ray distribution in laboratory frame (where the detectors usually are…)

Principle and advantages of γ-ray tracking

3D position sensitive Ge detector shell

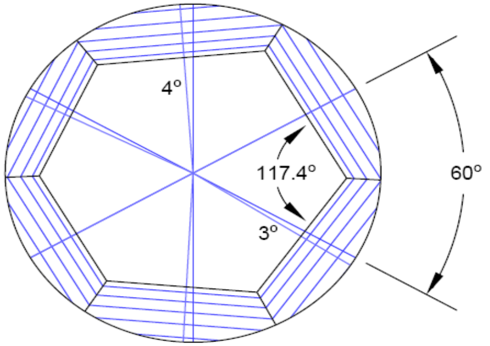
Resolve position and energy of interaction points

Determine scattering sequence

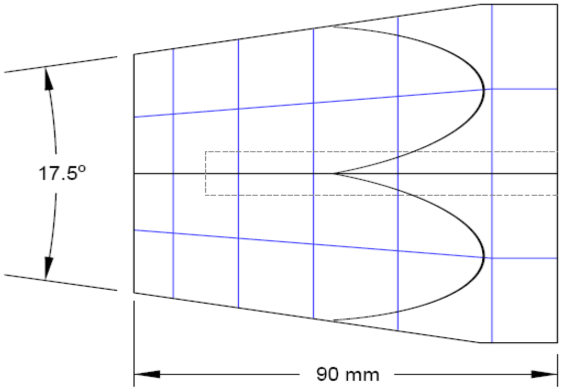


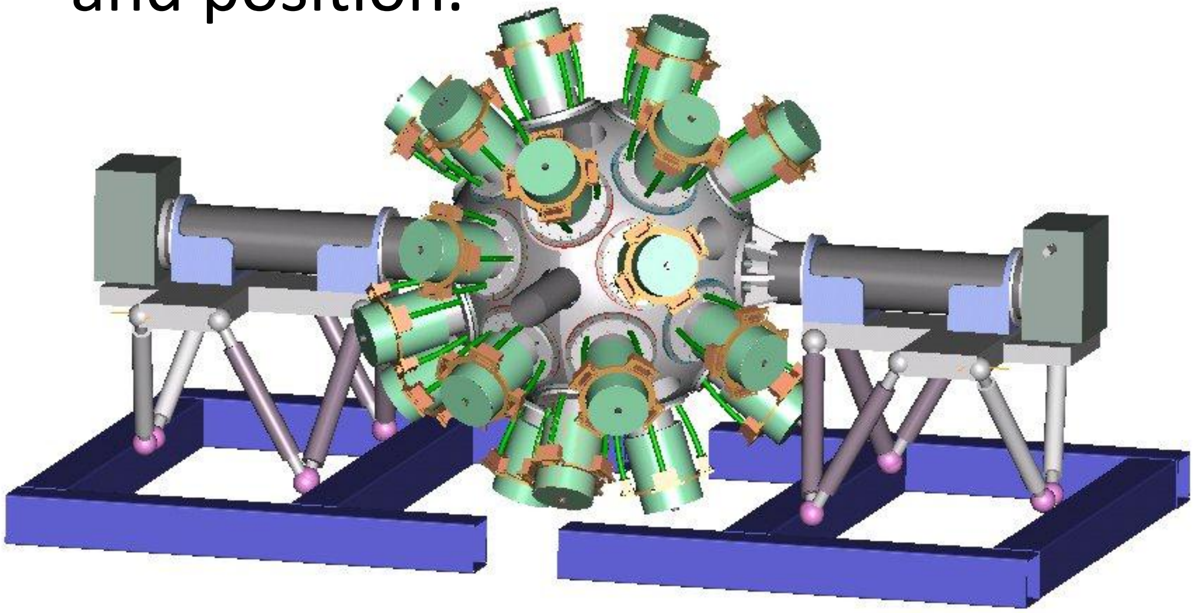
- **Efficiency (50% Ω)**
  Proper summing of scattered gamma rays, no solid angle lost to suppressors
- **Peak-to-background (60%)**
  Reject Compton events
- **Position resolution (1-2 mm)**
  Position of 1st interaction
- **Polarization**
  Angular distribution of the 1st scattering
- **Counting rate (50 kHz)**
  Many segments

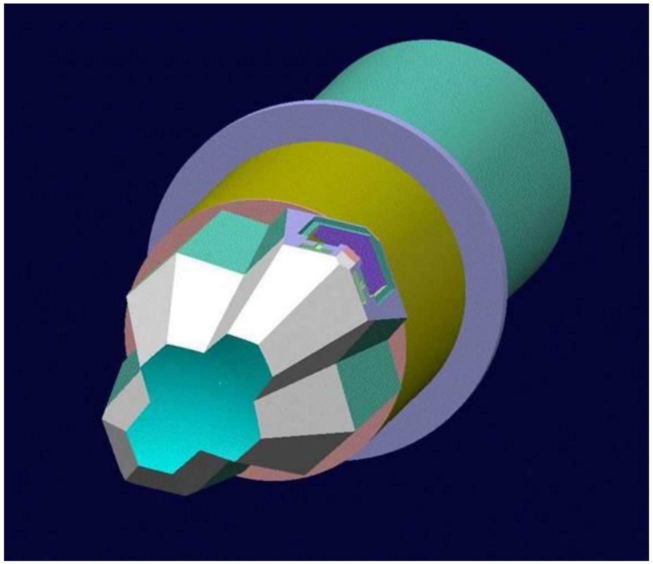
GRETINA Design



- 7 modules of 4 crystals each
- 6 x 6 external segmentation
- Covers ≈ 1π steradian solid angle (to cover 4π will take 30 modules - GRETA).
- Modules can be placed at 58.3º (4), 90º (8), 121º (4), and 148º (5 positions) .
- On-line processing gives γ-ray energy and position.







Gretina DAQ (I)

Each of the 28 crystals has:

- Separate VME backplane and IOC
  - Slow control in EPICS
  - Reads & timesorts digitizer data
  - Passes data to compute cluster
- 4 LBNL Digitizer Modules
  - 10 channels (9 segments + core)
  - 1 Flash ADC / ch, 14bit 100MHz
  - On-board FPGA filters
    - Energy (trapezoid)
    - Leading Edge (trigger primitive)
    - Pole-zero correction
    - Baseline Restoration
- Event data includes:
  - Timestamp
  - Filter data
  - Waveform subset

Gretina DAQ (I)

Trigger system:

- 5 ANL Trigger modules
  - 1 Master + 4 Routers
- Master clock distribution
- Multiple trigger types
  - Multiplicity
  - External (coincidence)
  - Isomer
  - Sum Energy
- Event validation by timestamp broadcast

Gretina DAQ (II): Computing

60 nodes
2 cpu / node
4 core / cpu

Data from GRETINA Detectors

Segment events — 37 segments per detector

Crystal Event Builder

Crystal events

Signal Decomposition

Interaction points — 1-28 crystals

Data from Auxiliary Detectors

Global Event Builder

This is where "events" may be defined!

Global Events

Tracking

Analysis & Archiving

Goal:

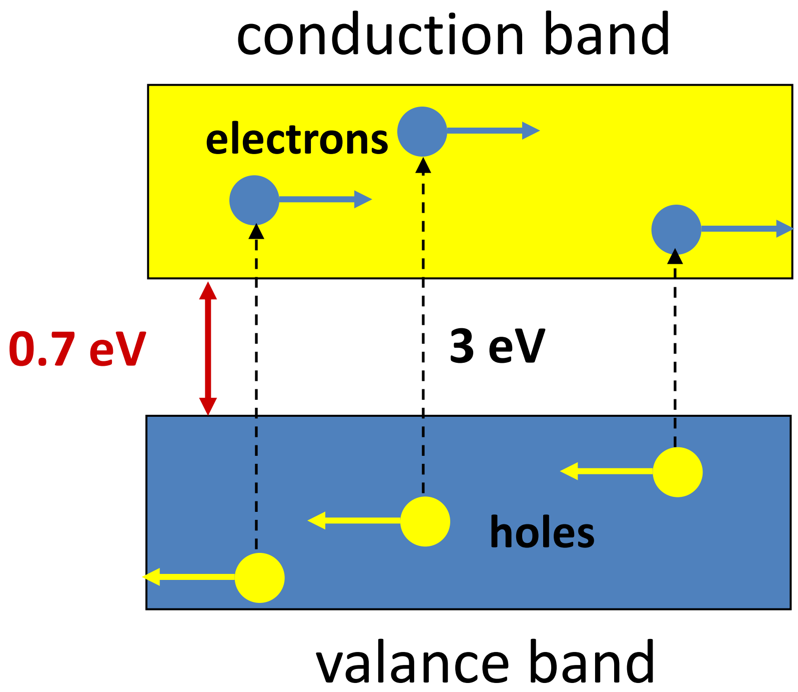
Processing 20,000 Gamma rays /sec

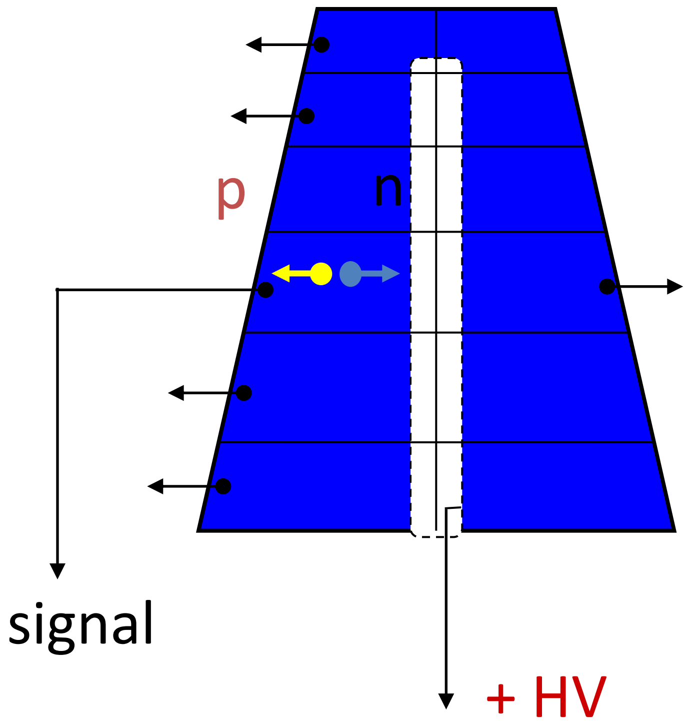
Gamma-Ray Tracking

- What is it?
  - A way to extract more information
  - A technology that improves P/T, Doppler-corrected resolution, and efficiency
- Why do we need it?
  - Exotic beams require we learn more while using less beam in inverse kinematics
- How do we do it?
  - Determine sub-segment interaction points from pulse shape analysis
  - Determine correct interaction point grouping and sequence from interaction points

Germanium detector

Energy resolution



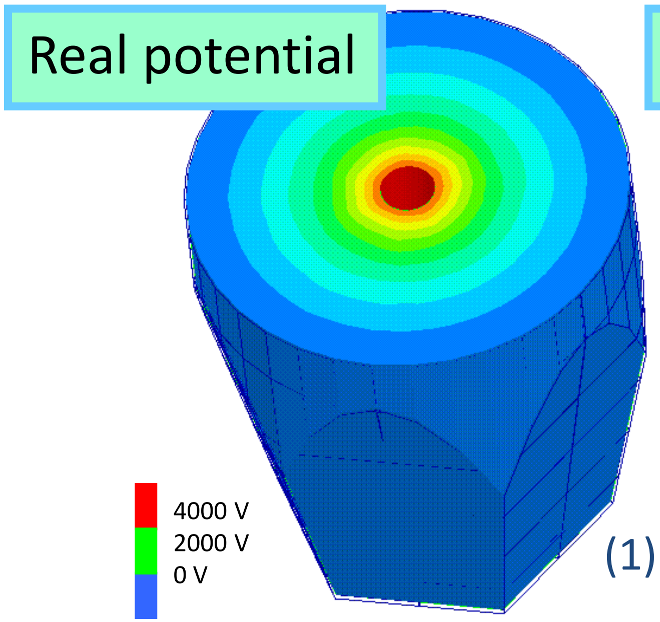


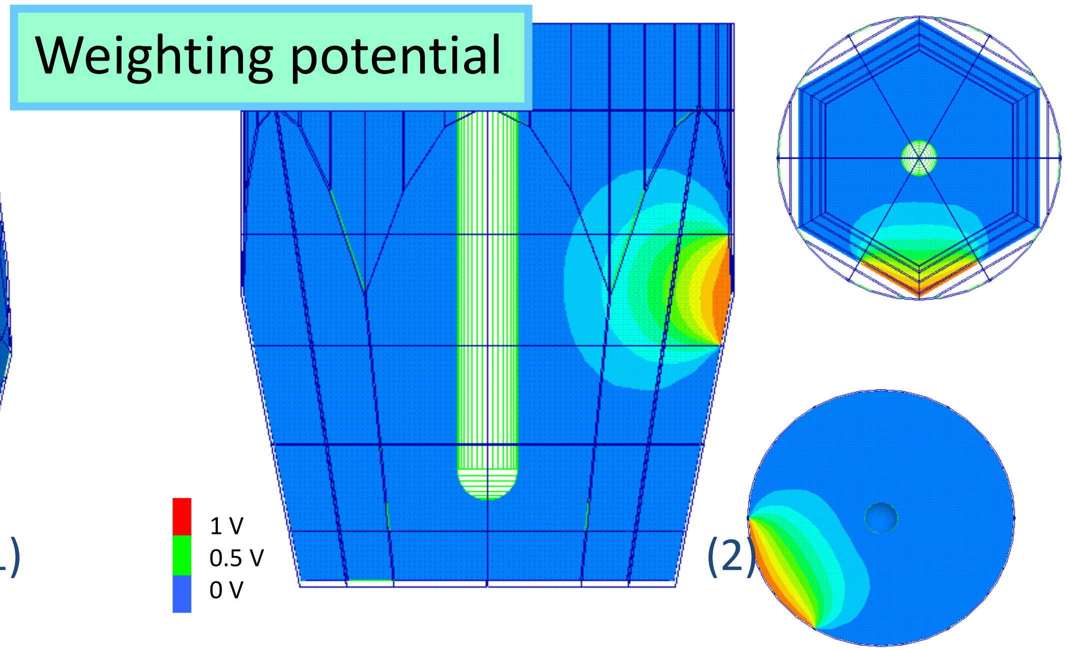
Number of e-h pairs for 1 MeV, $N = 10^6 / 3 = 3 \times 10^5$

$$Energy\ resolution = \sqrt{N} \big/ N = 0.0018 \rightarrow 1.8\,\mathrm{keV} \times \sqrt{\mathrm{E}_\gamma}$$

Signal generation in segmented contacts

Maxwell 3D





- Electrons and holes drift in the real potential and are collected, but they also produce image currents as they drift.
- Weighting potential is calculated by applying 1 V on the segment collecting the charge and 0 V to all the others (Ramo's Theorem).
- It measures the electrostatic coupling (induced charge) between the moving charge and the sensing contact.

Field and weighting potential

- **Electric field**

$$\vec{E} = \vec{\nabla} V$$

$$\nabla^2 V = \rho \qquad \rho : impurity\ concentration$$

Boundary condition : applied bias voltage

- **Weighting potential for segment *k***

$$\nabla^2 V_k = 0$$

Boundary condition : 1 V on the segment k
0 V on all other segments

Trajectory and signal

- **Trajectory : for electrons and holes**

$$\vec{v} = \vec{v}(\vec{E})$$

anisotropic

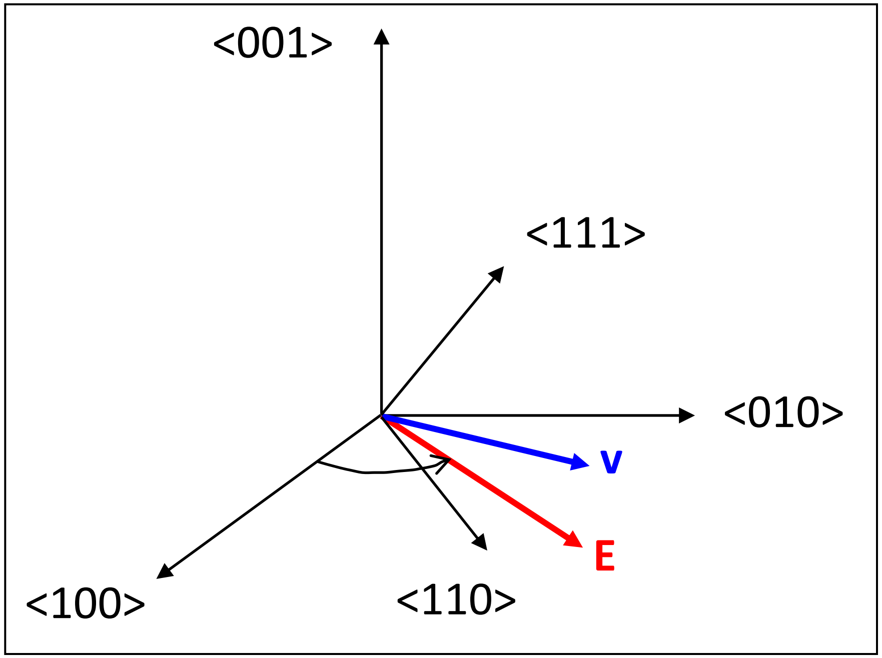
$$\vec{x}(t) = \vec{x}_0 + \int_0^t \vec{v}\, dt$$

