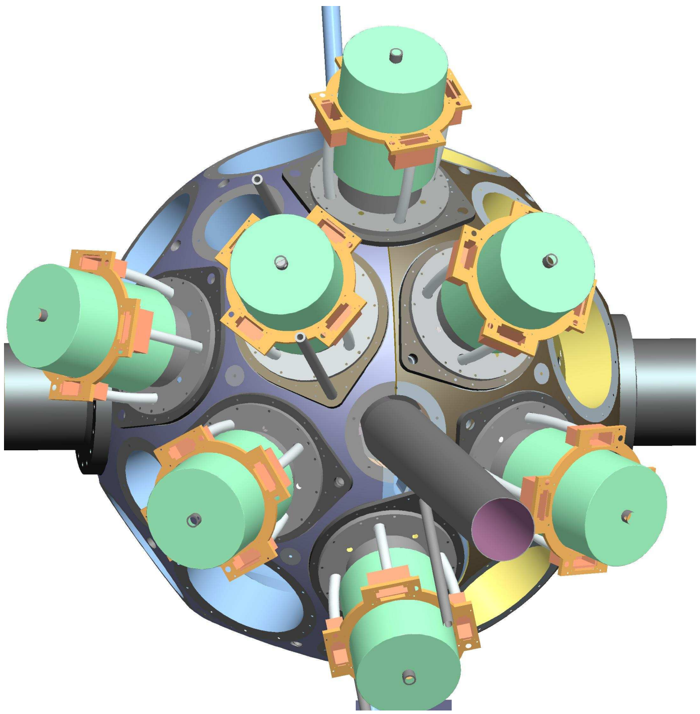
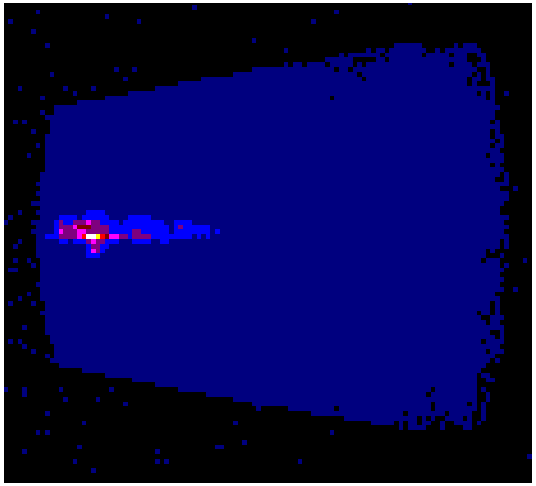
GRETINA : Recent Developments

David Radford

ORNL Physics Division

JUSTIPEN Workshop Jan 2008





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hribf
Holifield Radioactive Ion Beam Facility
Oak Ridge National Laboratory

GRETINA

- Gamma-Ray Energy Tracking Array for in-beam nuclear structure studies
- 28 highly segmented Ge detectors, in groups of four
- Total ~1π steradians
- Funded by DOE, under construction at LBNL
- People:
  - Contractor Project Manager: I-Yang Lee (LBNL)
  - GRETINA Advisory Committee (GAC):

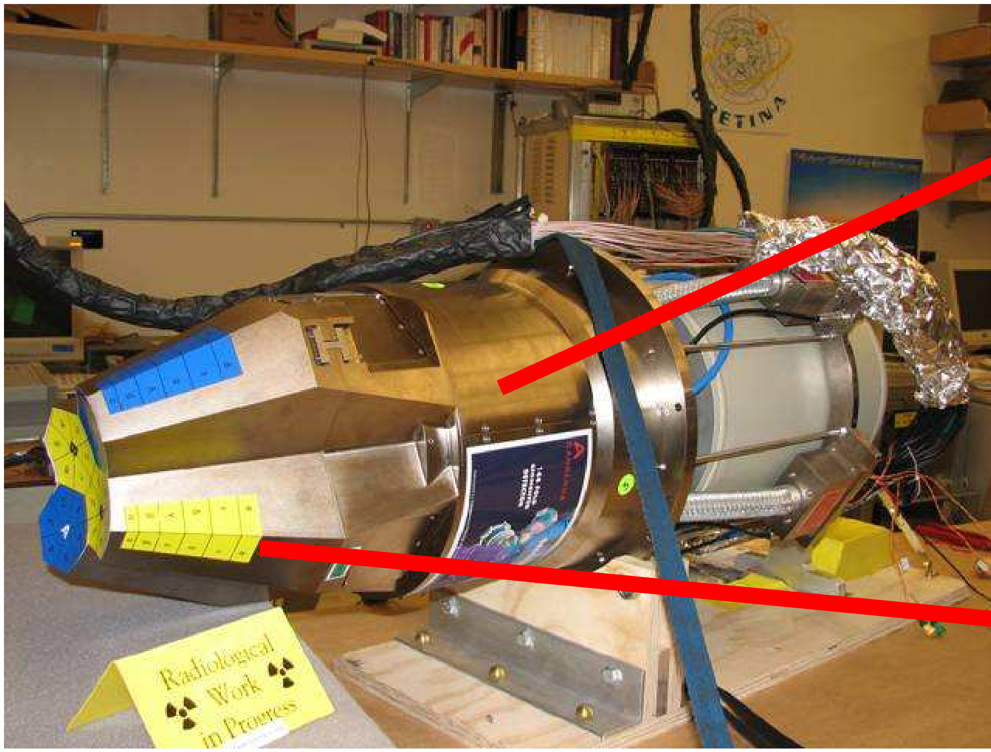
    Con Beausang (U. of Richmond)
    Doug Cline (U. of Rochester)
    Thomas Glasmacher (MSU / NSCL)
    Kim Lister (ANL)
    Augusto Macchiavelli (LBNL)
    David Radford (ORNL)
    Mark Riley (Florida State U.)
    Demetrios Sarantites (Washington U.)
    Kai Vetter (LLNL)
  - Many others, especially at LBNL

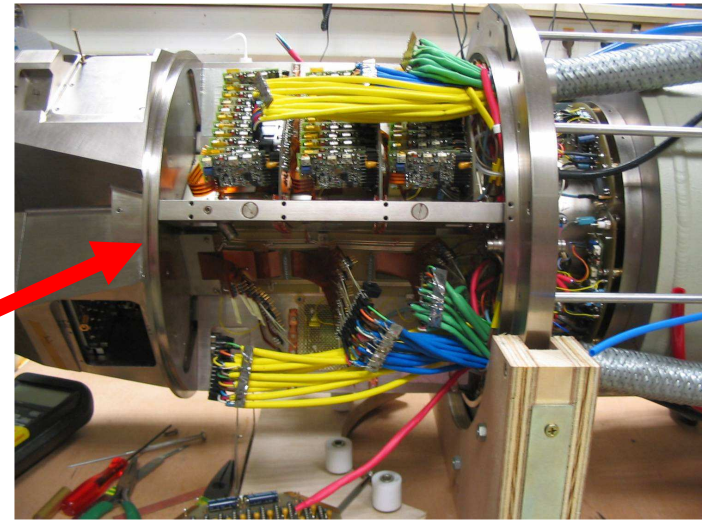
Highlights of 2006 - 2007 achievements

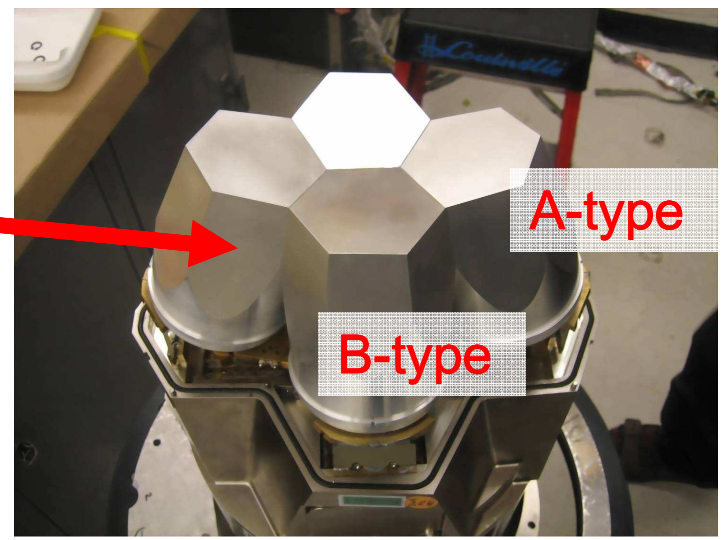
- ✓ Received and tested the first quadruple-detector module
- ✓ Developed a new version of signal decomposition program and signal basis.
- ✓ Achieved ≤ 2mm position resolution
- ✓ Understood and eliminated preamplifier crosstalk and oscillation
- ✓ Designed, fabricated, and tested prototypes of signal digitizer and trigger modules
- ✓ Performed an end-to-end test on an eight-node computing cluster
- ✓ Received CD2B/3B approval by DOE
- ✓ Developed a suggested national lab rotation schedule for the first round of experimental campaigns