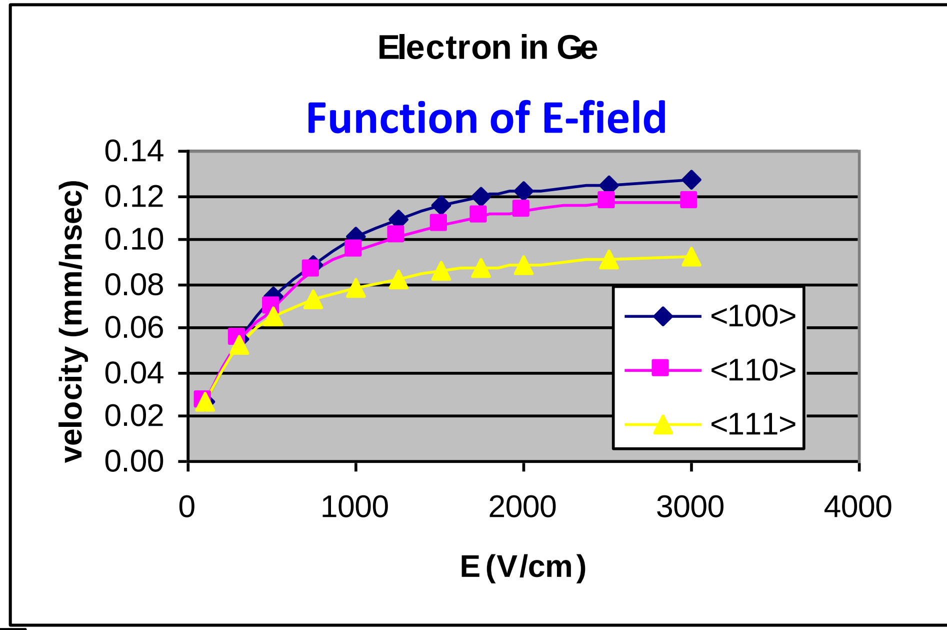
- **Induced charge (S. Romo, Proc. IRE 27(1939)584)**

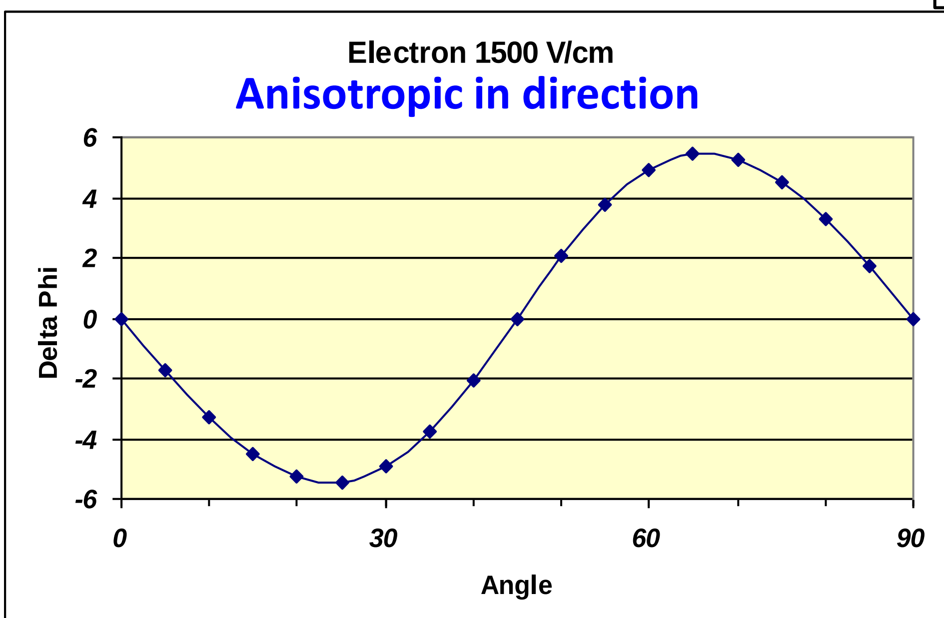
If a charge q moves from position x_1 to position x_2, then the induced charge on electrode k is

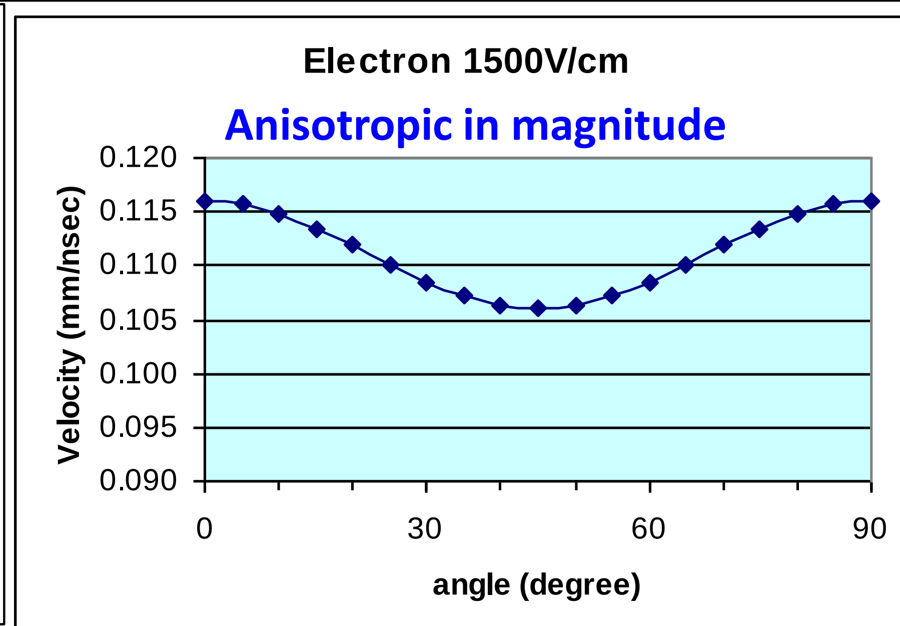
$$\Delta Q_k = q\left(V_k(\vec{x}_2) - V_k(\vec{x}_1)\right)$$

Drift velocity

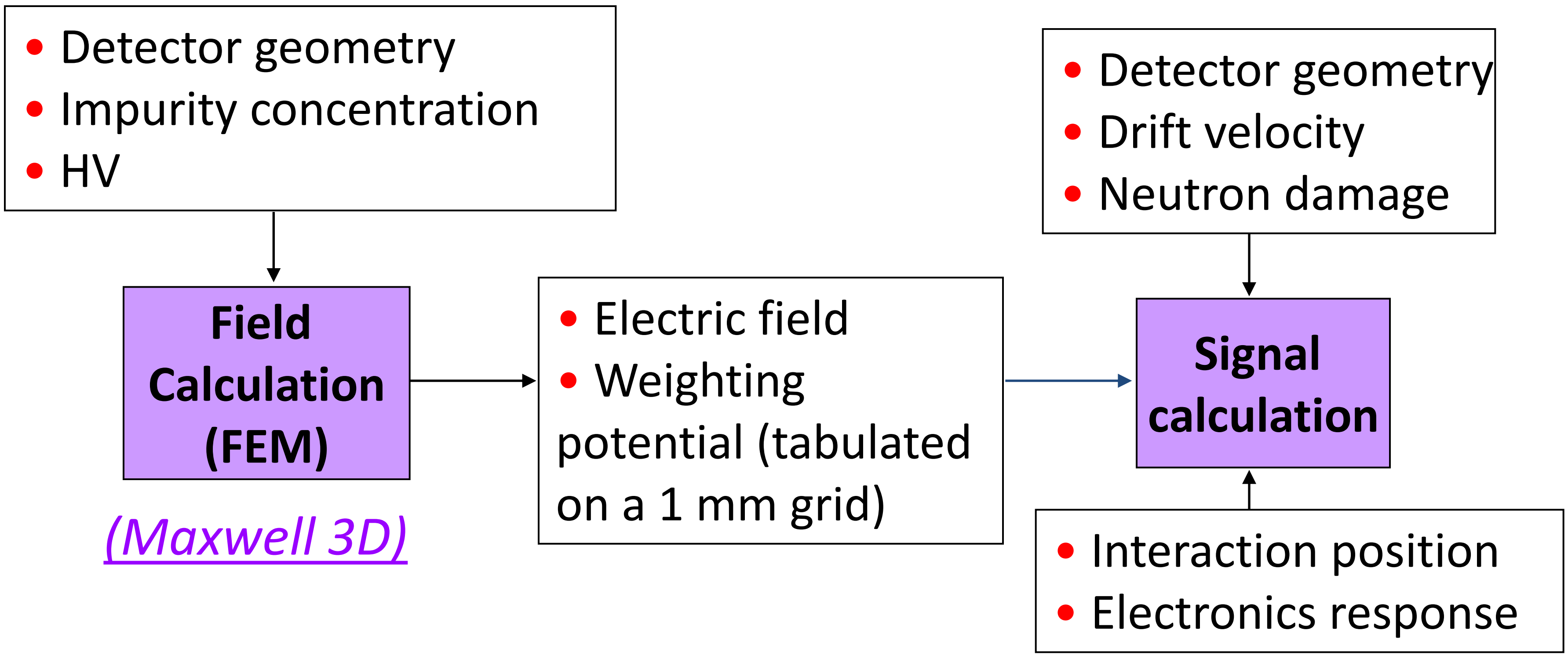




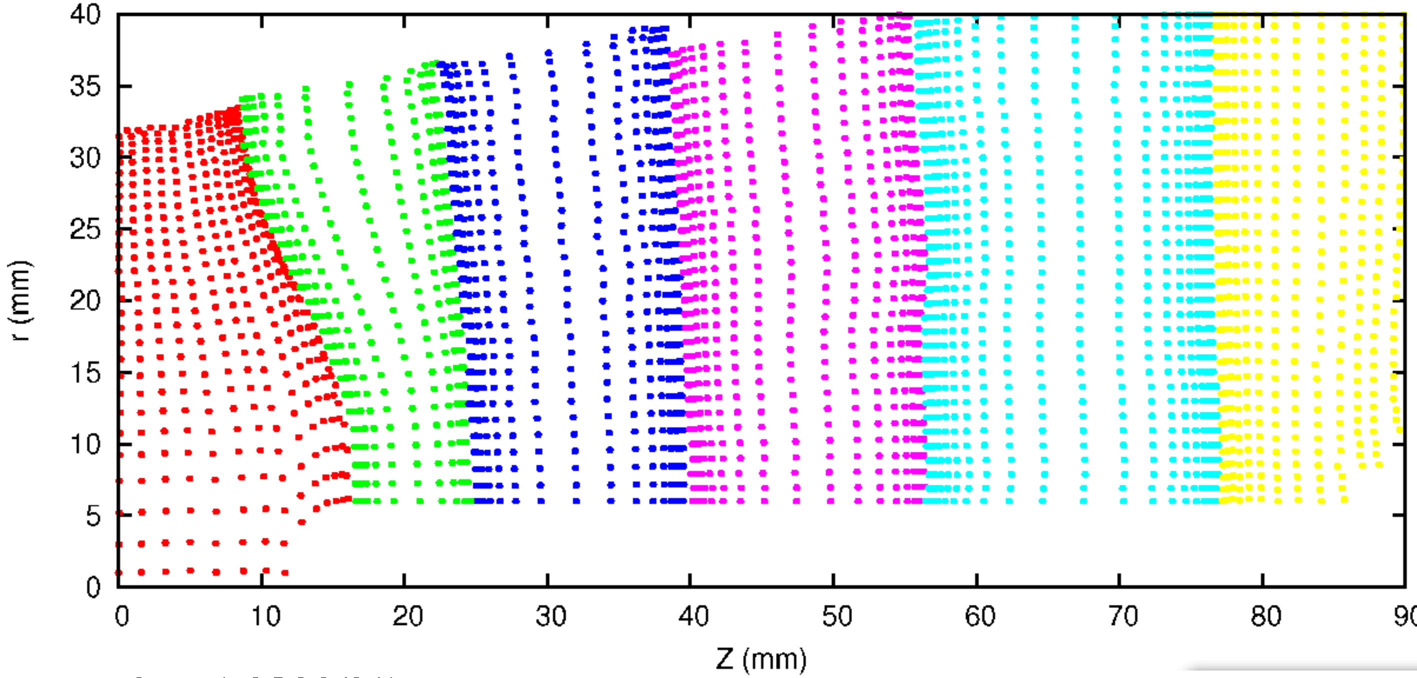


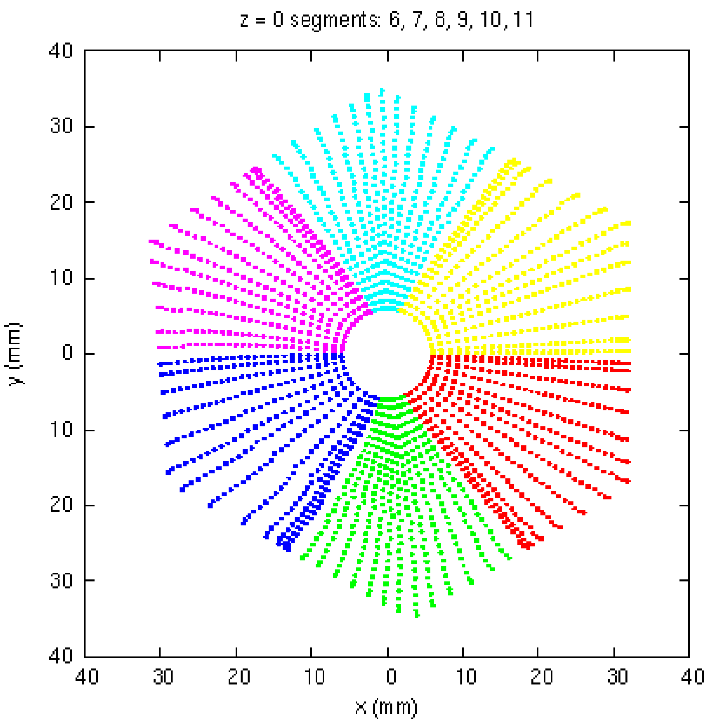


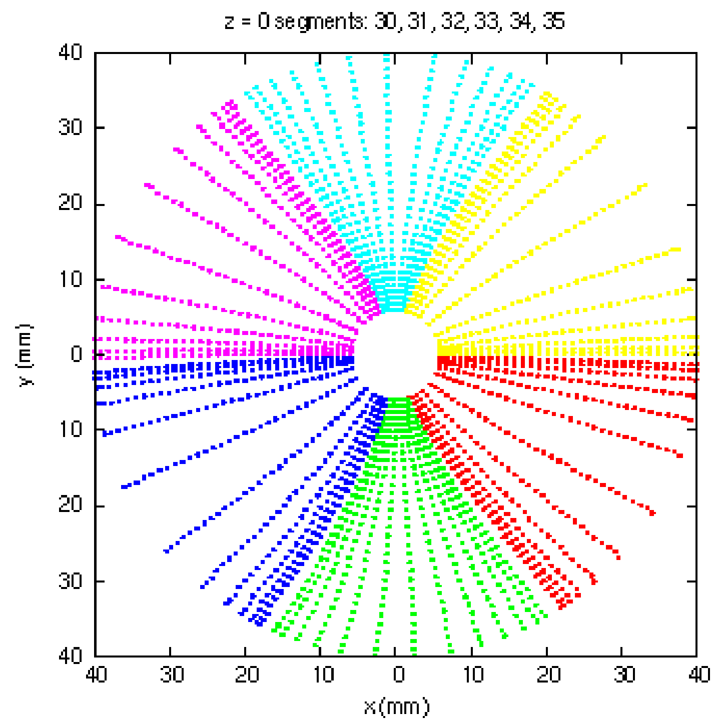
Signal Calculation



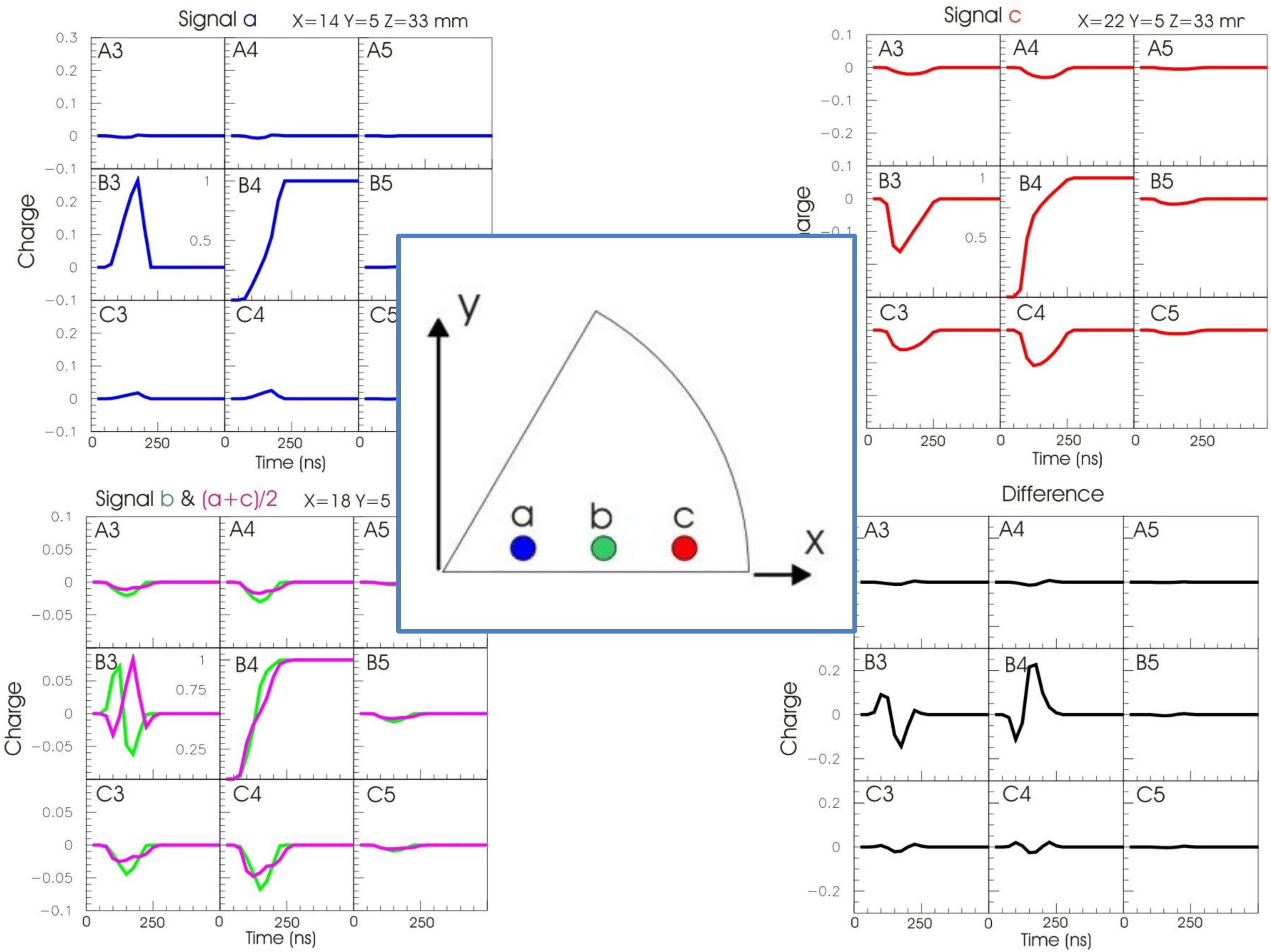
- Calculations are carried out for a grid of interaction points in crystals
- Pulse shape from the 36 outer contacts and core contact are calculated


r (mm)
Z (mm)
0 5 10 15 20 25 30 35 40
0 10 20 30 40 50 60 70 80 90

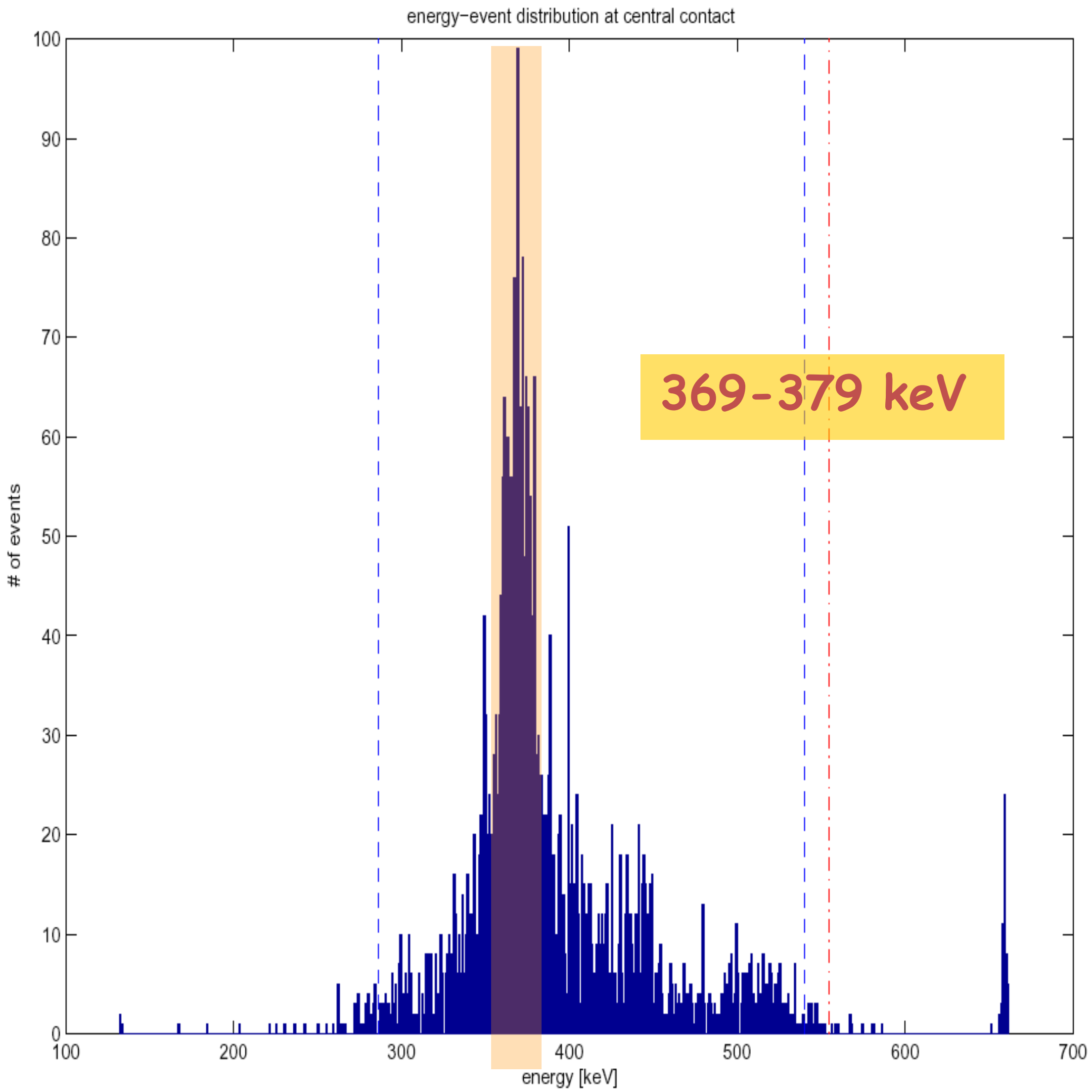

z = 0 segments: 6, 7, 8, 9, 10, 11
y (mm)
x (mm)
40 30 20 10 0 10 20 30 40

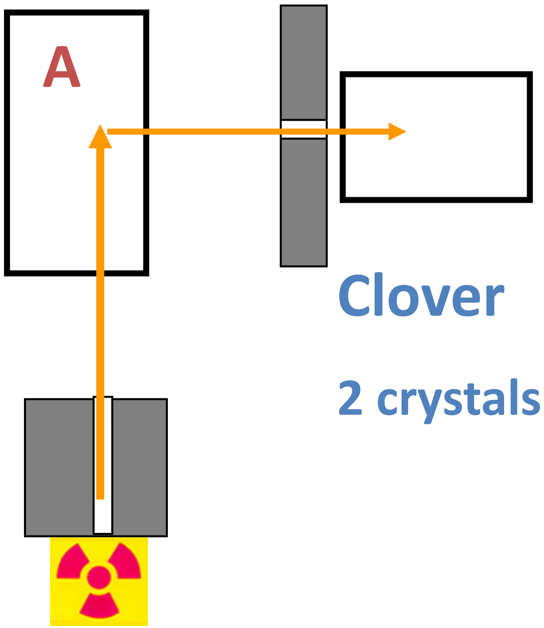

z = 0 segments: 30, 31, 32, 33, 34, 35
y (mm)
x (mm)
40 30 20 10 0 10 20 30 40

Separation of two interaction points



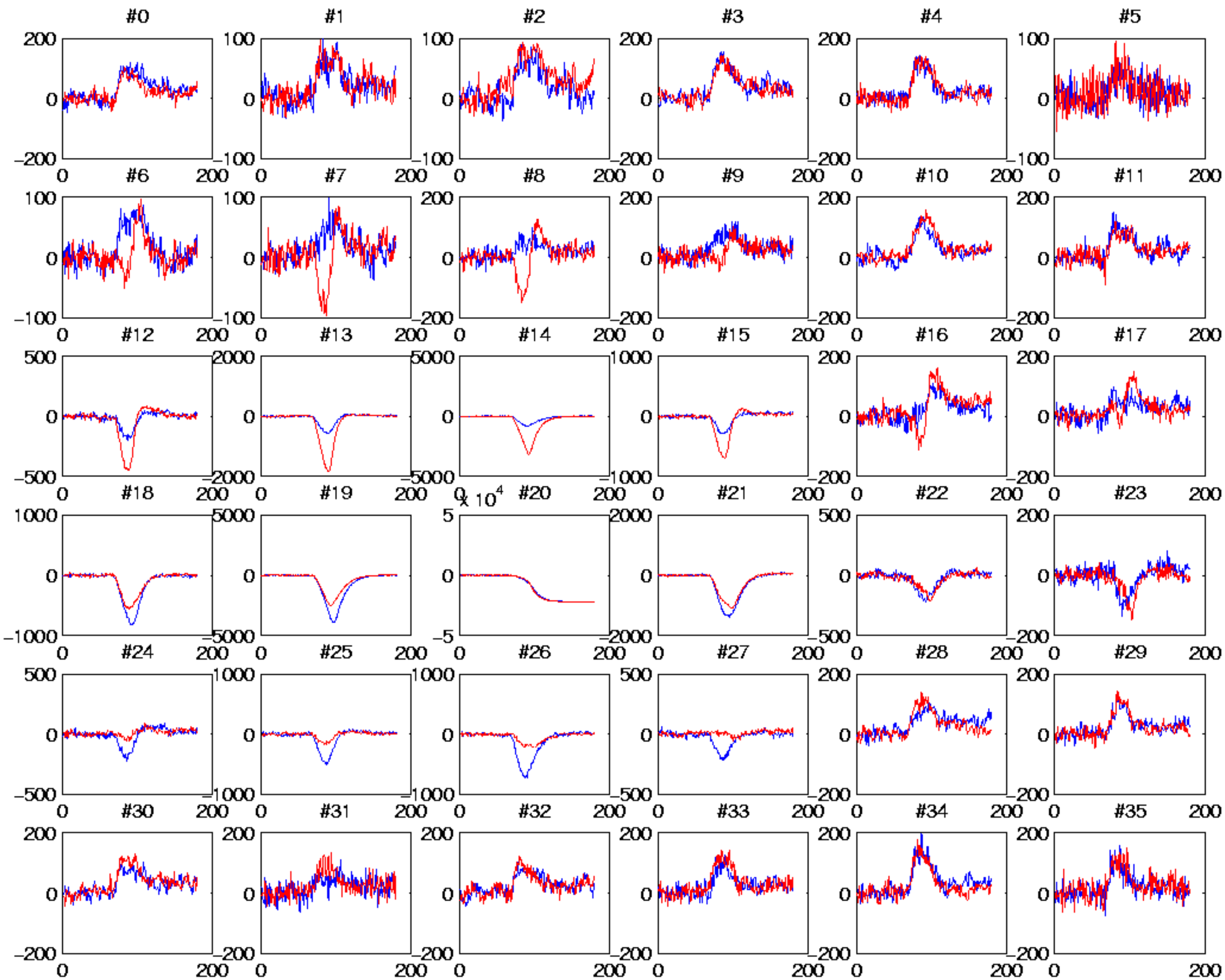
Coincidence scans



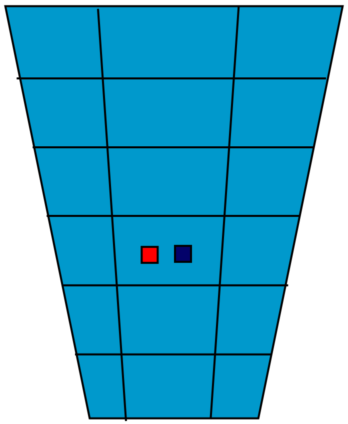


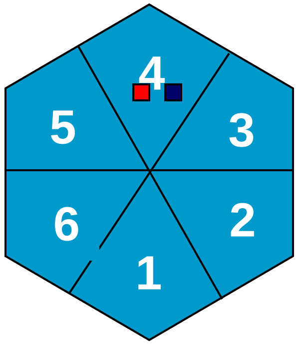
$E_{clover}+E_{A}= 662keV$

Pulse Shapes from coincidence scan



~ 200 events





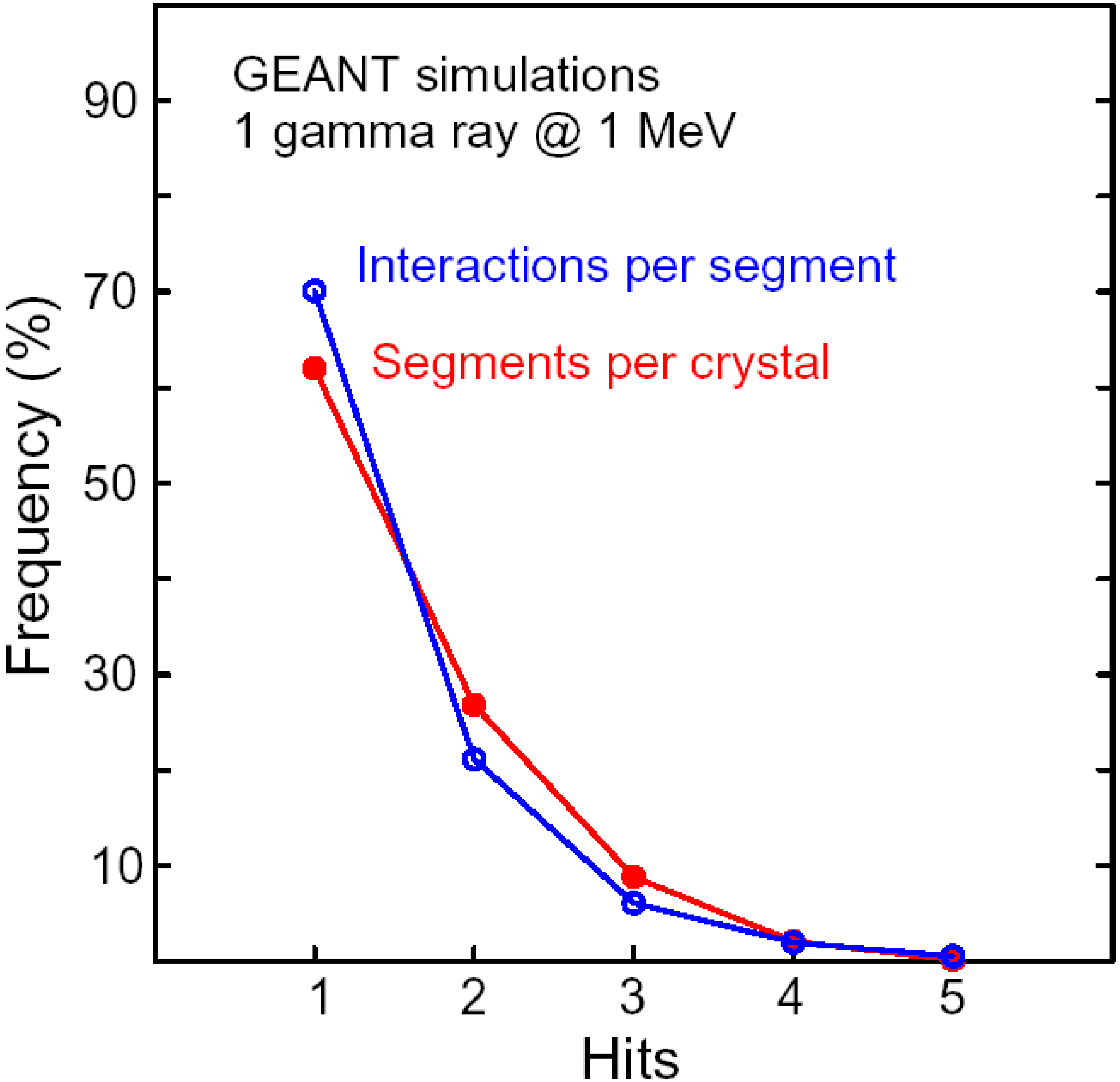
Δx =5mm

Multiple interactions

GEANT simulations; 1 MeV gamma into GRETA

Most hit crystals have one or two hit segments

Most hit segments have one or two interactions



Why is it hard?

Determine position and energy of several interaction points form signals which are the sum of the contributions from the individual interaction points

Large parameter space to search

Average segment ~ 6000 mm^3 ; so for ~ 1 mm position sensitivity:

– two interactions in one segment ~ 1.8 x 10^6 positions

– two interactions in each of two segments ~ 3 x 10^{12} positions

– two interactions in each of three segments ~ 6 x 10^{18} positions

PLUS energy fractionation, time-zero, …

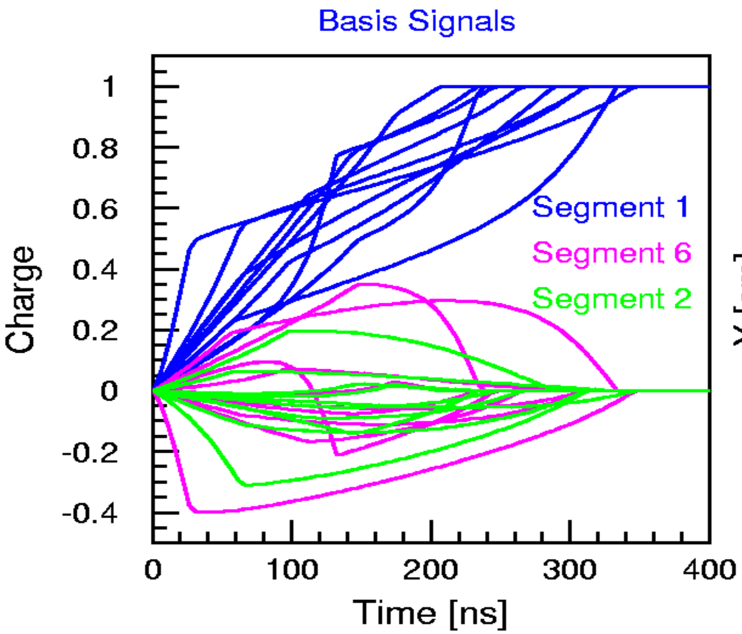
Underconstrained fits (especially with > 1 interaction/segment)

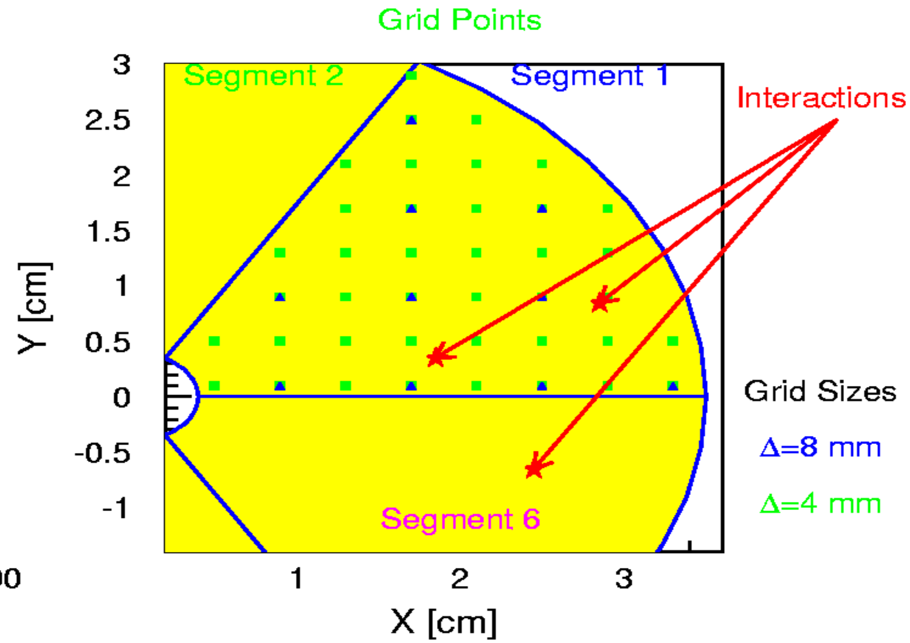
For one segment, have only ~ 9 x 40 = 360 nontrivial numbers