First Quadruple Cluster (Q1)

Delivered Dec 2006





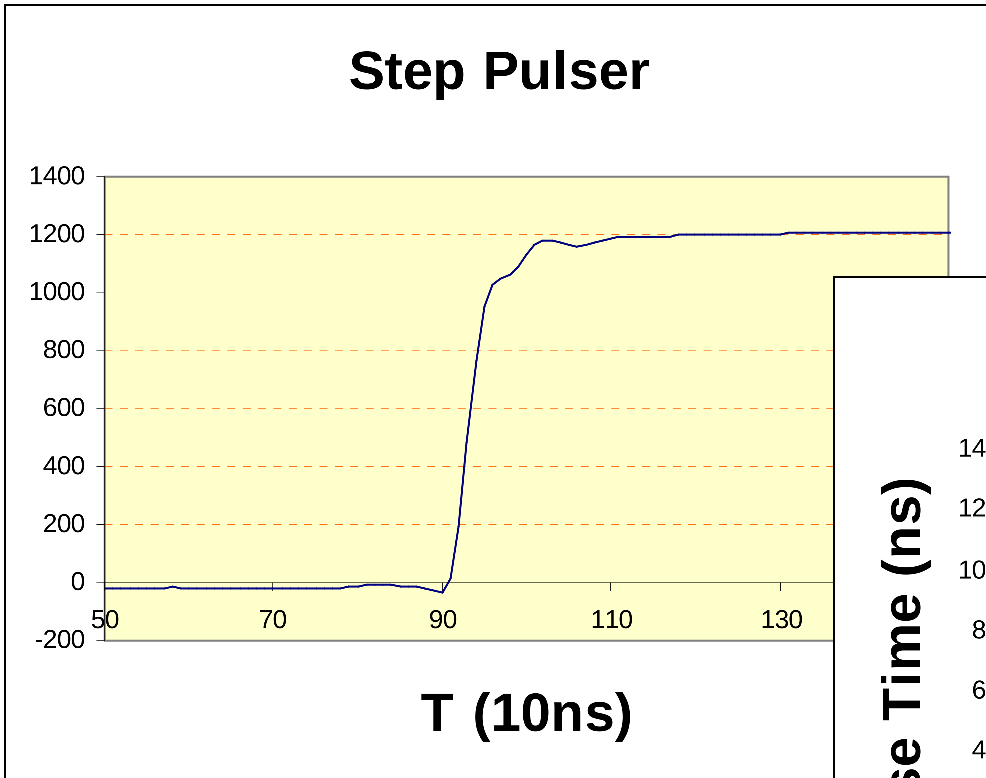


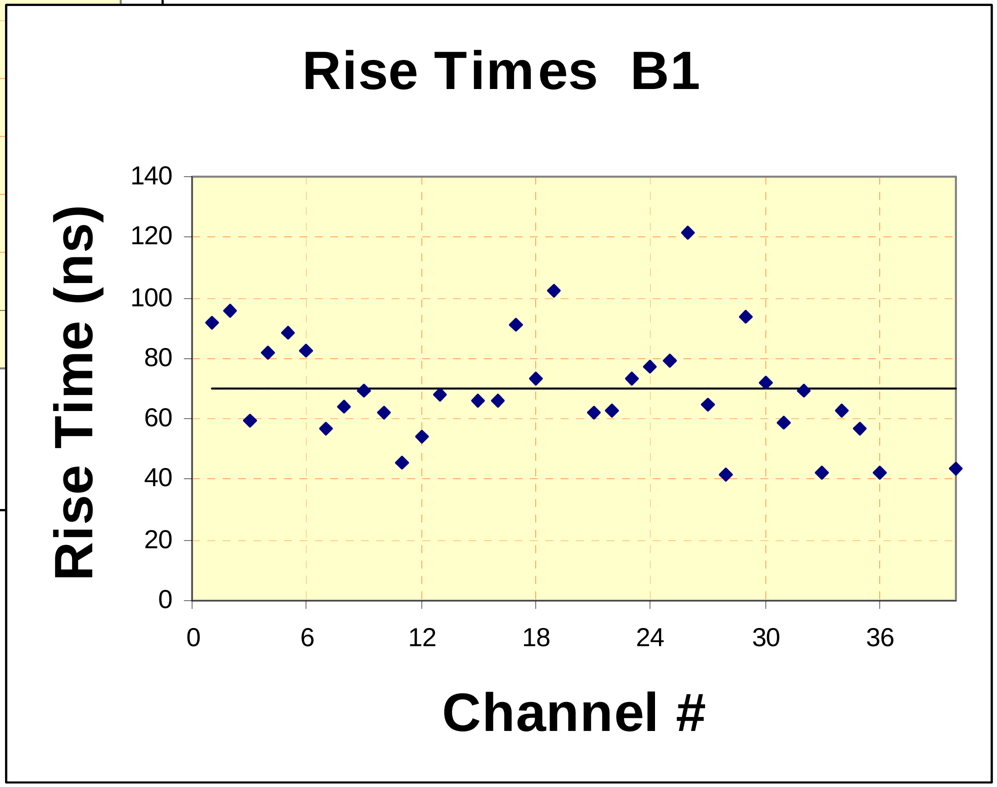
First Quadruple Module (Q1)

- First delivered Dec 2006
- Easily met all mechanical specifications and tolerances
- One nonfunctional segment in one of the four crystals
- Central channels and front segments were microphonic
- Many measurements during 2007, including in-beam
- Attempt to repair bad crystal at LBNL was unsuccessful
- Detector was returned to Canberra; repaired module was (re)delivered Dec 2007
  - ✓ Central channel microphonics fixed
  - ✓ Cause of front segment microphonics identified
- Now undergoing a second round of tests and measurements at LBNL

Q1 Signal Rise Times

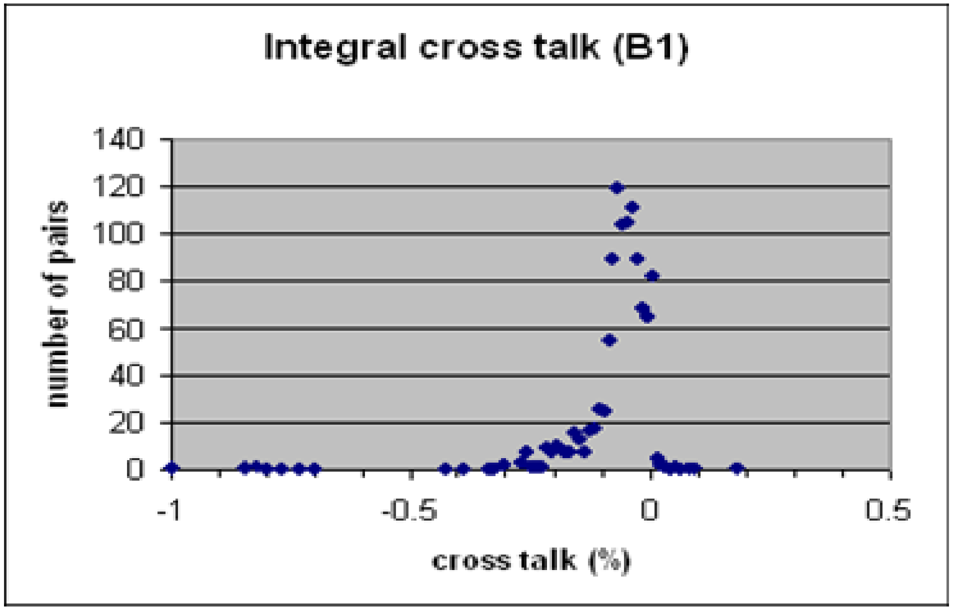
Many of the rise times were much slower than the specification (≤ 70ns)