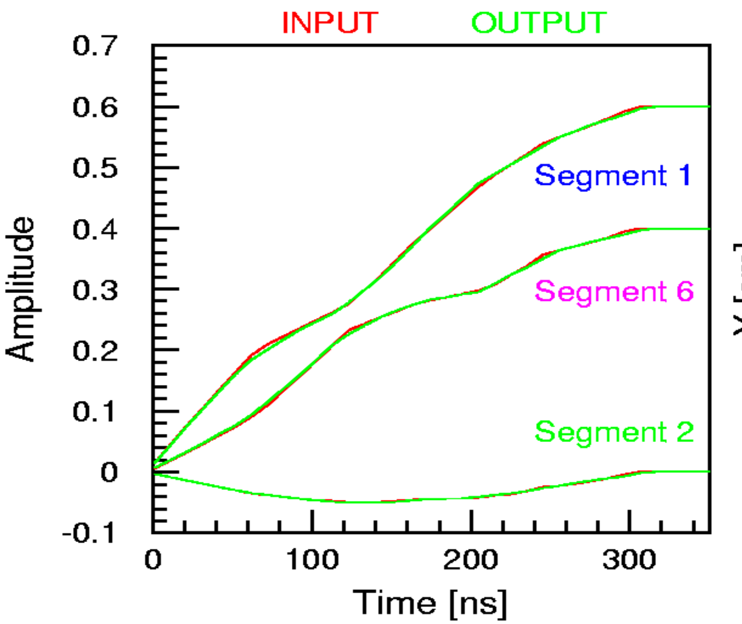
Strongly-varying, nonlinear sensitivity

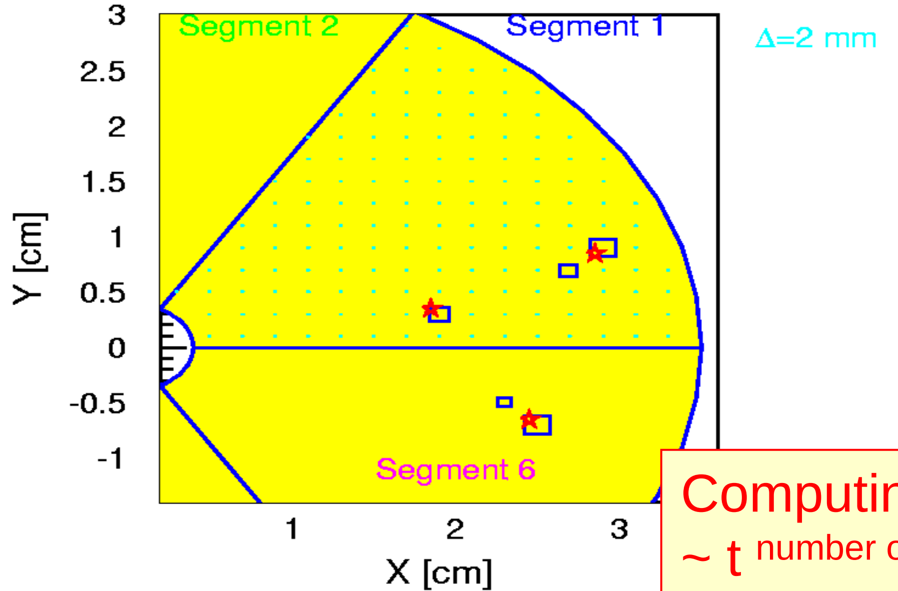
– $\delta\chi^2/\delta(\theta z)$ much larger near segment boundaries

Signal Decomposition: Adaptive Grid Search







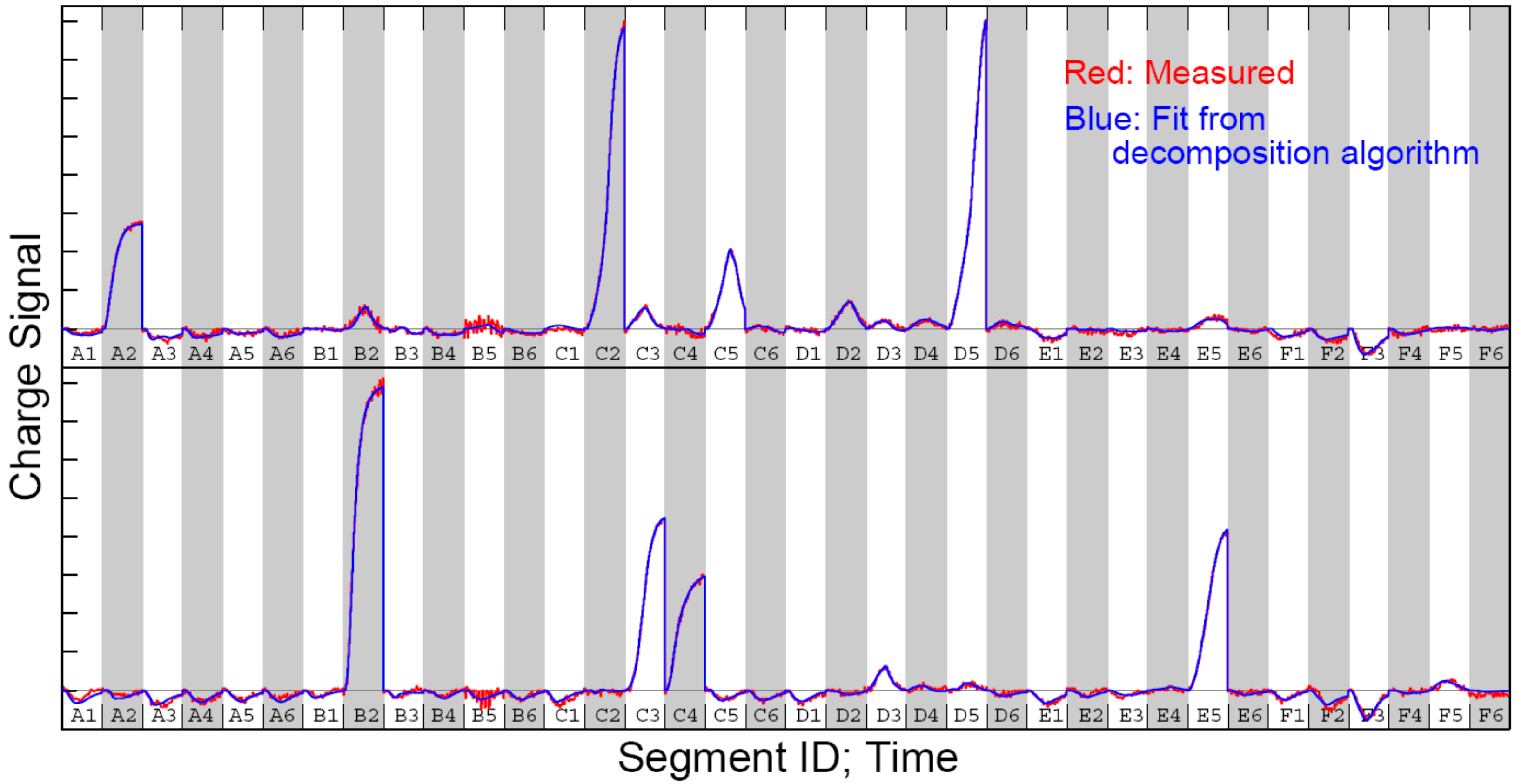


Computing time

$\sim t^{\text{number of interactions}}$

Excellent fit to data

- Measured signals with multiple gamma ray hits (red), fitted with a linear combination of basis signals (blue) , using Grid search followed by least-square fitting.
- The analysis gives (x, y, z, E) of the interaction points.



AGS performance

Current Adaptive Grid Search algorithm:

- AGS, followed by constrained least-squares
- 1 or 2 interactions per hit segment
- Grid search in position only; energy fractions are L-S fitted
- Coarse grid is 2x2x2 mm (front) or 3x3x3 mm (rear)
  - Gives N < 600 coarse grid points per segment.
  - For two interactions in one segment, have

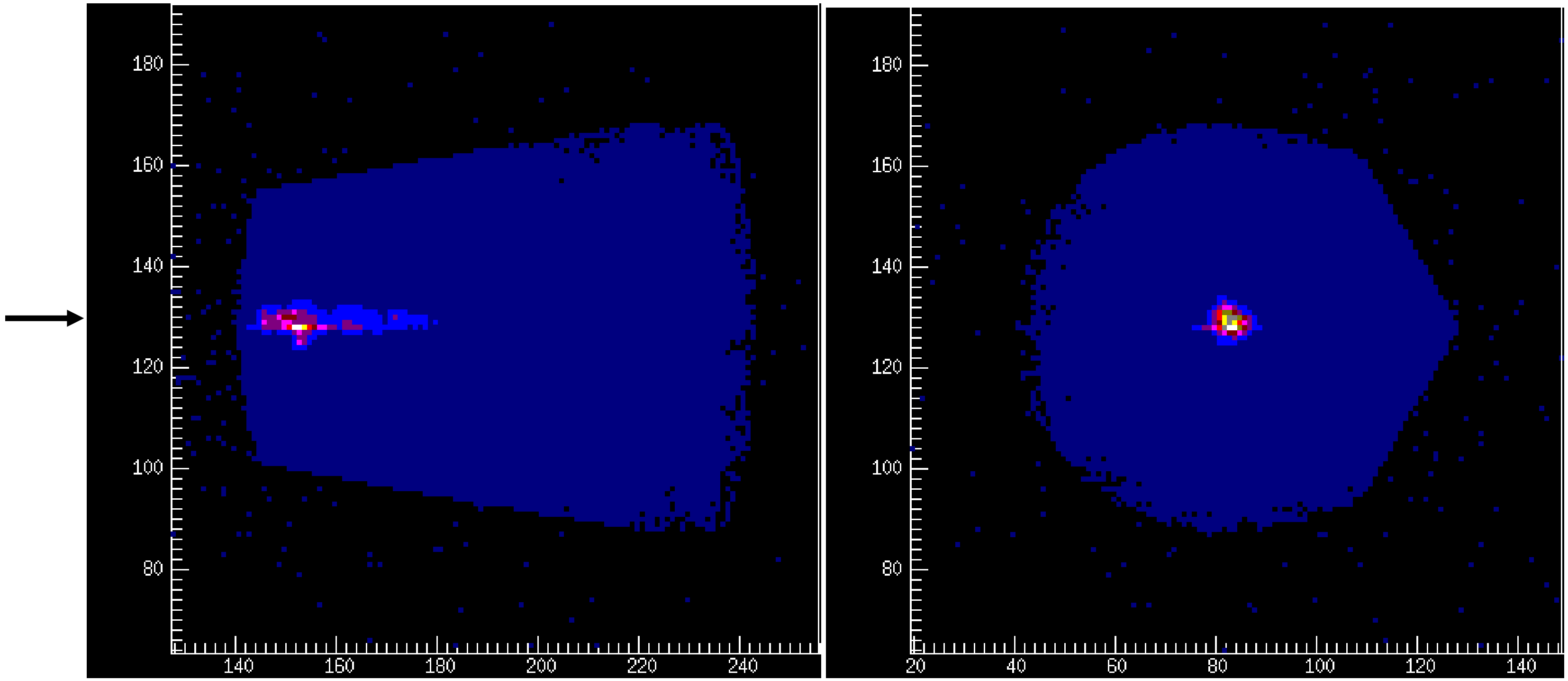
    $N(N-1)/2 < 1.8 \times 10^5$ pairs of points for grid search.
  - This takes ~ 3 ms/cpu to run through.
- Works very well for both 1- and 2-segment events
  - Reproduces positions of simulated events to ~ ½ mm
  - Very fast; ~ 3-8 ms/event/CPU for 1 seg;

    ~ 15-25 ms/event/CPU for 2 seg. (2GHz P4)

Pencil beam results

Using the latest decomposition program and basis, we have achieved <2 mm (RMS) resolution in PIII:

Pencil beam of 662 keV, 1 mm diameter

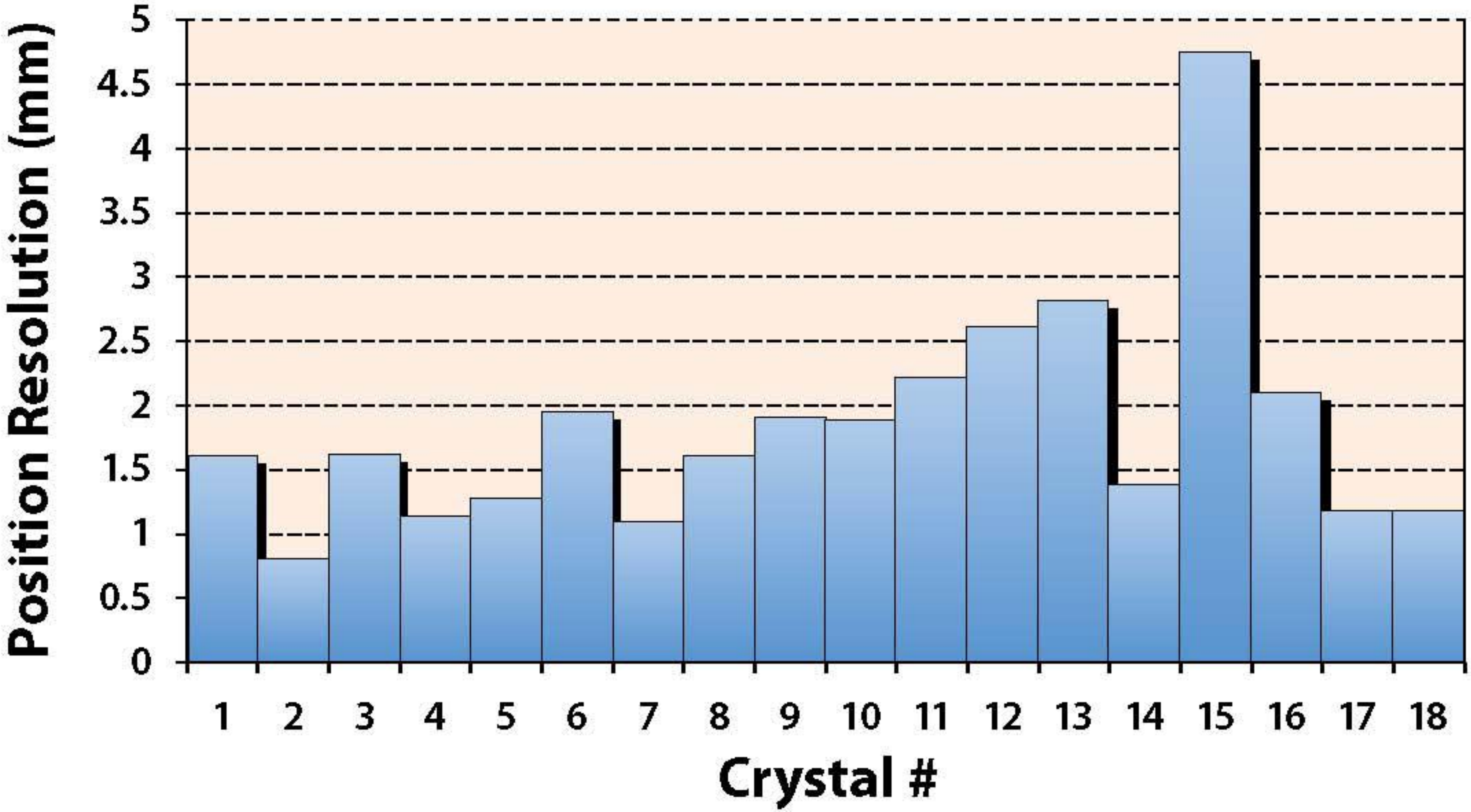


Position resolution :

σ_x = 1.5 mm; σ_y = 1.7 mm

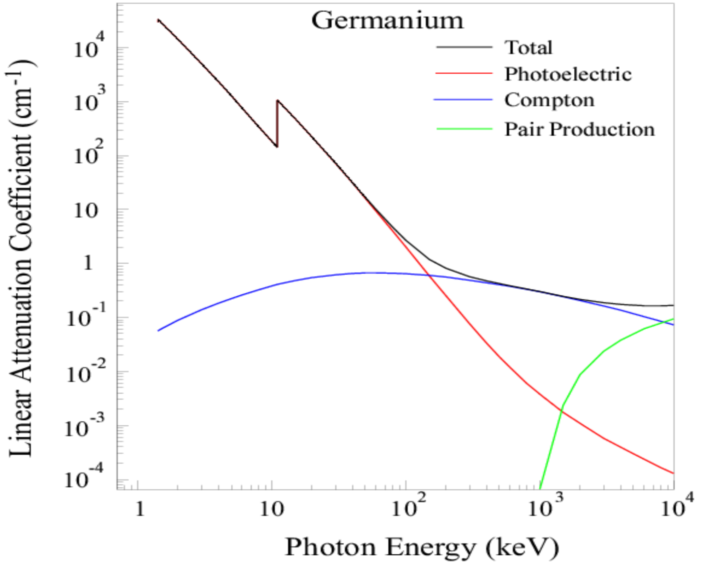
Pencil beam σ’s

1 interaction per crystal



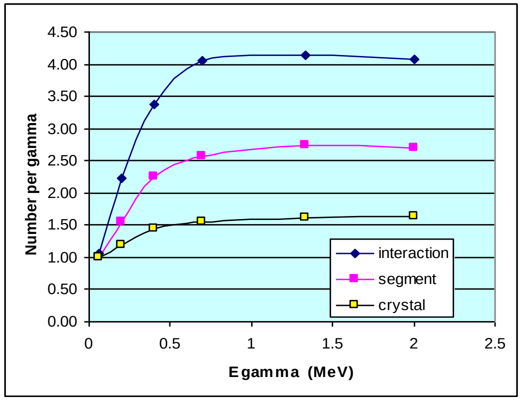
Tracking introduction

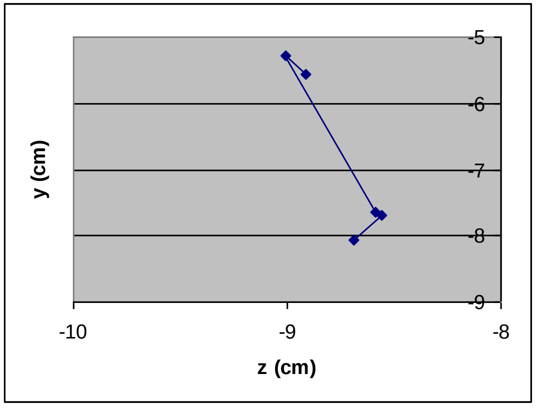
Tracking - Use properties of γ-ray interaction with Ge to determine the γ-ray scattering sequence