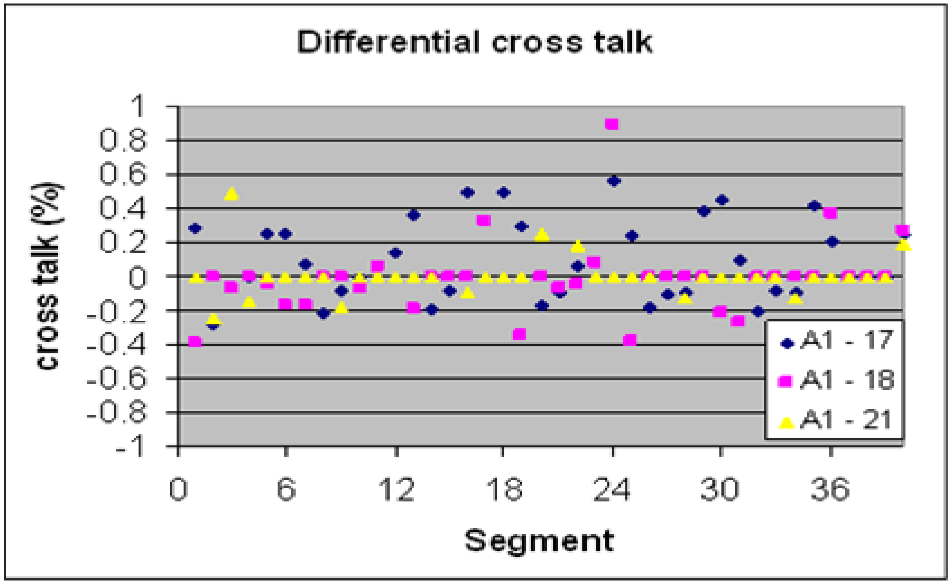


Q1 Cross-Talk

- “Integral crosstalk” (energy)
  - Average = 0.09%
  - σ = 0.10%



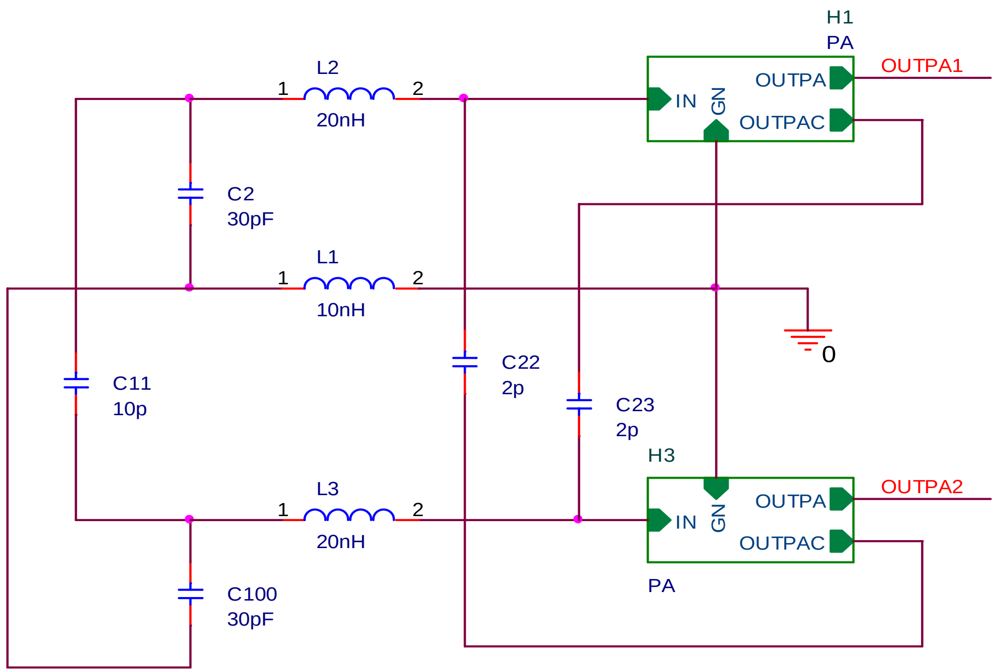
- “Differential crosstalk”
  - Average = 0.11%
  - σ = 0.42%



Specifications: <0.1%

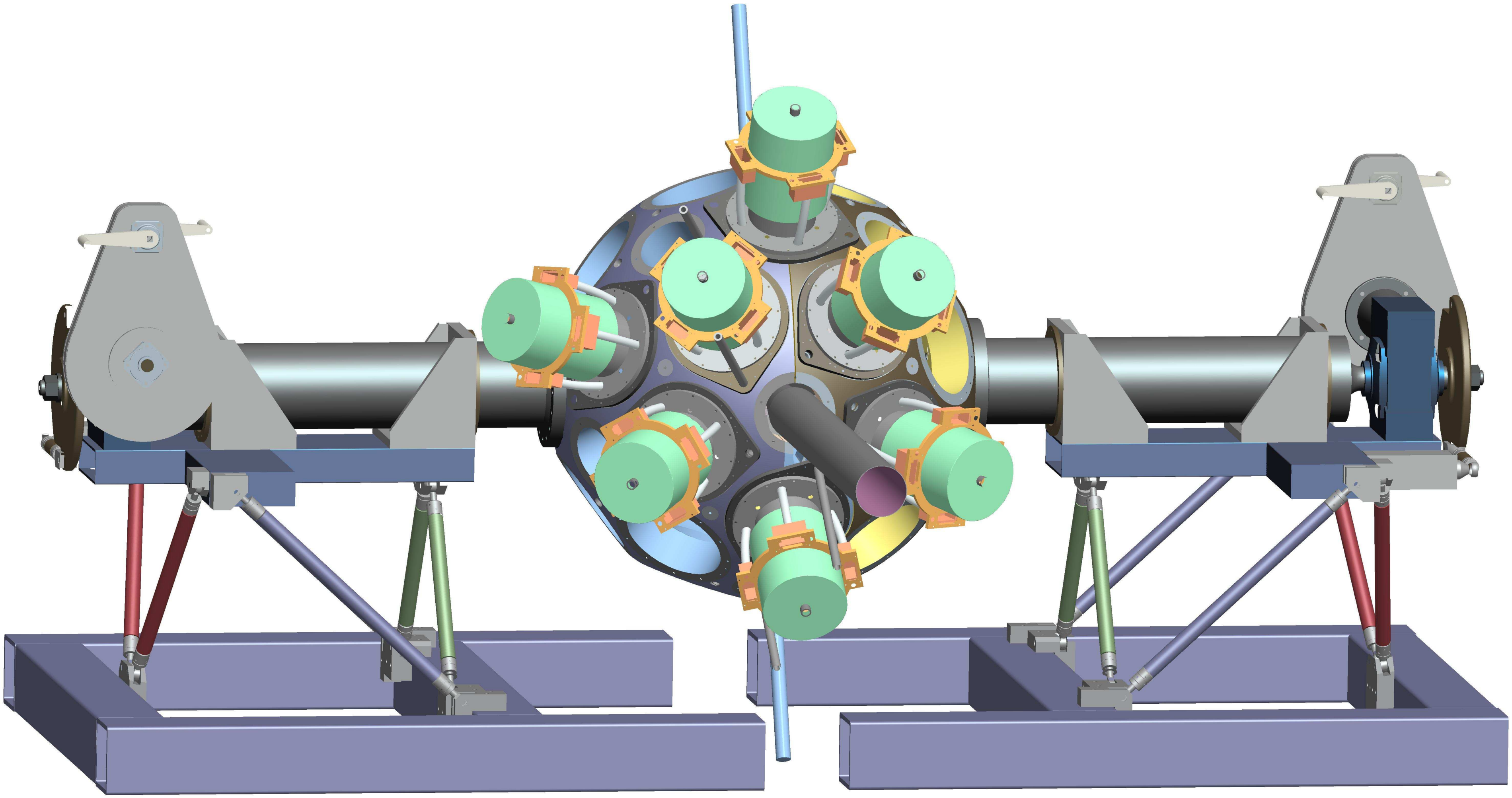
Cross-talk and Oscillation

- Differential cross talk arises from capacitive coupling across the inputs to the preamplifiers
- Working with Canberra and SPICE models, we have understood and eliminated the preamplifier oscillation
- ✓ The rise times of the Q1 preamplifiers have now been reduced to the value required by the specification



Mechanical Design Completed

Mechanical system: Support structure, LN system, target chamber, etc.