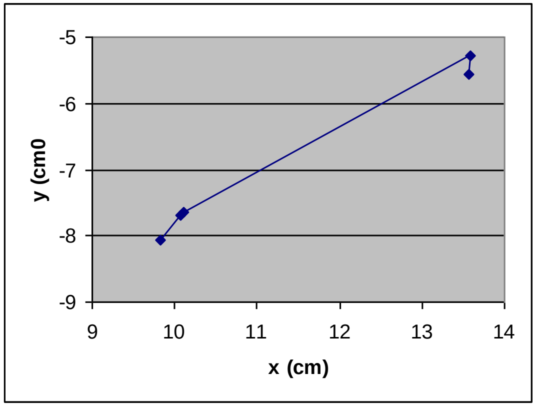


Example; 1.33 MeV
5 interactions: 4 Compton, 1 photo
Separation of interactions: 0.5 – 5 cm

x (cm)	y (cm)	z (cm)	E (MeV)
9.82	-8.07	-8.69	1.0184
10.07	-7.68	-8.56	0.0418
10.11	-7.65	-8.59	0.0044
13.58	-5.27	-9.01	0.1202
13.57	-5.55	-8.91	0.1452







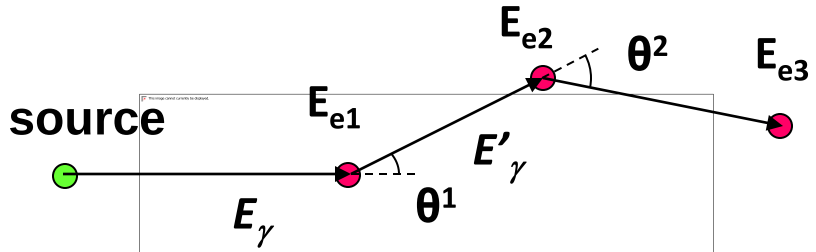
Tracking principle

Source location and interaction points are known

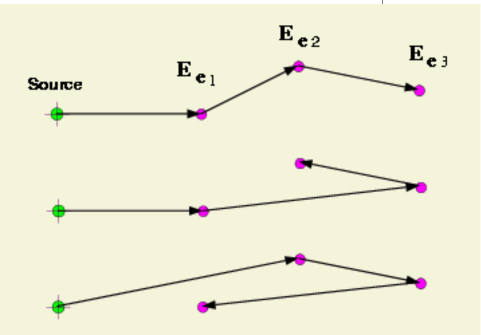
1) Assume full energy is deposited

$$E_\gamma = E_{e1} + E_{e2} + E_{e3}$$

2) Start tracking from the source

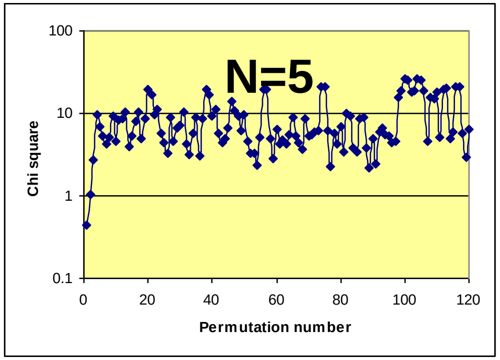


For N! possible permutations, check each interaction point for Compton scattering conditions



$$\cos\theta_C = 1 + \frac{0.511}{E_\gamma} - \frac{0.511}{E'_\gamma}$$

$$\chi^2 = \frac{1}{N-1}\sum_{i=1}^{N-1}\left(\frac{\theta^i - \theta^i_C}{\sigma^i_\theta}\right)^2$$



Select the sequence with the minimum $\chi^2 < \chi^2_{max}$

➔ **correct scattering sequence**

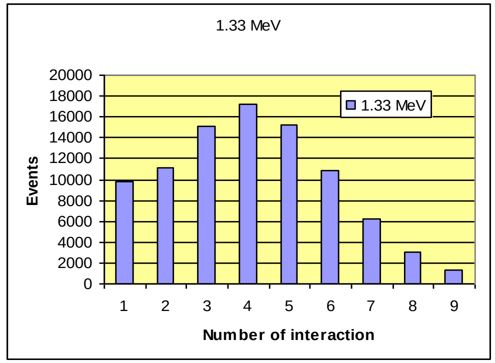
➔ **rejects partial energy event**

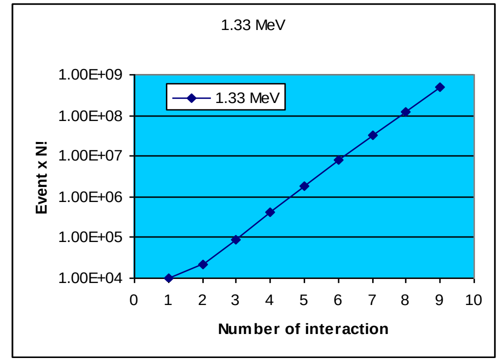
➔ **reject gamma rays with wrong direction**

Tracking issues

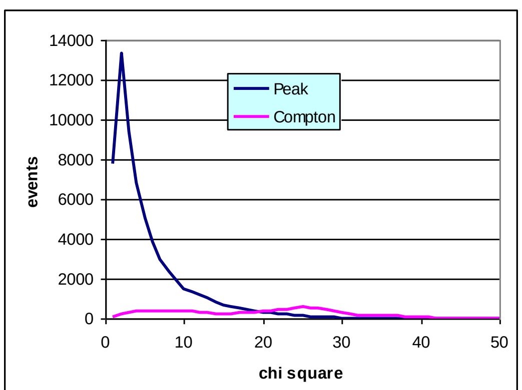
- **Computing time ≈ N!.** Cut off large N events, or better algorithm

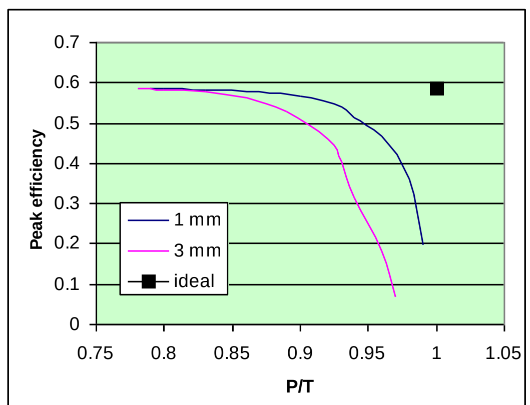
4 ! =	24
8 ! =	40,320
12! =	479,001,600

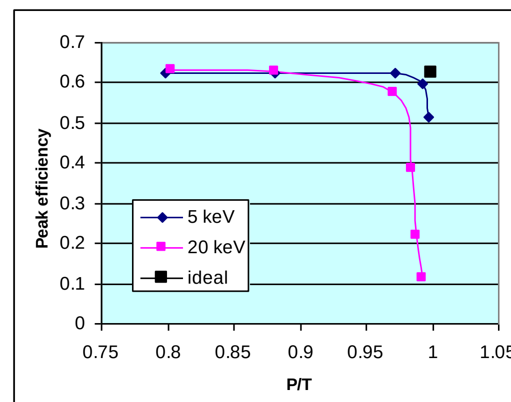




- **Finite position and energy resolutions**. Trade-off efficiency vs. P/T depending on experimental requirements



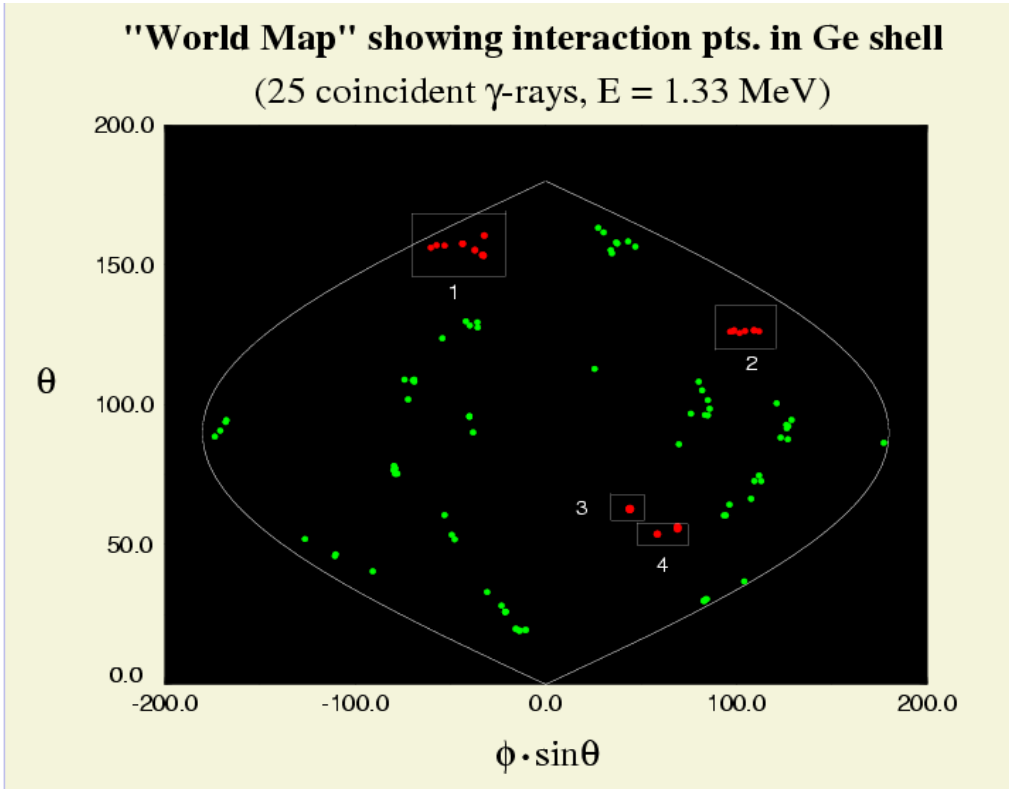


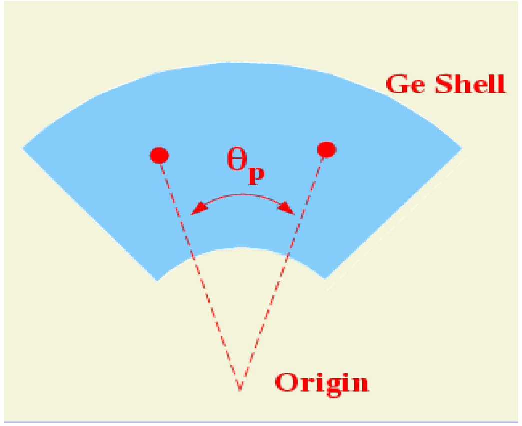


Tracking algorithm

- **multiple γ-ray hitting the detector**

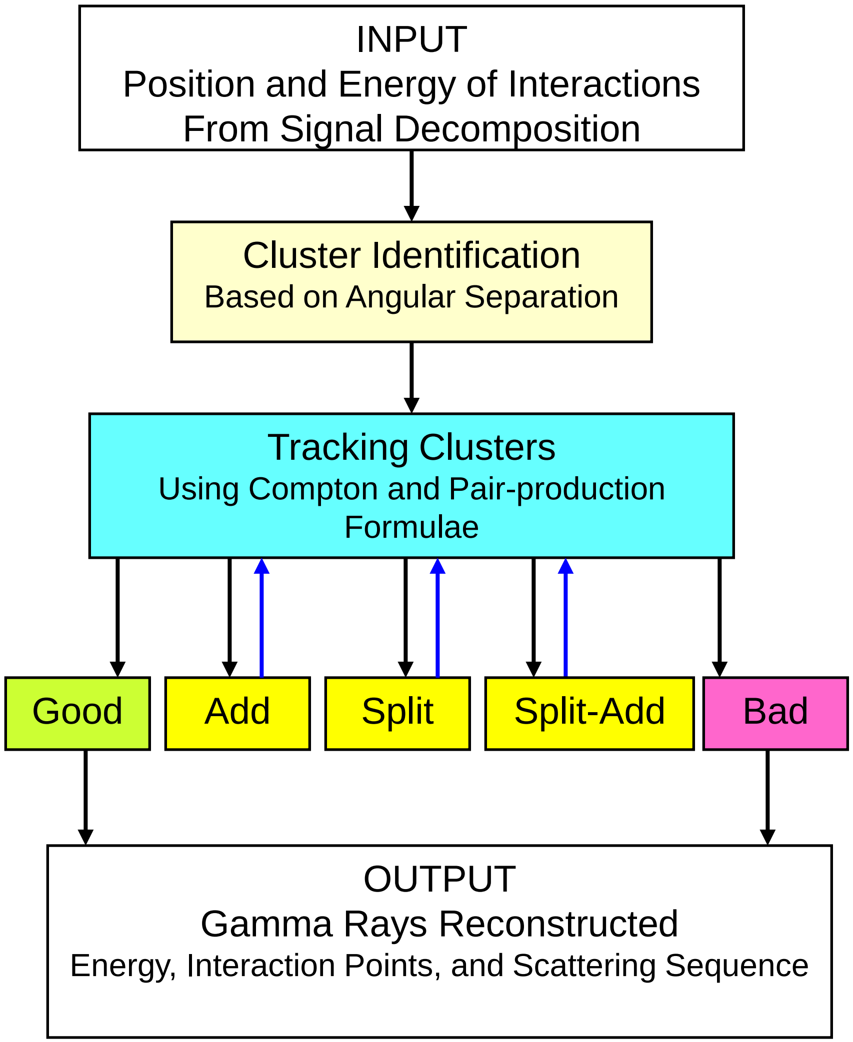
  1) Group interaction into clusters
  2) Tracking each cluster





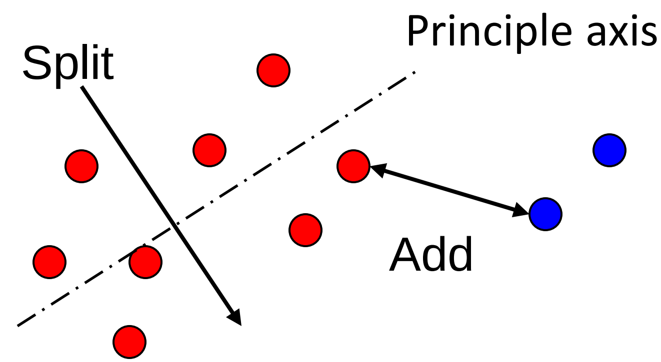
Any two points with $\theta < \theta p$ are grouped into the same cluster

Tracking algorithm



Split Clusters

- Use 3-D position of interactions
- Determine principle axes of cluster moment
- Split cluster perpendicular to the axes



Tracking improvements

- Improve χ^2
- Speed up tracking
- Improve cluster creation and splitting
- Coupling with signal decomposition
- Correct for range of electrons
- Other tracking methods

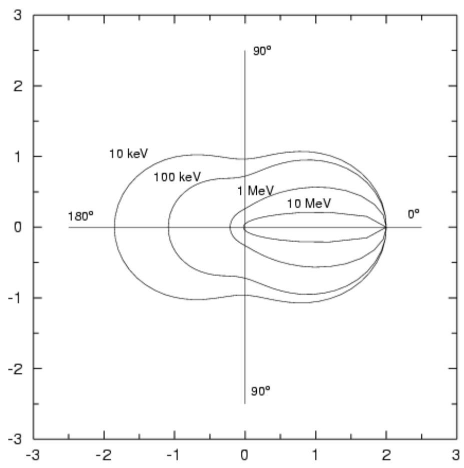
  e.g. Back tracking (AGATA)

Tracking improvements

Improve sensitivity of χ^2 using additional physics constrains

- **Use angular distribution information**

$$\frac{d\sigma(\theta)}{d\Omega} = \frac{r_0^2}{2}\left(\frac{E'_\gamma}{E_\gamma}\right)^2\left(\frac{E_\gamma}{E'_\gamma}+\frac{E'_\gamma}{E_\gamma}-\sin^2\theta\right)$$



- **Use absorption length information**

$$\frac{dN}{dx} = \exp(x/a)$$

However, These are probabilistic formulae

Tracking improvements

Speed up tracking

- **Skip bad sequences (implemented)**

If $\chi^2 > \chi^2_{max}$ after the first scattering

2 3 1 4 5
2 3 1 5 4
2 3 4 1 5
2 3 4 5 1
2 3 5 1 4
2 3 5 4 1
2 4 1 3 5

Skip all permutations with the same sequence

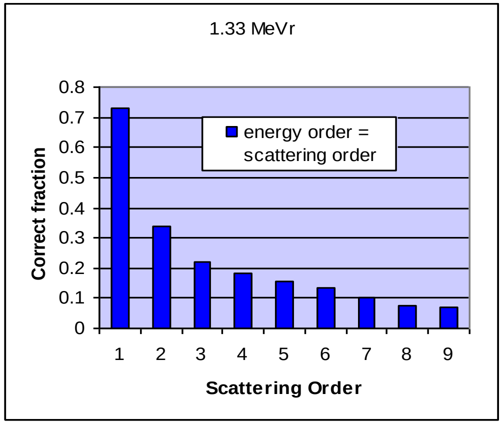
- **Calculate χ2 using points < total number of interactions (implemented)**

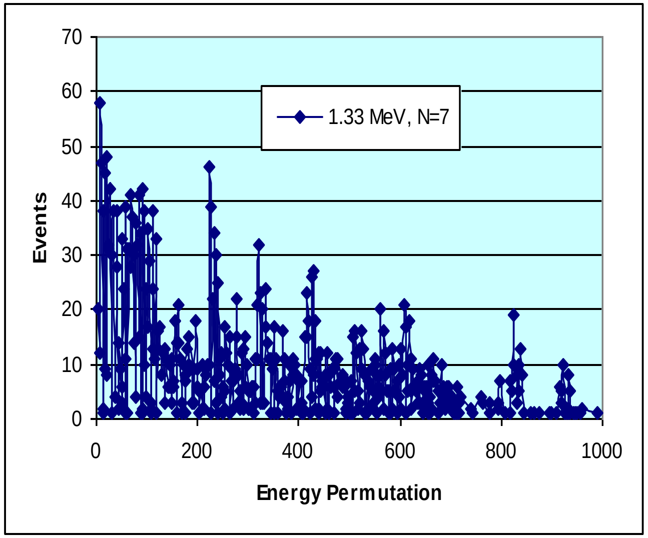
Time is reduced by a factor = N(N-1)(N-2)..(N-M)/N!

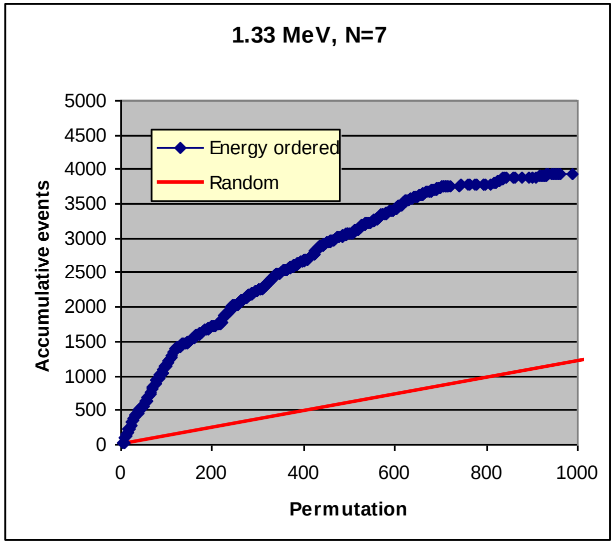
Tracking improvements

Speed up tracking

- Physics based permutation sequence
  - Order interactions by energy
  - Permute low energy points first
  - Examine fewer permutations than N!







1.33 MeV, N=7
7!=5040

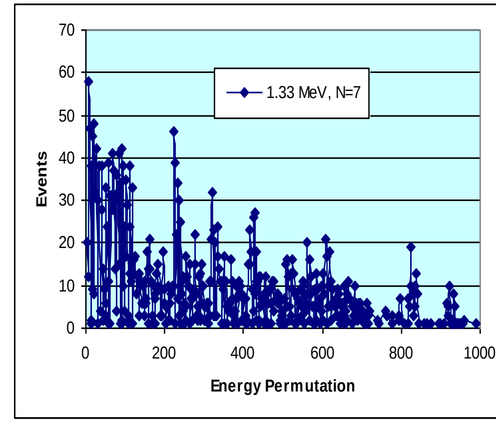
Permu.	Event
5%	33%
10%	50%
15%	62%
20%	65%

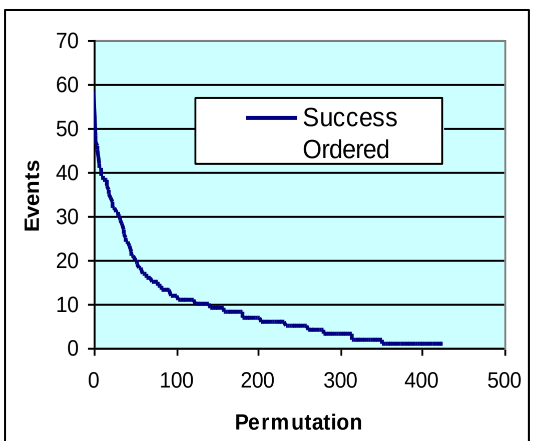
Another possible parameter — radial position of interactions

Tracking improvements

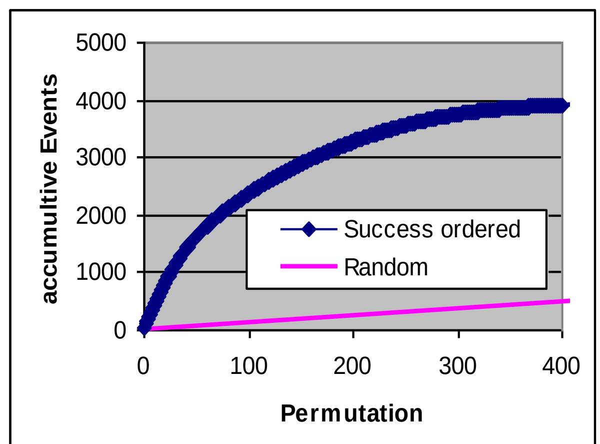
Speed up tracking

- Adaptive permutation sequence
  - Track energy ordered events (learning mode)
  - Arrange permutation by frequency
  - Track with learned order of permutation (production mode)





1 2 3 5 6 7 4
1 2 3 7 5 6 4
1 2 3 5 7 6 4
1 3 2 5 6 7 4
1 2 3 6 5 7 4
1 2 4 5 7 6 3
1 2 6 5 7 4 3
1 2 5 4 6 7 3
1 2 6 4 5 7 3
1 2 5 7 4 6 3



1.33 MeV, N = 7

7! = 5040

Permu.	Event
3.4%	50%
5.0%	59%
7.0%	64%
8.4%	65%

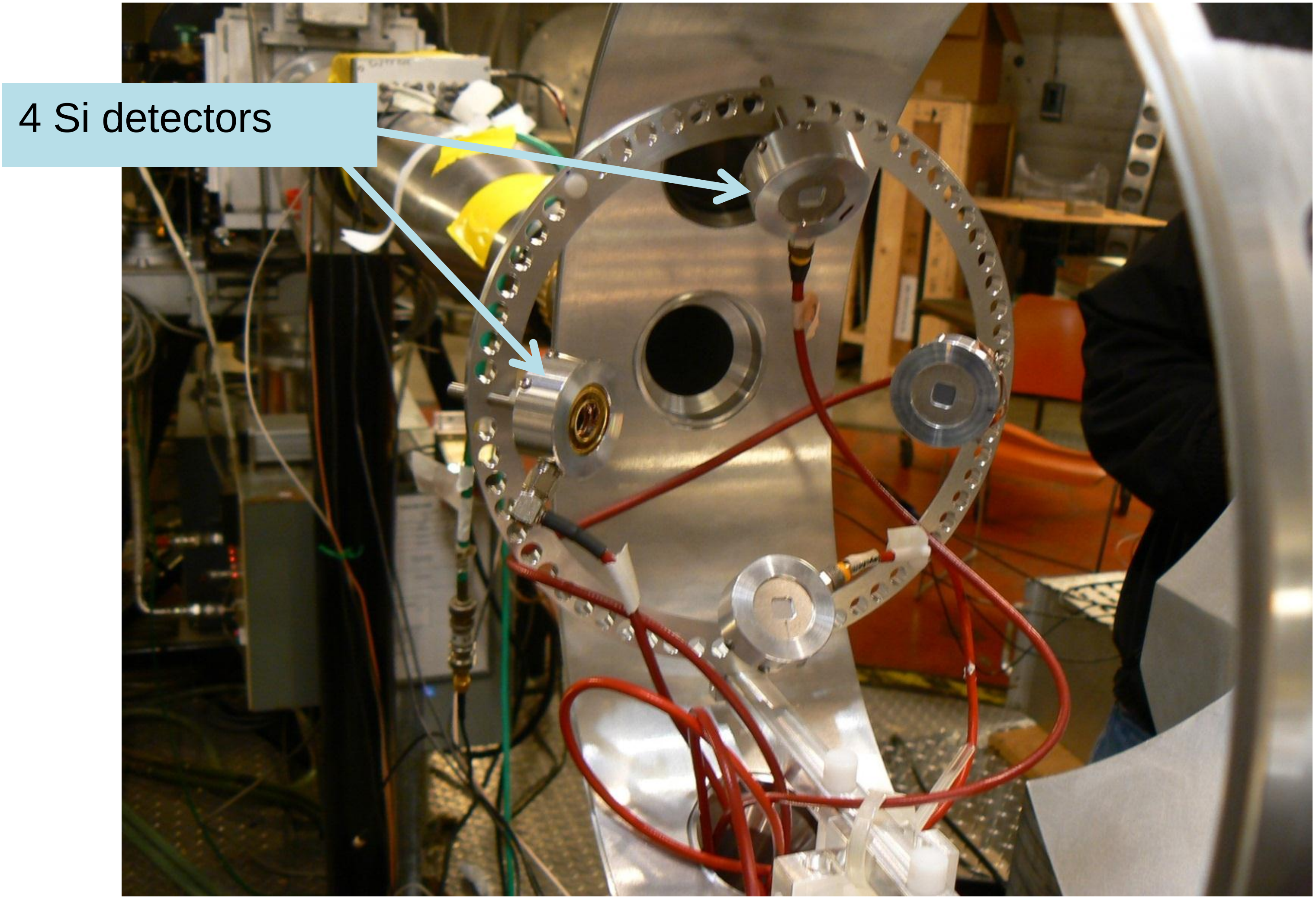
Coulomb excitation

- $^{58}Ni(^{136}Xe,^{136}Xe')^{58}Ni$, 500 MeV, 0.6 mg/cm^2
- Ni detected at 4 Si detectors at 40°(3), 35.9°(1) with Corresponding Xe angles of 24.4°, 24.9°
  - ^{136}Xe, v/c= 0.056

    $E\gamma(2 \rightarrow 0)$ = 1.3131 MeV; τ = 0.52 psec
  - ^{58}Ni, v/c=0.091

    $E\gamma(2 \rightarrow 0)$ = 1.4544 MeV; τ = 0.94 psec
- Test acquisition system with auxiliary detector.
  - Trigger system, clock distribution/synchronization, and data merging using the BGS acquisition system.

Coulomb excitation setup

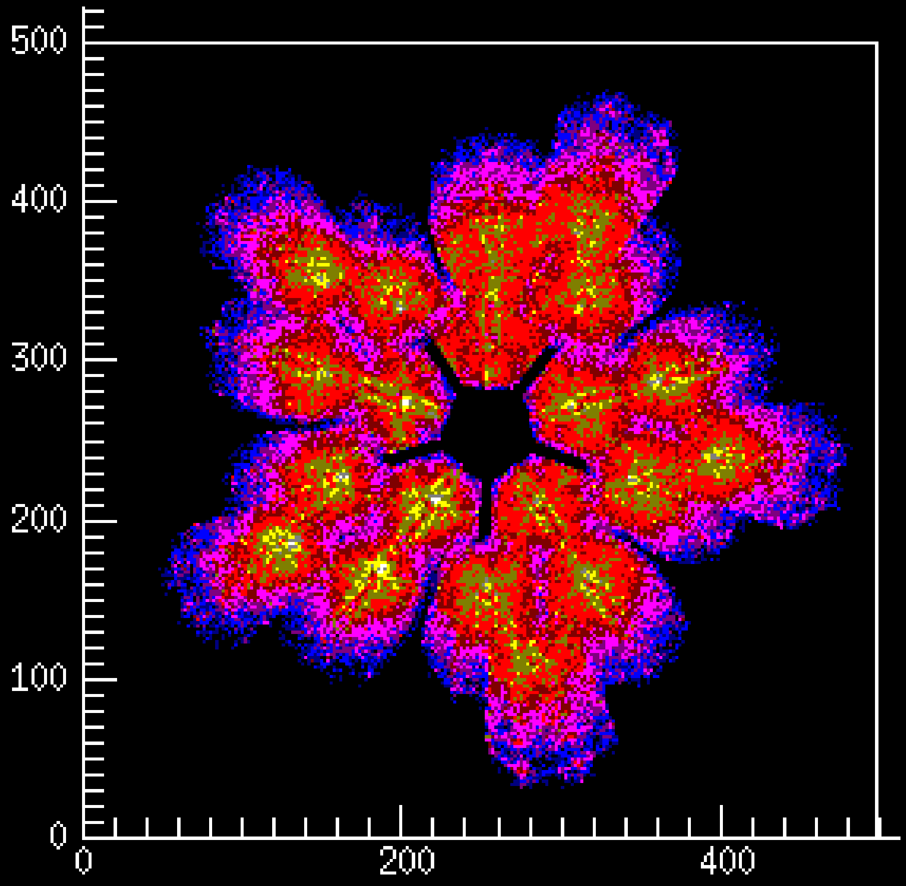


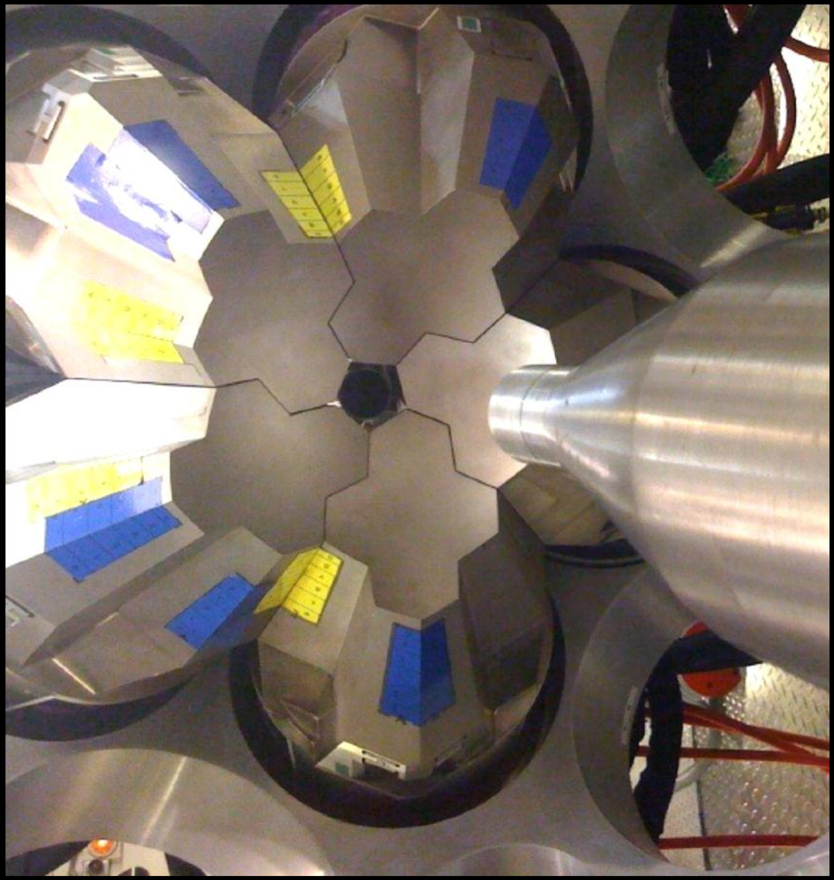
Demetrios Sarantites (W.U.)

Interaction points

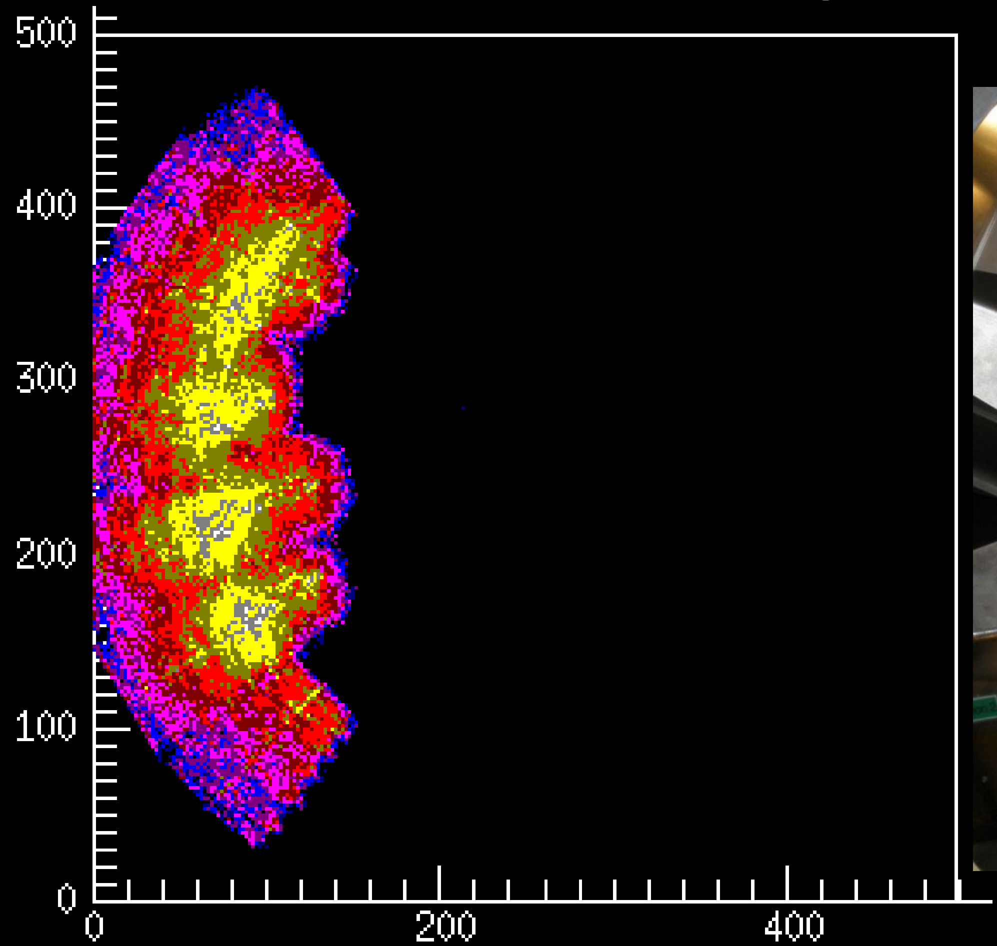
Position of interaction points determined by signal decomposition

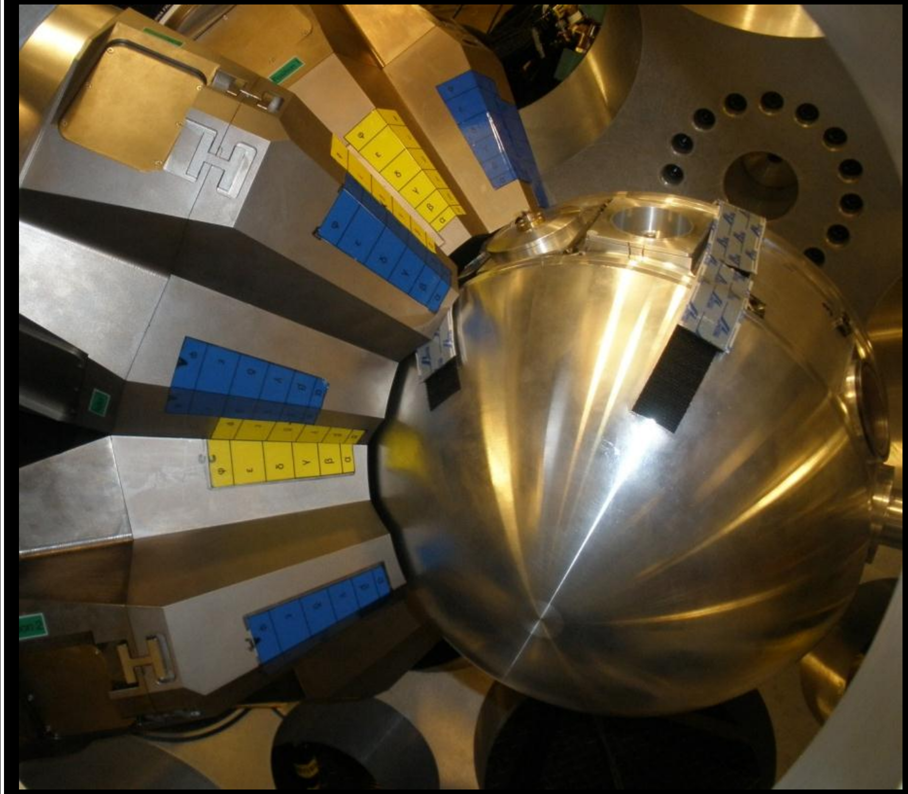
$^{122}Sn(^{40}Ar,4n)^{158}Er$, 170 MeV, v/c = 0.022