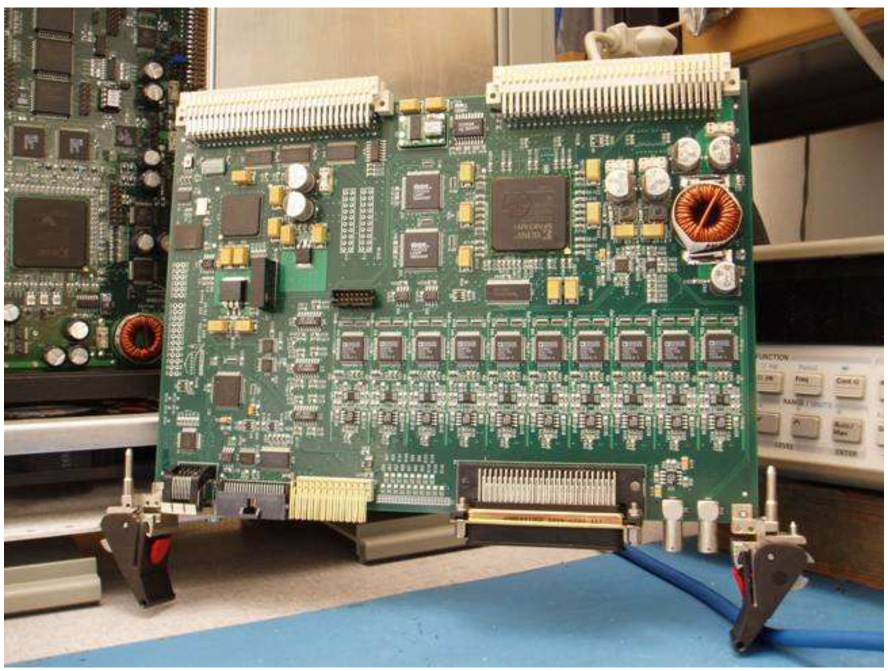


Electronics Prototypes

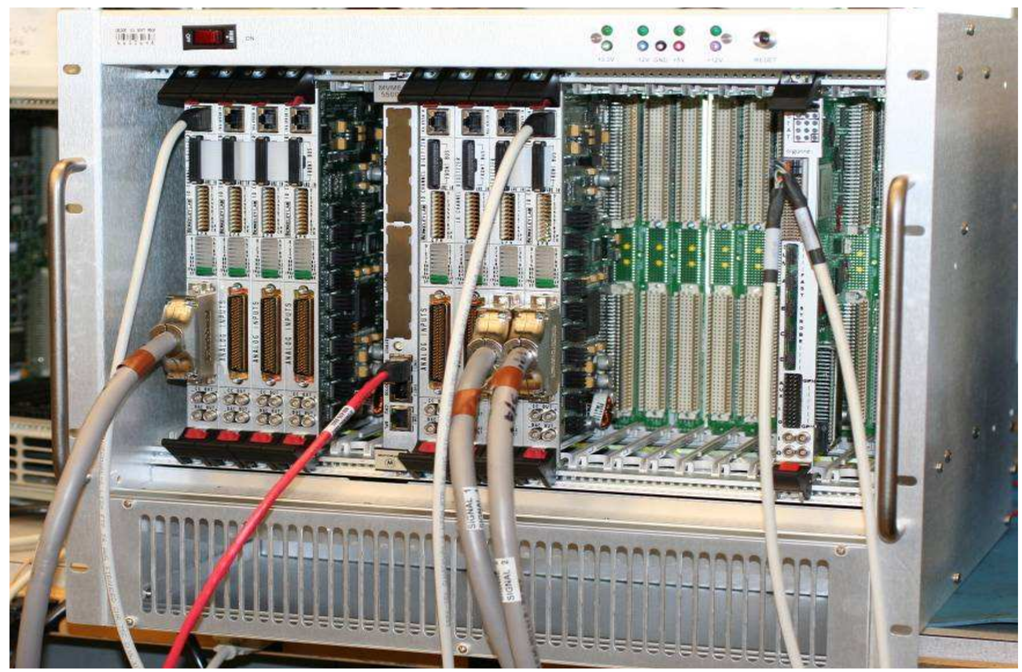
Designed, fabricated, and tested prototype of digitizer module (LBNL) and trigger module (ANL)

- Worked beautifully together on first try

Digitizer module



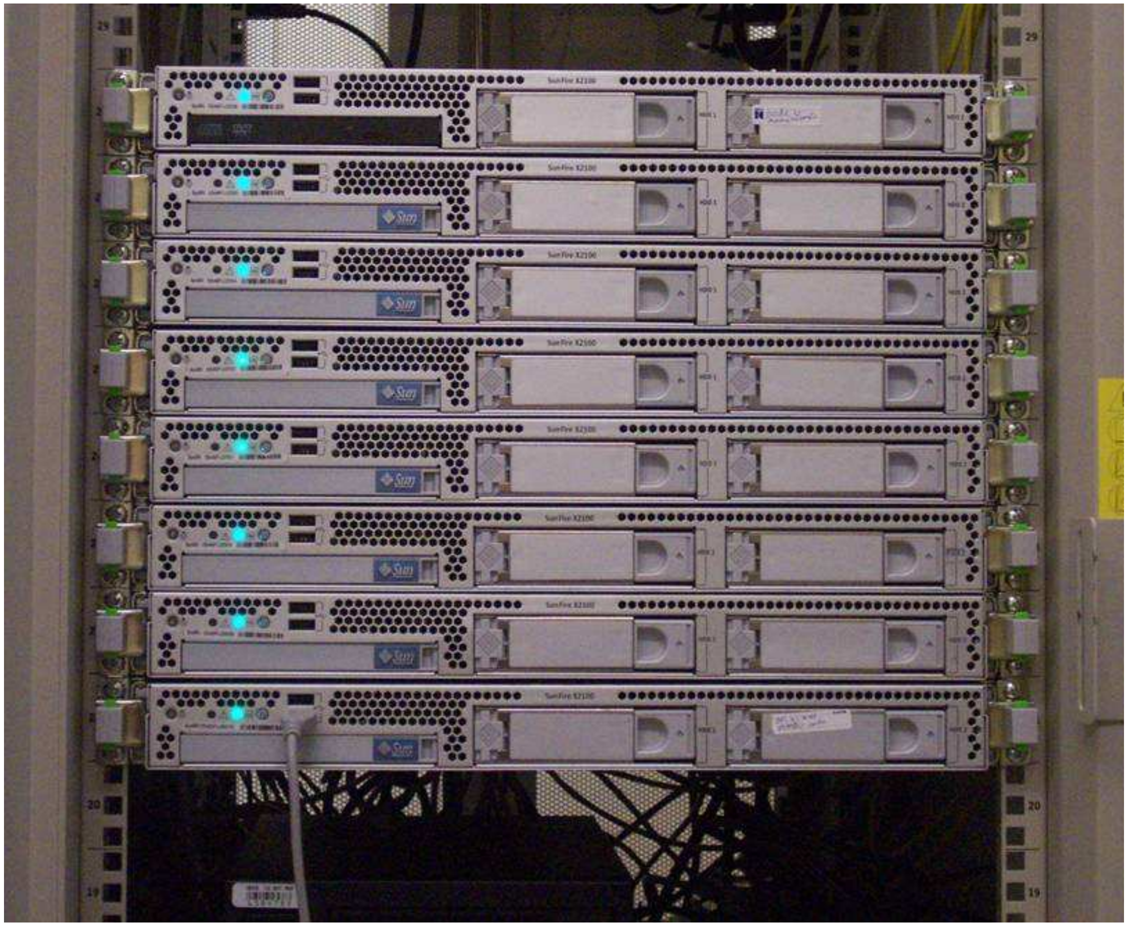
Digitizer and trigger modules under test



Computing System

End-to-end software test carried out on an eight-node prototype computer cluster

- Read out
- Event building
- Signal decomposition
- Tracking
- Storage
- Analysis



Signal Decomposition

Tracking depends on knowing the positions and energies of the Compton interactions

Digital pulse processing of segment data

- Extracts multiple γ-ray interaction positions & energies
- Uses data from both hit segments and image charges from neighbors
- Must allow for at least two interactions per hit segment
- Uses a set of calculated basis pulse shapes
- Done on a per-crystal basis
- Ideally suited to parallel processing

Requires about 90% of CPU cycles used by GRETINA

- The major processing bottleneck
- Baseline design allows only ~ 4 ms/crystal/node for decomposition