GRETINA and Target Chamber Interactions points: Side view

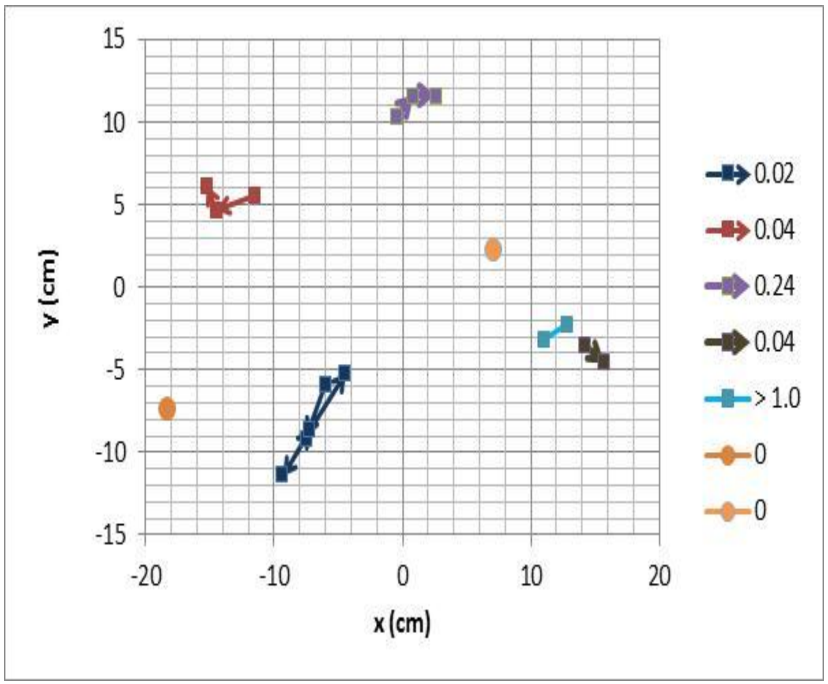


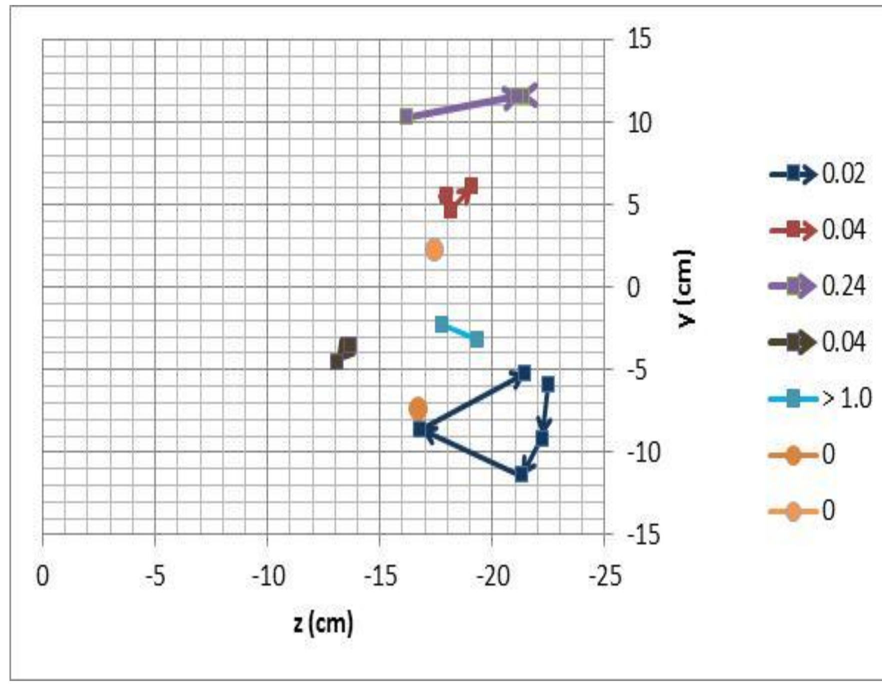


Too much structure. More work to be done.

Tracking example

- Event with 17 interaction points given by decomposition.
- Tracking constructed 4 good gamma rays from 13 points.



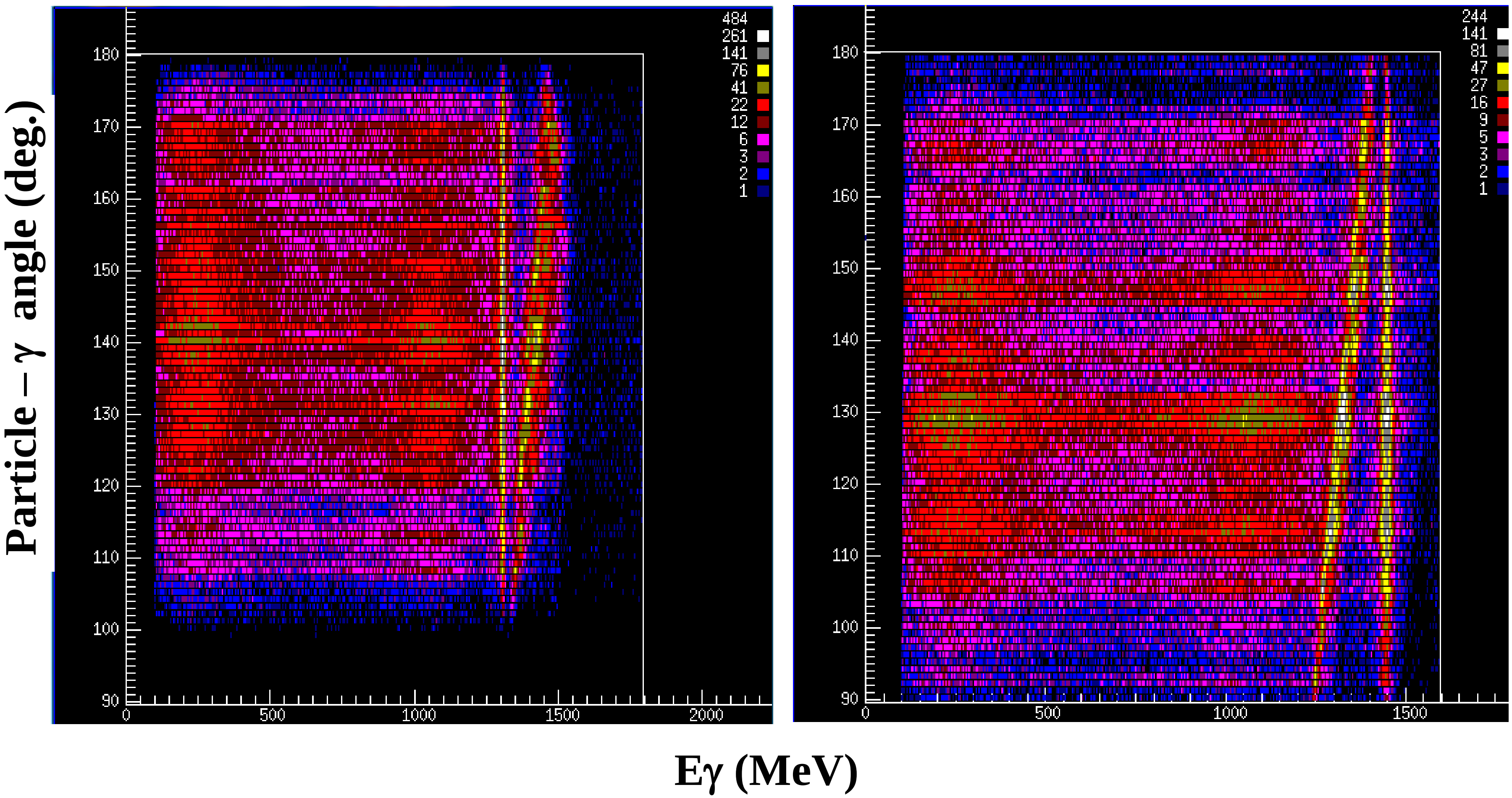


/global/data1x/gretina/Cave4CApr11/Run056/Global.dat
2nd event

Doppler correction

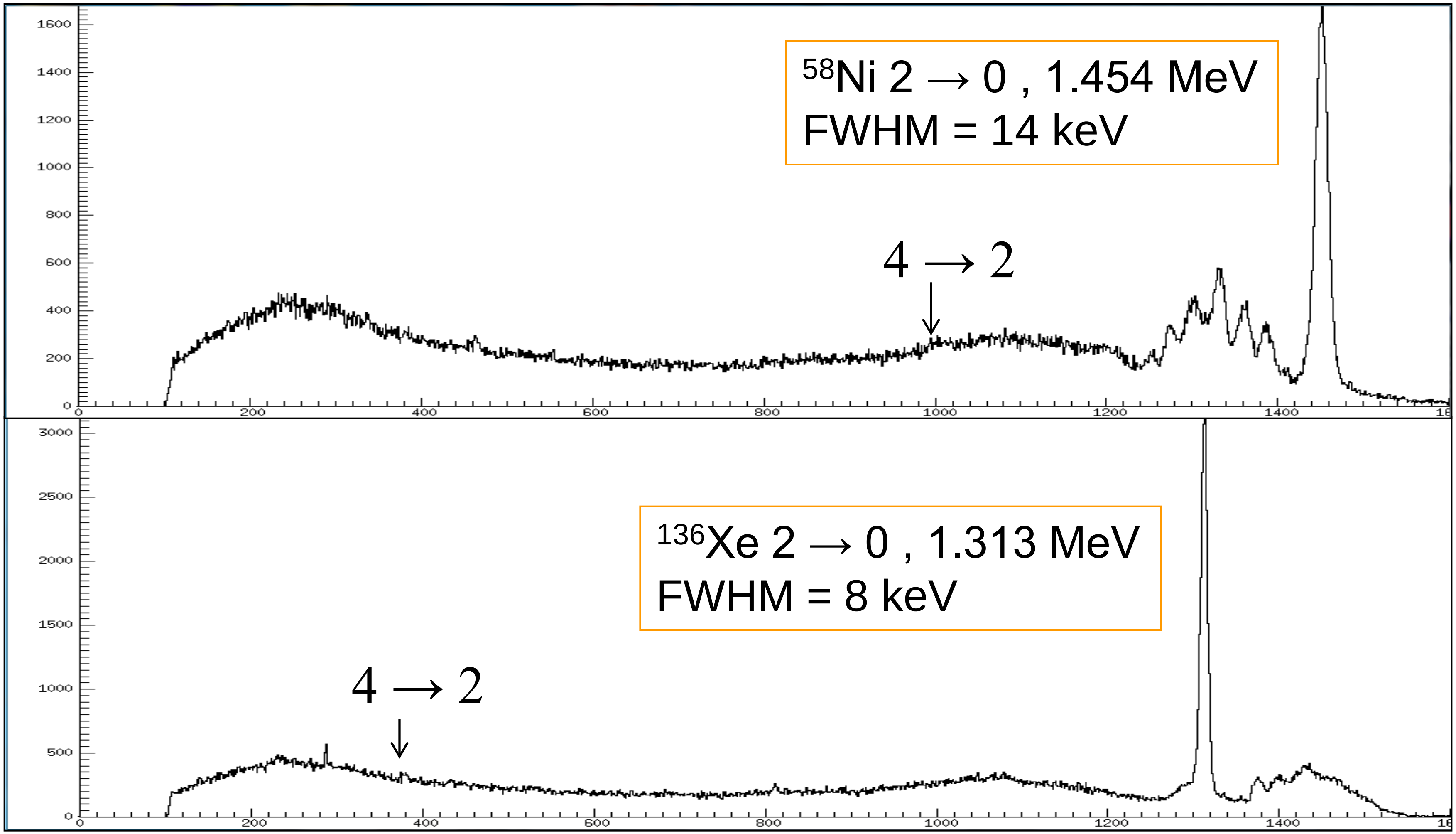
Coulomb excitation: $^{58}Ni(^{136}Xe,^{136}Xe')^{58}Ni$

Corrected for ^{136}Xe | Corrected for ^{58}Ni



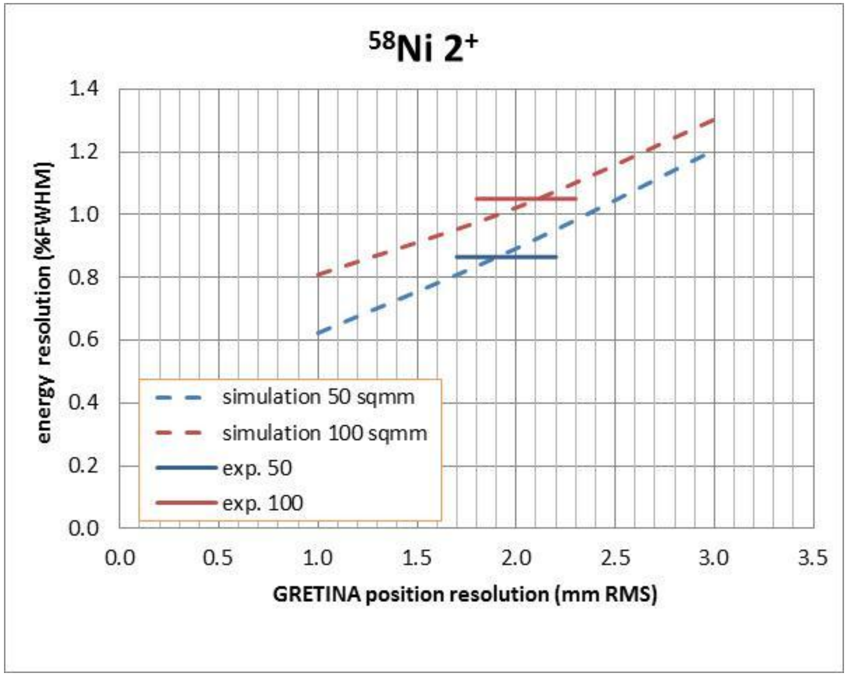
Doppler corrected spectra

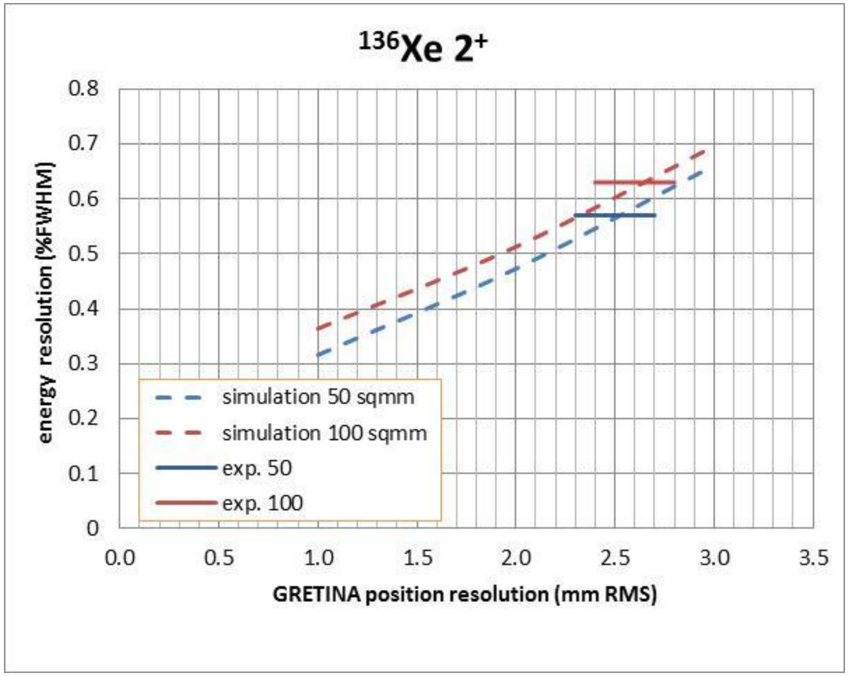
GRETINA position resolution of 2.0 – 2.5 mm RMS determined from gamma-ray energy resolution after Doppler correction.