Status

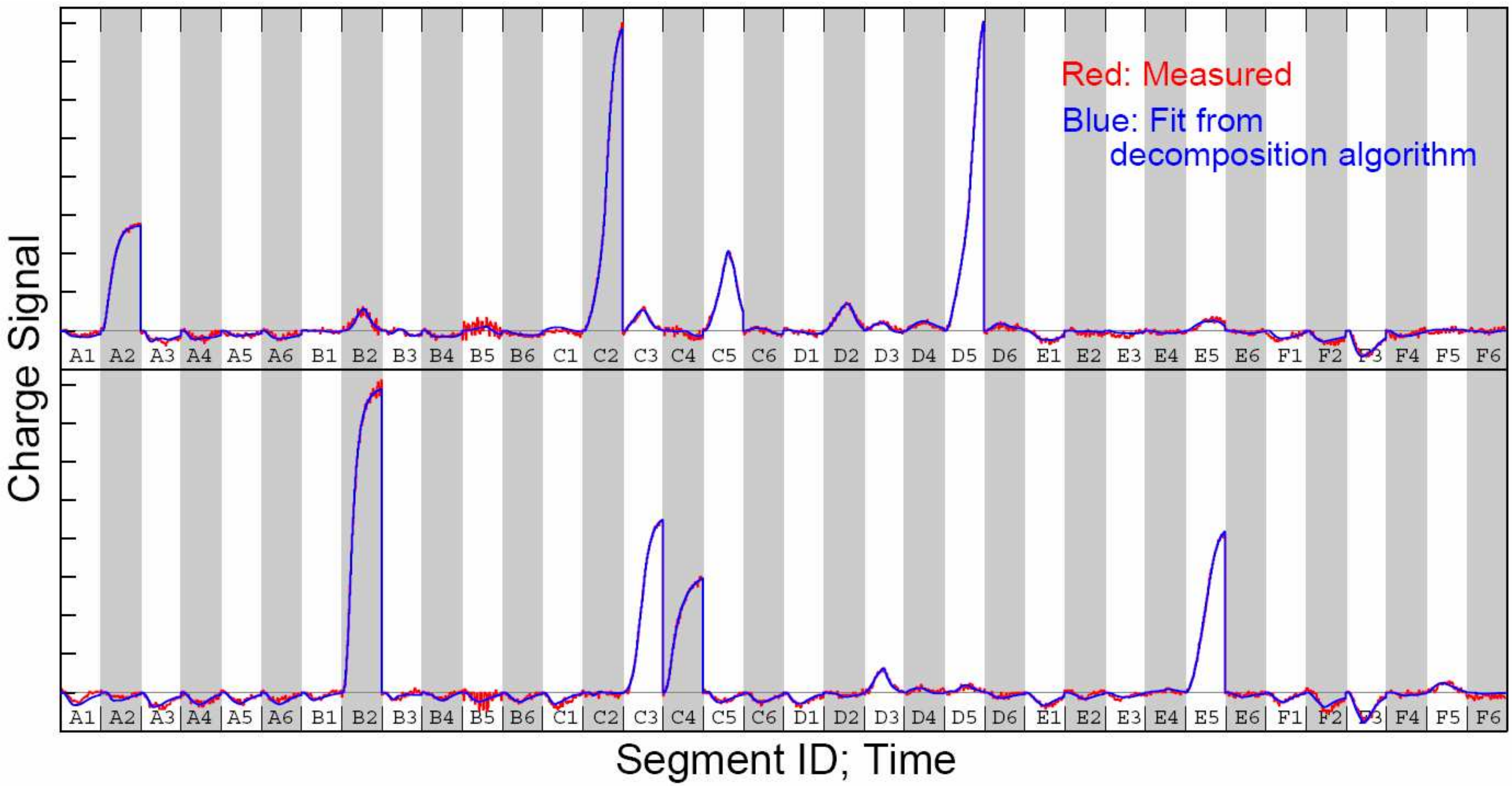
Status of GRETINA signal decomposition algorithm

- ✓ Three orders of magnitude improvement in CPU time
- ✓ Much improved fits (χ^2 values)
- ✓ Can now handle any number of hit detector segments, each with up to two interactions
- ✓ Never fails to converge
- ✓ Developed new optimized, irregular grid for the basis signals
- ✓ Incorporated fitting of signal start time t_0
- ✓ Developed method to accurately correct calculated signals for preamplifier response and for two types of cross talk

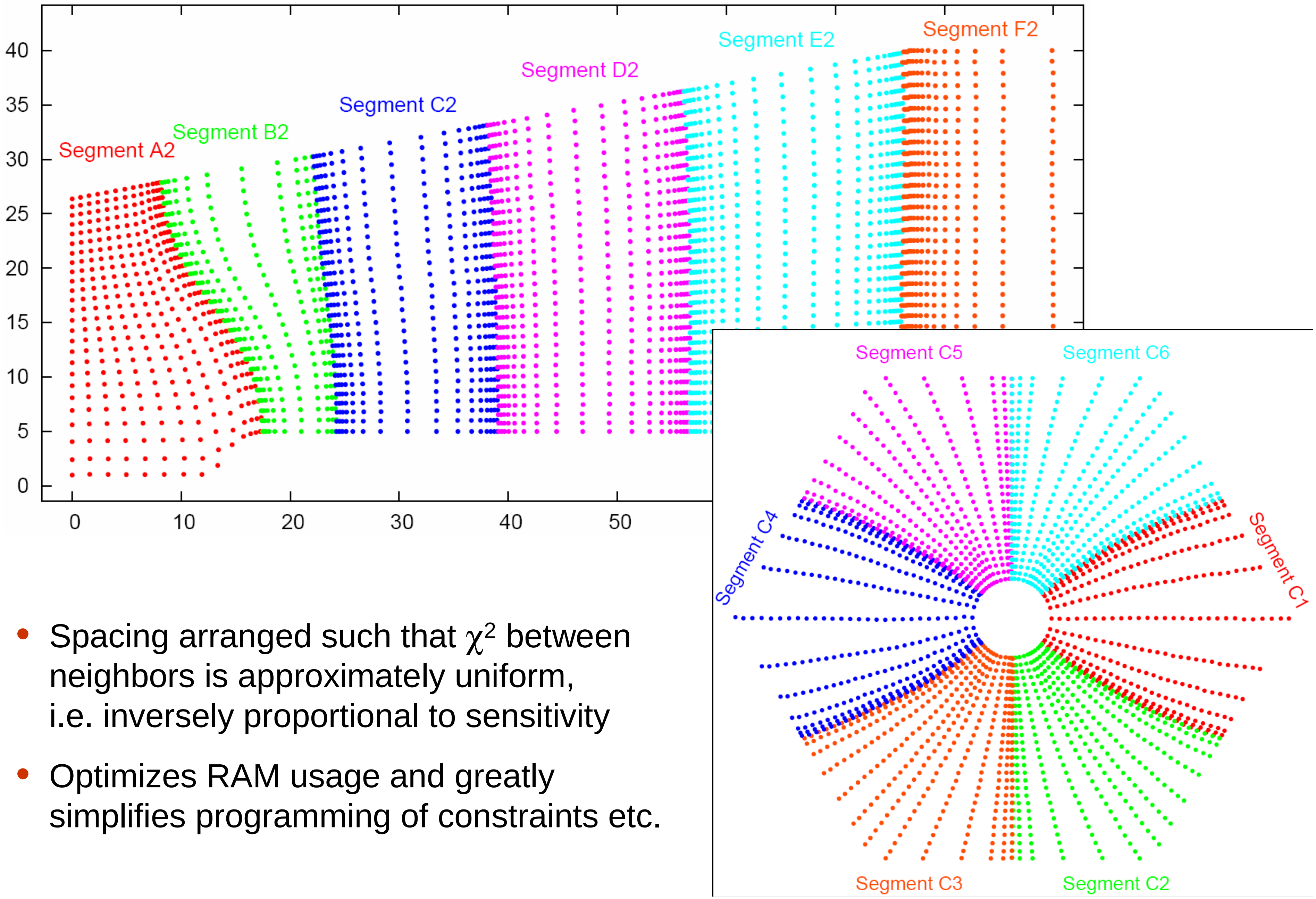
Although some work remains to be done, we have demonstrated that the problem of signal decomposition for GRETINA is solved

Latest Decomposition Algorithm: Excellent Fits

- Red: Two typical multi-segment events measured in prototype triplet cluster
  - concatenated signals from 36 segments, 500ns time range
- Blue: Fits from decomposition algorithm (linear combination of basis signals)
  - includes differential cross talk from capacitive coupling between channels