Position resolution

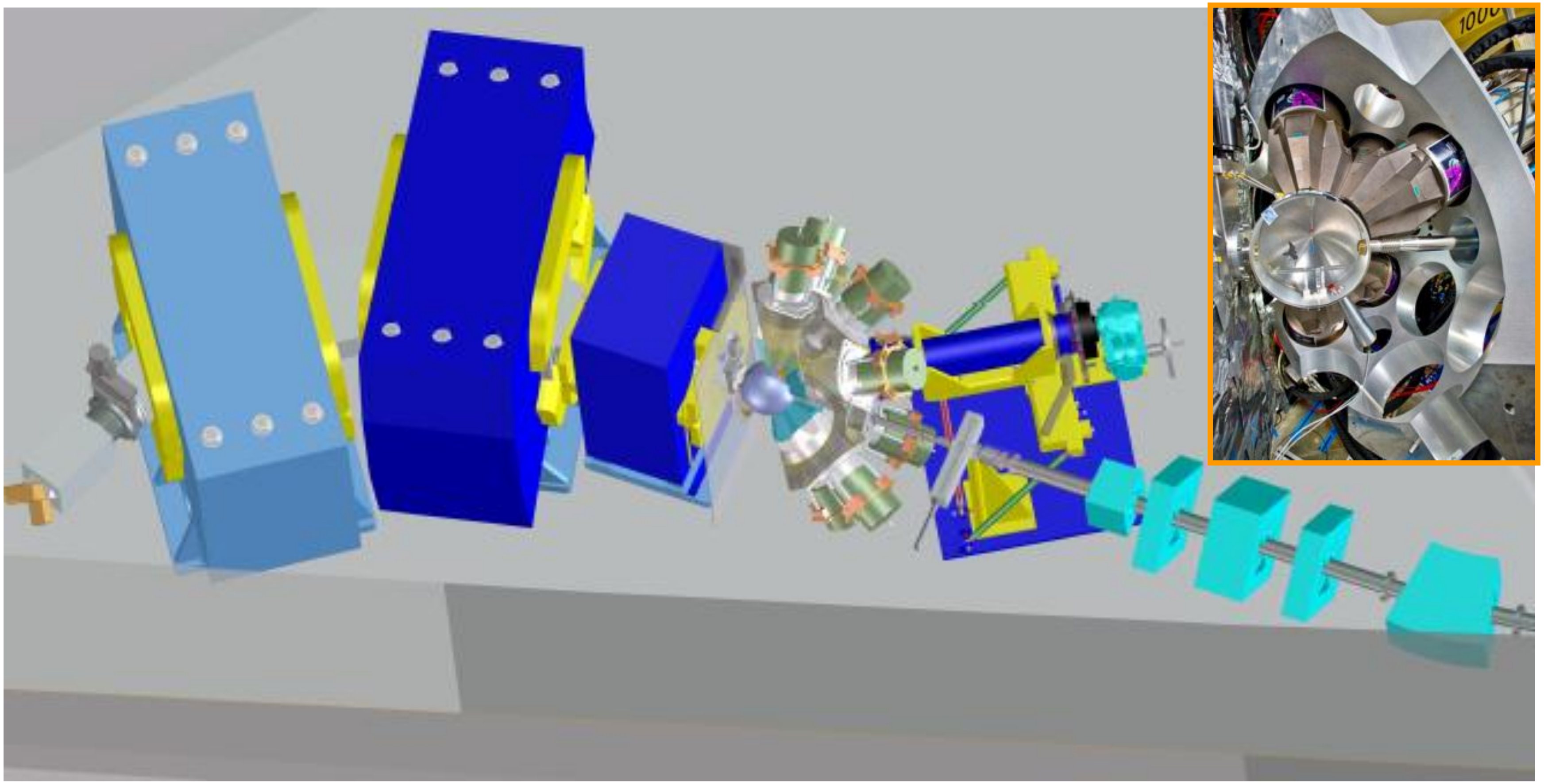
- GRETINA position resolution of 2.0 – 2.5 mm RMS determined from gamma-ray energy resolution after Doppler correction.





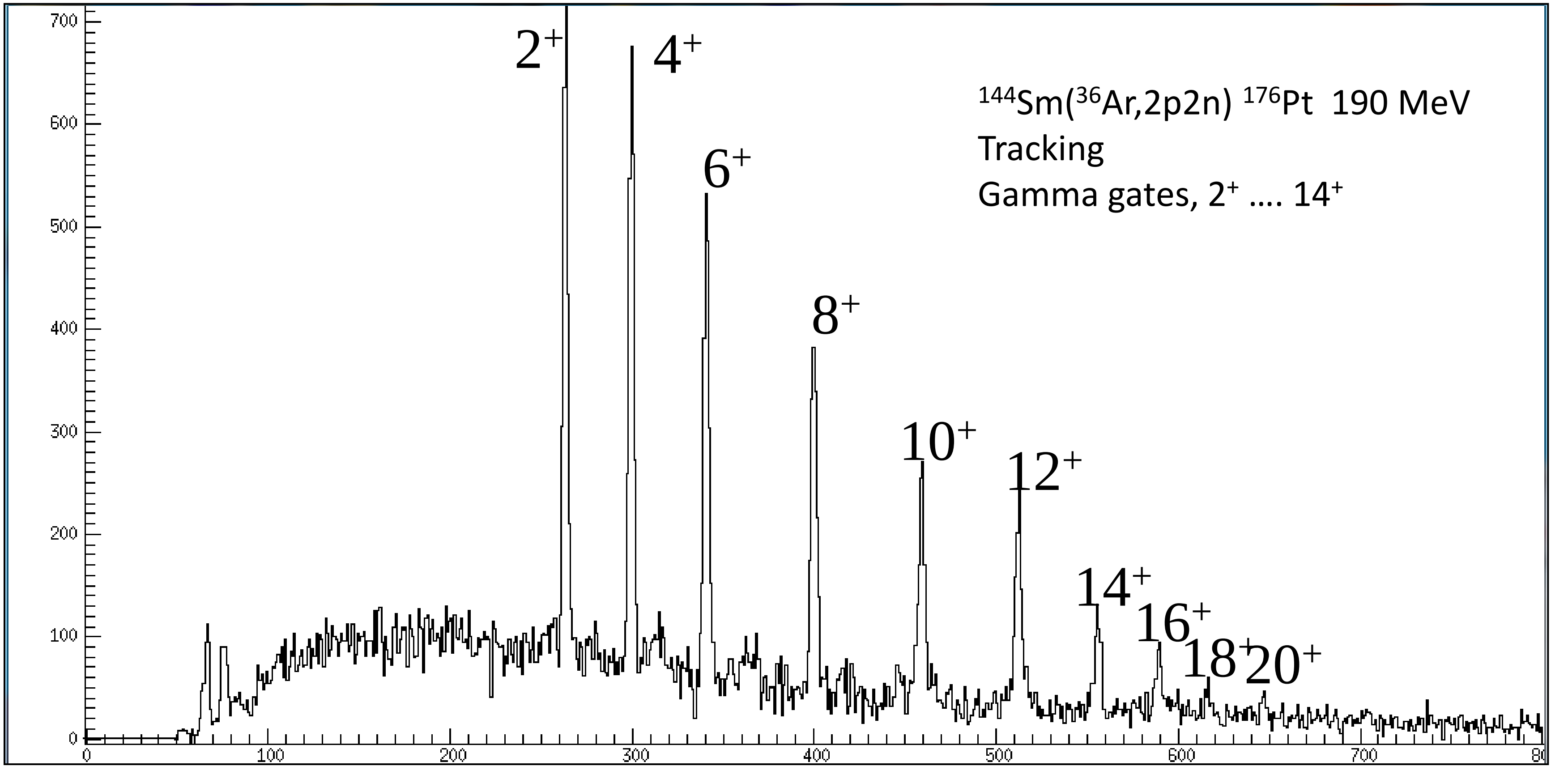
GRETINA at BGS

- GRETINA set up at BGS target position
- Experiment September 7, 2011 – March 23, 2012



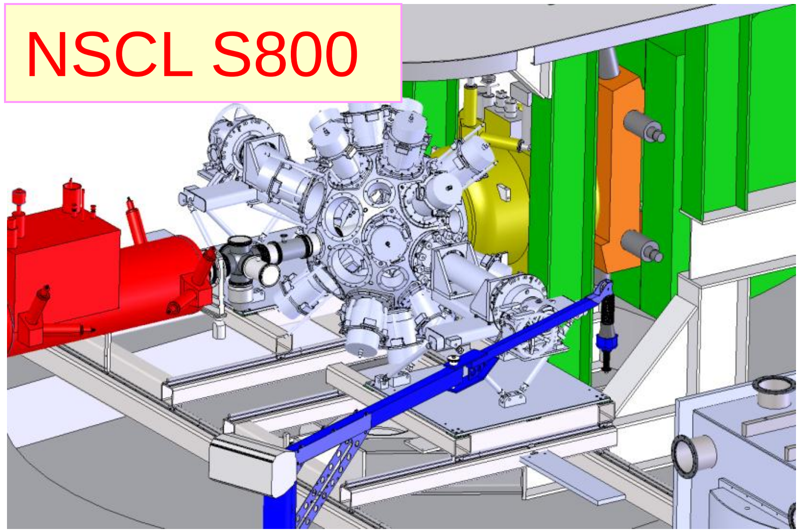
Test experiment

- GRETINA – BGS coincidence
- Data are acquired using separate systems
- Use time stamps to correlate data



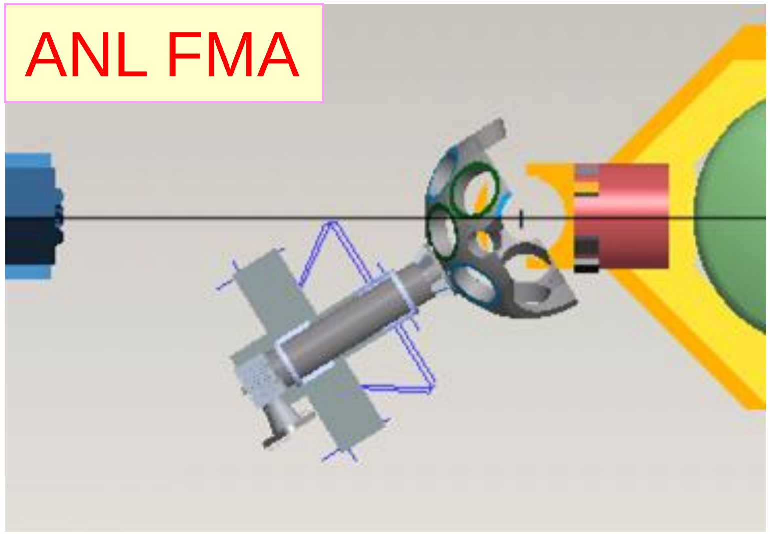
Science campaigns

July 2012



- Single particle properties of exotic nuclei – knock out, transfer reactions.
- Collectivity – Coulomb excitation, lifetime, inelastic scattering.
- 24 experiments approved for a total of 3351 hours.

2013



- Structure of Nuclei in ^{100}Sn region.
- Structure of superheavy nuclei.
- Neutron-rich nuclei – CARIBU beam, deep-inelastic reaction, and fission.

Acknowledgements

Work force

I-Yang Lee, Sergio Zimmermann, John Anderson, Thorsten Stezeberger, Augusto Macchiavelli, Stefanos Paschalis, Chris Campbell, Heathre Crawford, Carl Lionberger, Mario Cromaz, Torben Lauritsen, Steve Virostek, Tim Loew, Dirk Weisshaar, David Radford

Advisory Committee members

Con Beausang**,** Mike Carpenter, Partha Chowdhury, Doug Cline, Augusto Macchiavelli, David Radford (**Chair**), Mark Riley, Demetrios Sarantites, Dirk Weisshaar,

Working Groups and chairs

- Physics M. A. Riley
- Detector A. O. Macchiavelli
- Electronics D. C. Radford
- Software M. Cromaz
- Auxiliary Detectors D.G. Sarantites

Collaborating Institutions

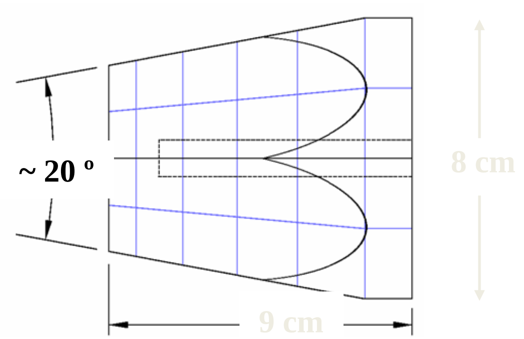
- **Lawrence Berkeley Laboratory**
  - Lead laboratory
- **Argonne National Laboratory**
  - Trigger system
  - Calibration and online monitoring software
  - Tracking program upgrade
- **Michigan State University**
  - Detector testing
- **Oak Ridge National Laboratory**
  - Liquid nitrogen supply system
  - Data processing software
- **Washington University**
  - Target chamber

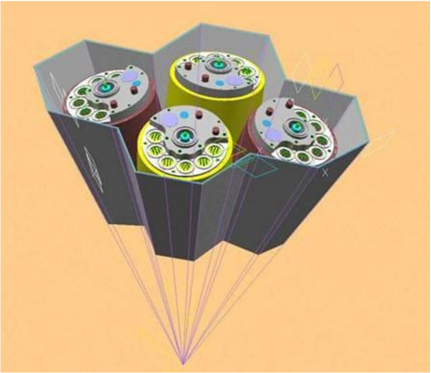
Summary

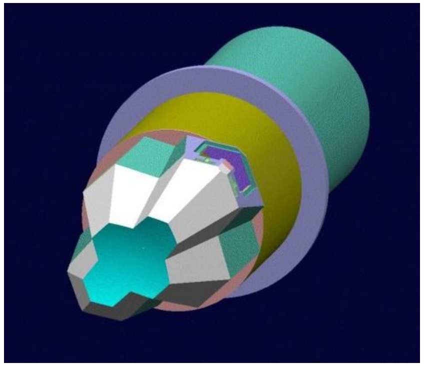
- GRETINA is completed, engineering runs and commissioning runs were carried out.
- A number improvements and optimizations were implemented successfully.
- Exciting period of physics campaigns schedule through 2013 at MSU and ANL.
- GRETINA/GRETA will be a major instrument for the next generation of facility such as FRIB.
- Gamma-ray tracking arrays will have large impact on a wide area of nuclear physics.

Backup

GRETINA Detector module

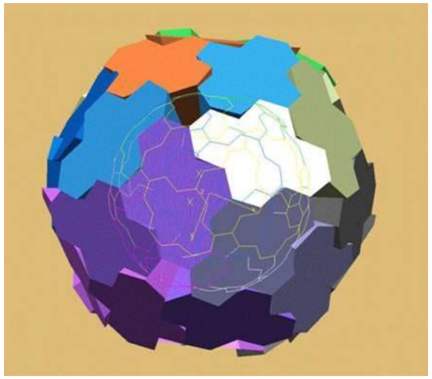






36 segments per Ge crystal

4 crystals per module

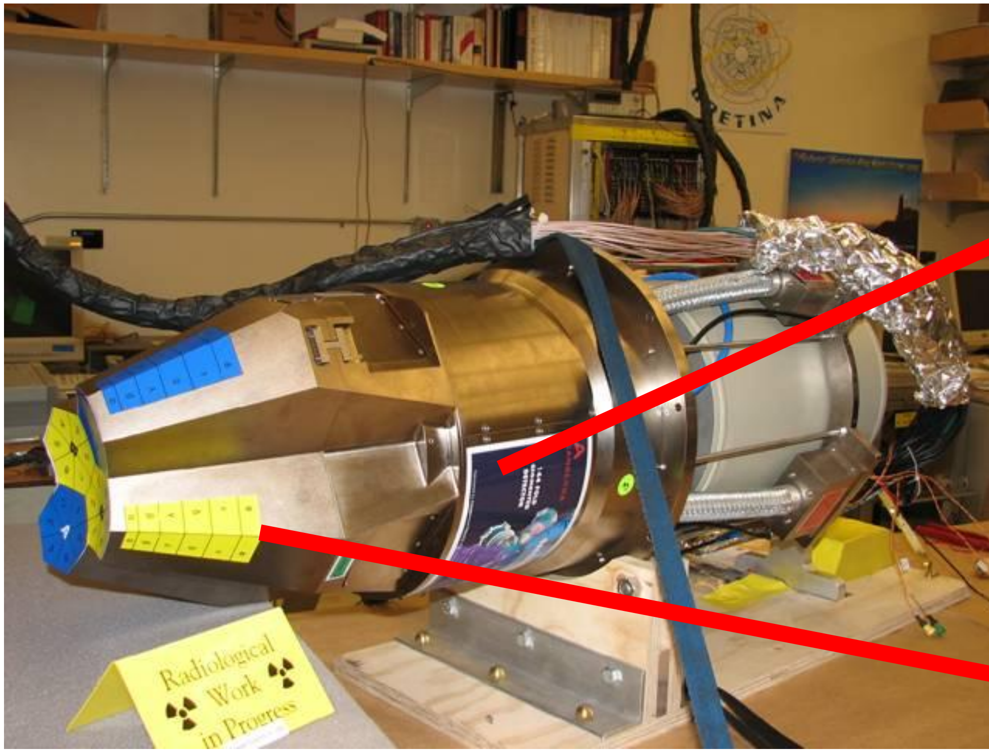


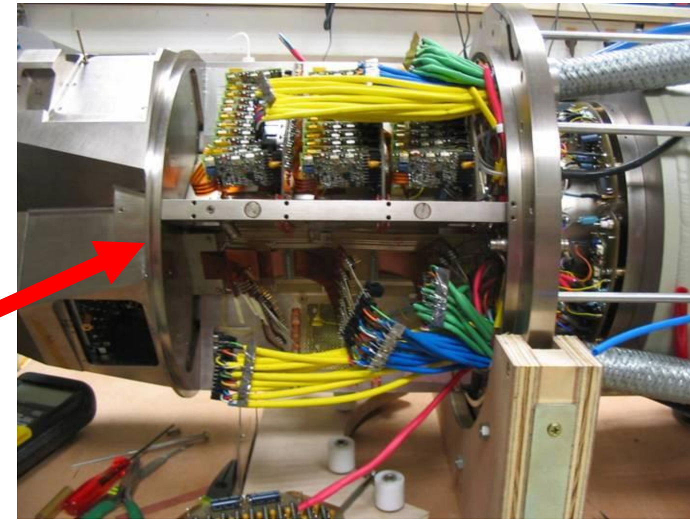
30 modules for 4π

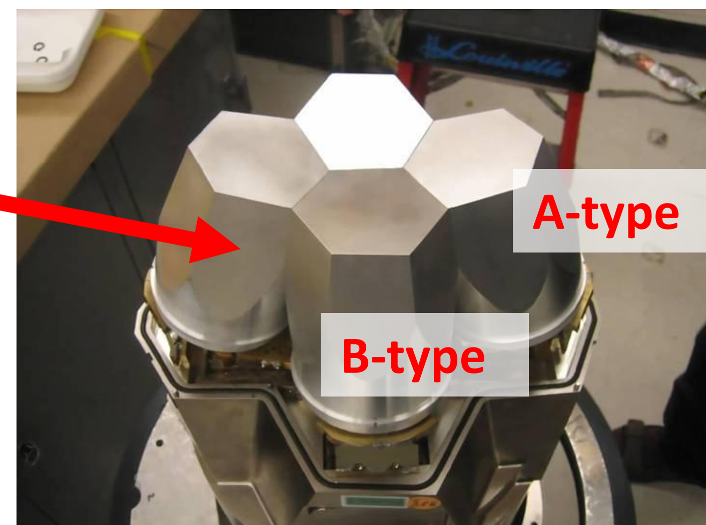
- Two types of crystal, one cryostat – simple geometry
- Warm FET for the segments – easy to replace, higher availability

Detector modules

Seven received







36 segments/crystal

4 crystal/ module

148 signal channels /module

Electronics

All modules produced

Digitizer module (LBNL)
14bit, 100 MHz
Energy
Leading edge time
Constant fraction time
Pulse shape

Trigger Timing & Control module (ANL)
Fast trigger (<300 nsec)
Trigger conditions:
- Multiplicity
- Sum energy
- Hit pattern