Optimized Quasi-Cylindrical Grid

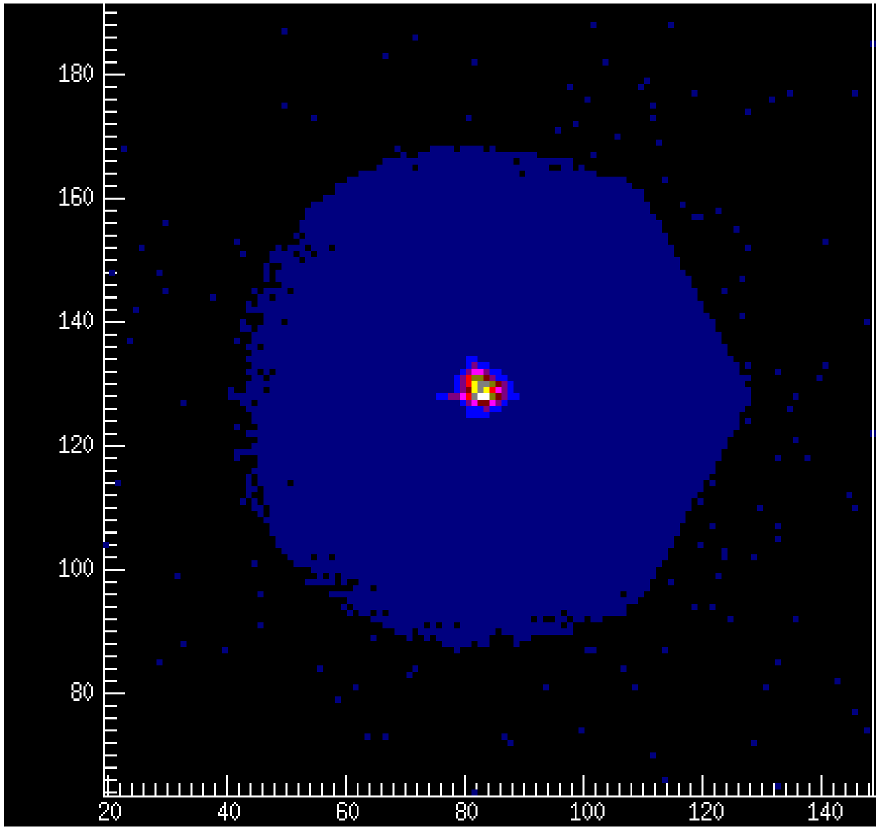


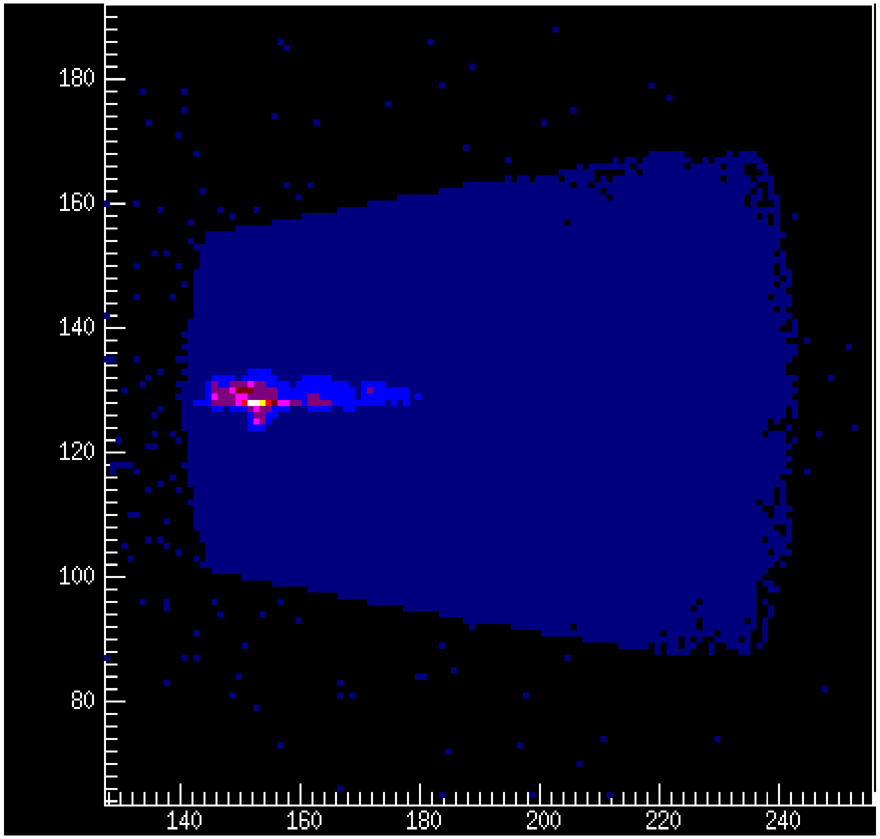
- Spacing arranged such that χ^2 between neighbors is approximately uniform, i.e. inversely proportional to sensitivity
- Optimizes RAM usage and greatly simplifies programming of constraints etc.

Collimated Cs-source test

Pencil beam of 662 keV:

Distribution of deduced interactions points throughout the crystal, from decomposition plus tracking algorithms





Position resolution: σ_x = 1.5 mm; σ_y = 1.7 mm

Singular Value Decomposition

Collaboration with Tech-X Corp.

- Funded under DOE SBIR grant to investigate alternative algorithms

Developed two-step SVD:

- Coarse grid (50 eigenvalues) to localize interaction region, followed by fine grid (200 eigenvalues) over reduced space
- Works perfectly for a single interaction
- Currently tested for up to 3 segments x 2 interactions
- Results are certainly good enough to be used as input for standard least-squares
- < 6 ms / segment / CPU (2GHz G5)

Recent breakthrough:

Speed-up of SVD algorithm by factor 30 to 40 using Graphics Processing Units (GPUs) rather than CPUs.

CD2B / 3B

Approval to start construction of all systems

- Presentations at DOE panel (*Aug. 14-15, 2007*)
- Responded to 12 recommendations from the review panel (*Sept. 6*)
- Energy Systems Acquisition Advisory Board approval granted (*Oct. 30*)
- **Scheduled completion date (CD4) : *Feb. 14, 2011***

Siting

- GRETINA is scheduled for completion by Feb 2011; it is time to begin planning for its utilization
- Workshop in Oct 2007, organized by the GAC
  - "Optimizing GRETINA Science: A workshop dedicated to planning the first rounds of operation."
  - Focused on how to best optimize the physics impact of GRETINA with unstable and stable beams. Also discussed the physics opportunities and infrastructure issues at each lab.
  - Participation and presenation by Susumu Shimoura, U. of Tokyo; expressed interest in hosting GRETINA at RIKEN

Siting

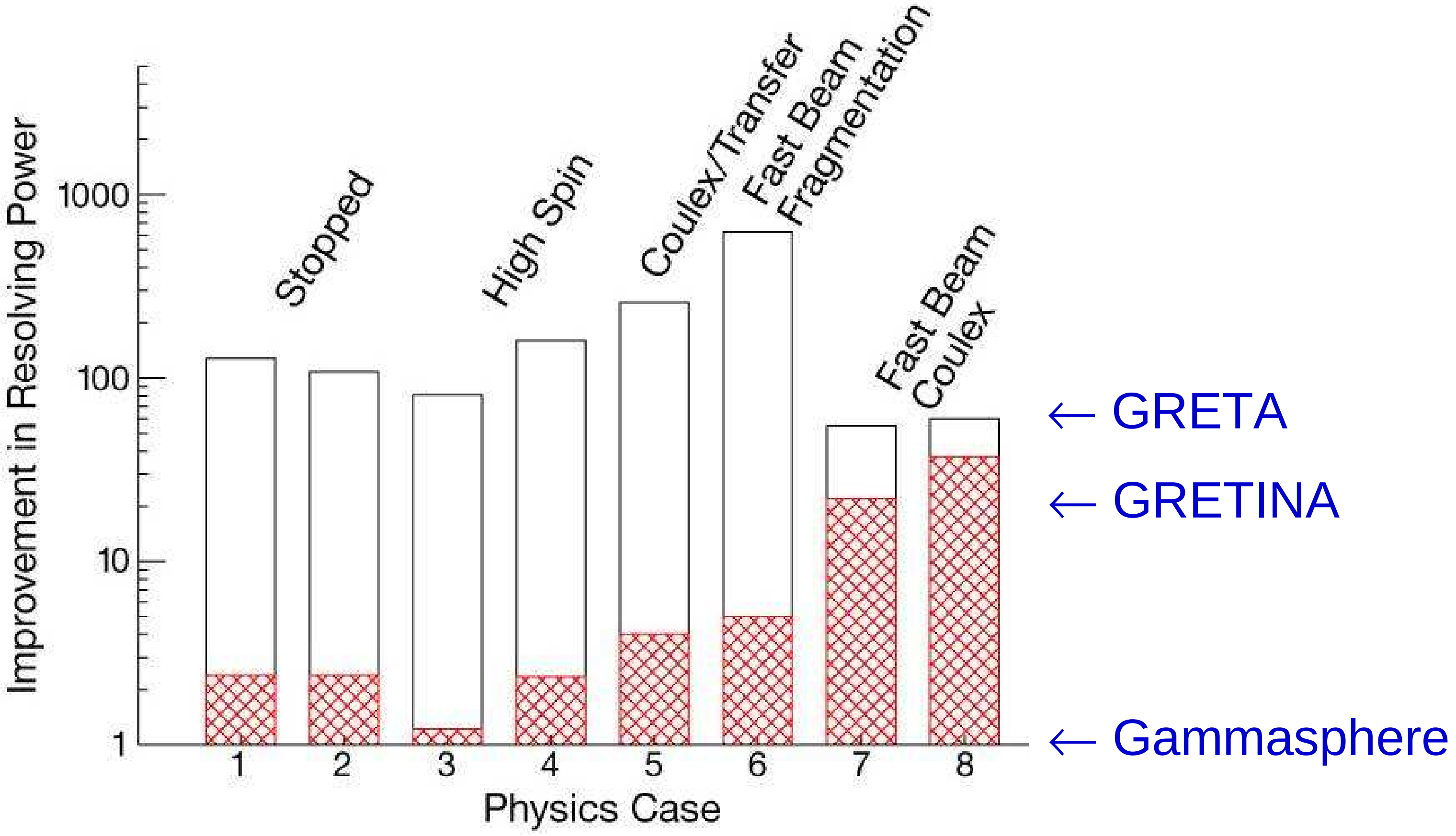
Outcomes of the workshop:

- Unanimous agreement on a plan for the first physics campaigns
- GRETINA should be assembled, tested, and commissioned at LBNL
  - Commissioning runs coupled to the BGS, coordinated by the GAC
  - Will serve as the major debugging phase for GRETINA, and produce important physics results on the spectroscopy of super heavy elements
- Then rotated among the other national laboratories
  - ~ 6 month campaigns at each location
  - Suggested sequence for the first cycle:
    1. MSU - NSCL
    2. ORNL - HRIBF
    3. ANL - ATLAS
- "We look forward to further discussions with our Japanese colleagues and are excited about the possibility of future collaborations."

From GRETINA to GRETA

1π → 4π coverage,   28 → 120 detectors

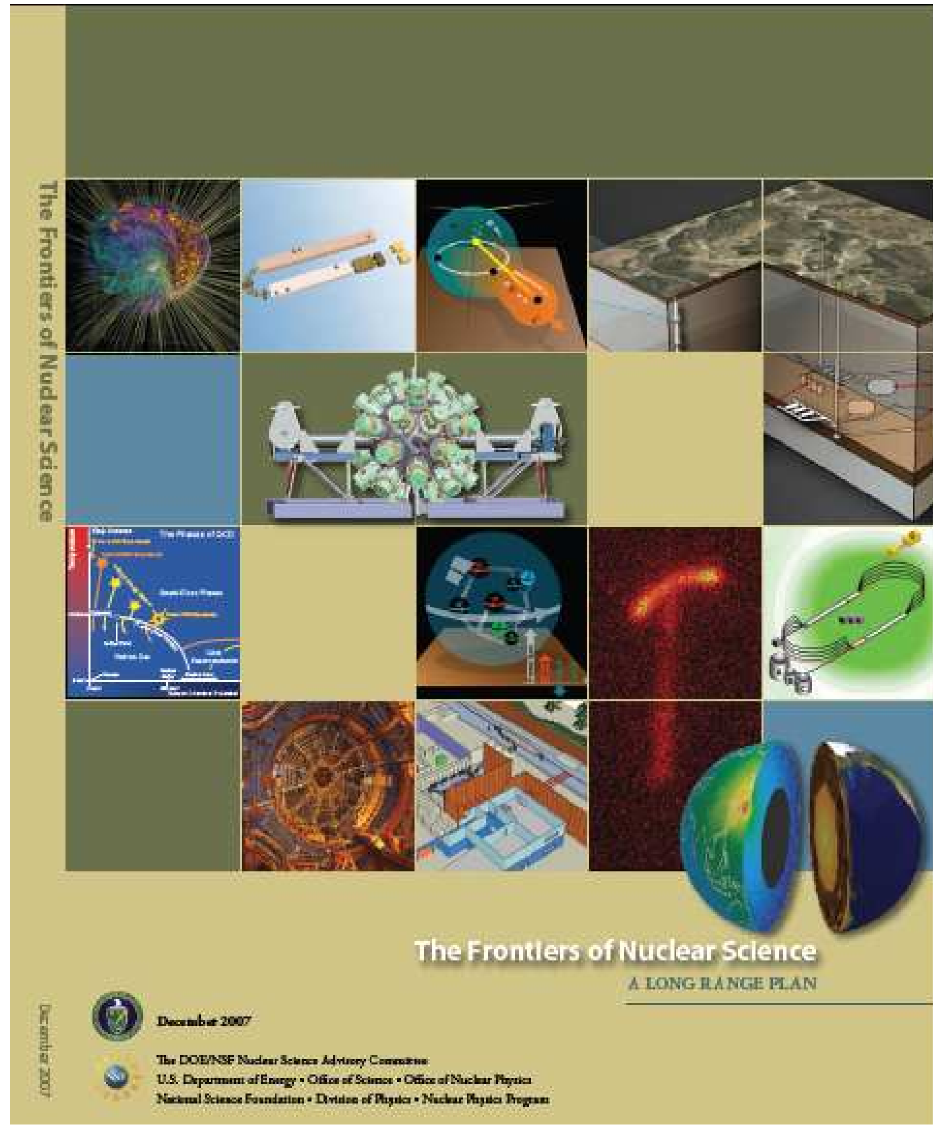
- Greater resolving power by factors of up to 100
- GRETA will be in great demand at the next generation RIB facility   - RIA Facility Workshop,   March 2004



GRETA in the 2007 NSAC Long Range Plan

Gamma-Ray Tracking

"… The construction of GRETA should begin upon successful completion of GRETINA. This gamma-ray energy tracking array will enable full exploitation of compelling science opportunities in nuclear structure, nuclear astrophysics, and weak interactions."



Summary

- ✓ GRETINA design is complete
- ✓ Construction is proceeding

  Received CD2B / 3B approval Oct 2007
- ✓ Scheduled completion date: 14 Feb 2011
- ✓ We have proposed a plan for the first round of physics campaigns
- ✓ GRETA received strong community support in LRP

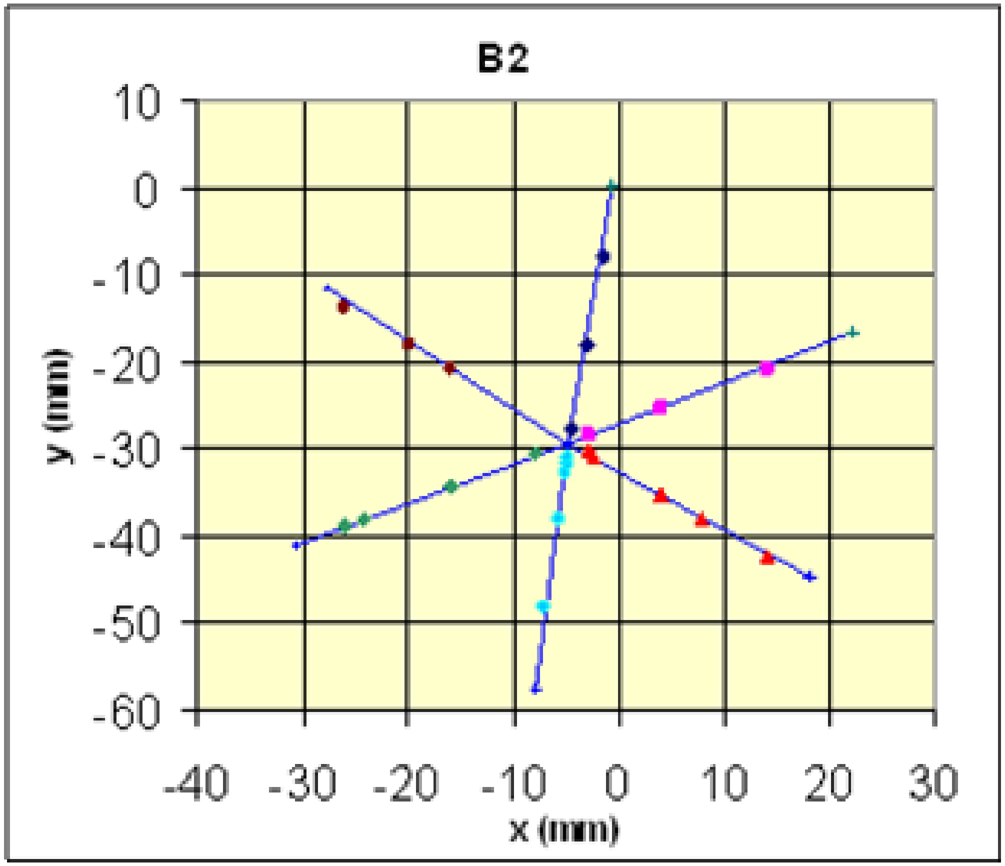
  "… construction of GRETA should begin upon successful completion of GRETINA"

Latest newsletter: http://www.physics.fsu.edu/Gretina/

Join the users group: http://radware.phy.ornl.gov/greta/join.html

Backup Slides

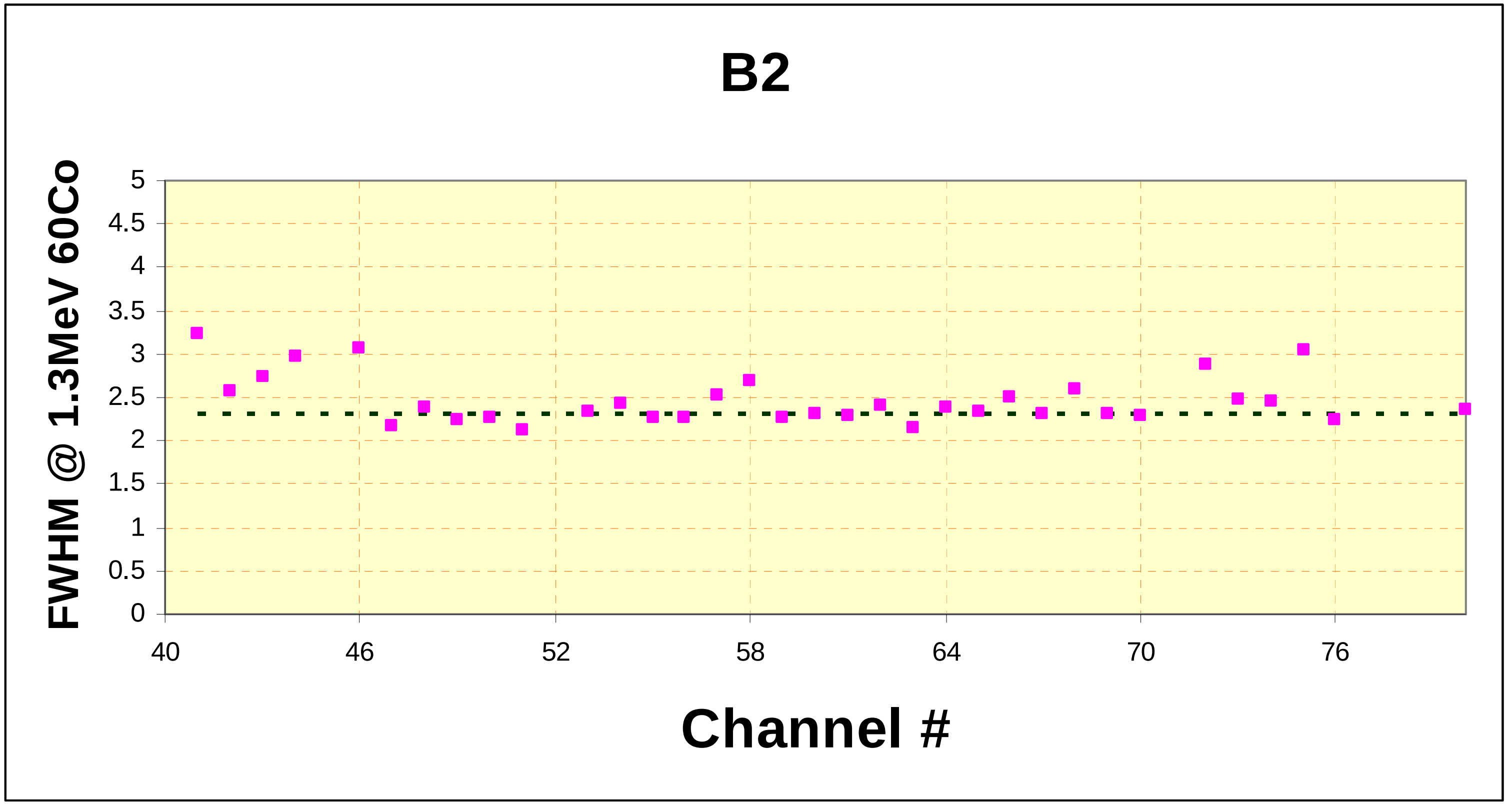
Q1 Front Surface Scan



Best fit to the segmentation lines

- Front segmentation lines are within 0.2 mm of correct position
- Accuracy of measurement is 0.15 mm
- Reproducibility after crystal replacement is 0.2 mm

Q1 Energy Resolution



Energy resolution specifications (keV FWHM)

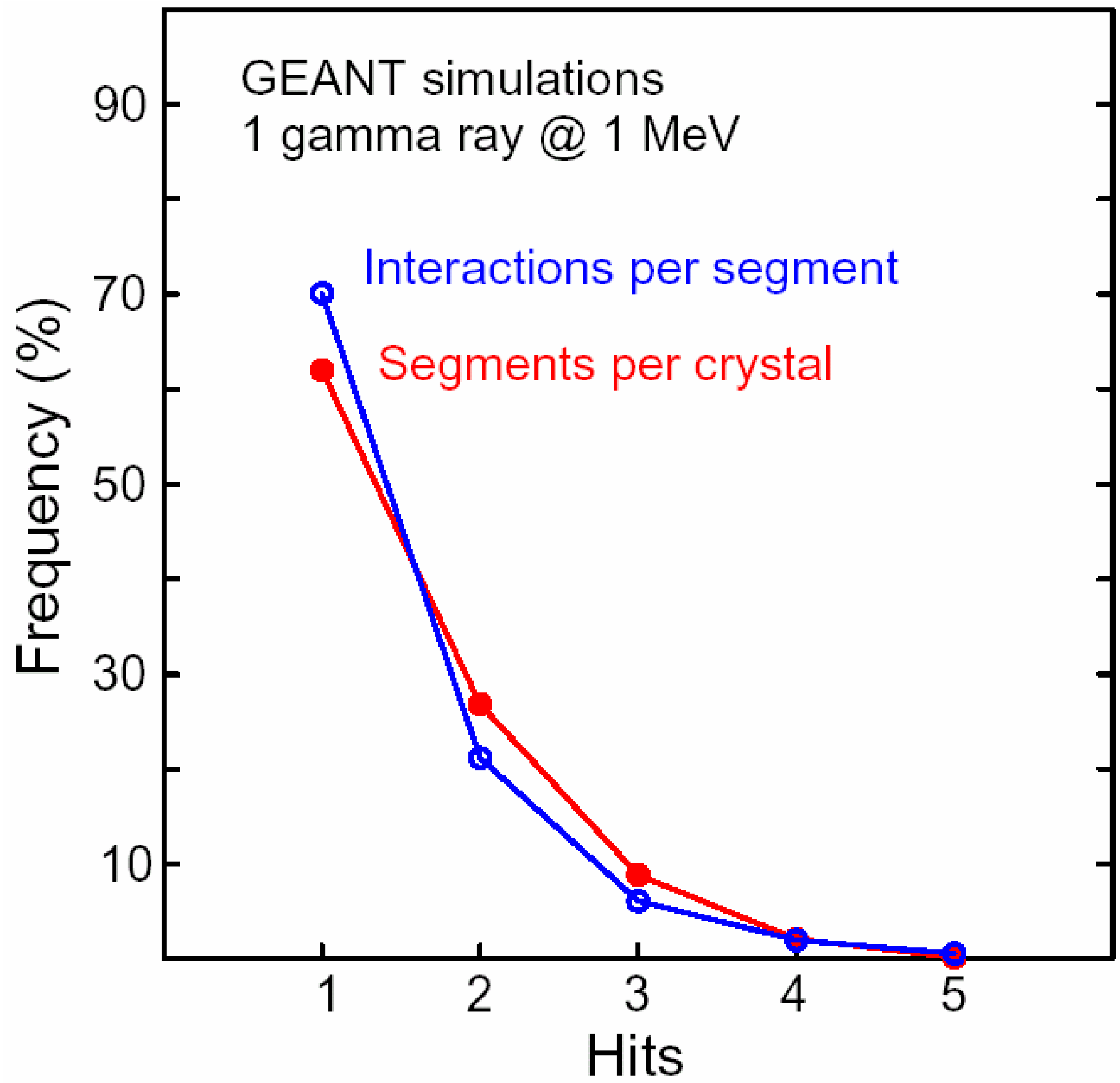
	(mean)	(max.)	
Central Contact	2.25	2.35	at 1332 keV
	1.25	1.35	at 122 keV
Segments		2.3	at 1332 keV
		1.4	at 122 keV

Signal Decomposition

GEANT simulations;
1 MeV gamma into
GRETA

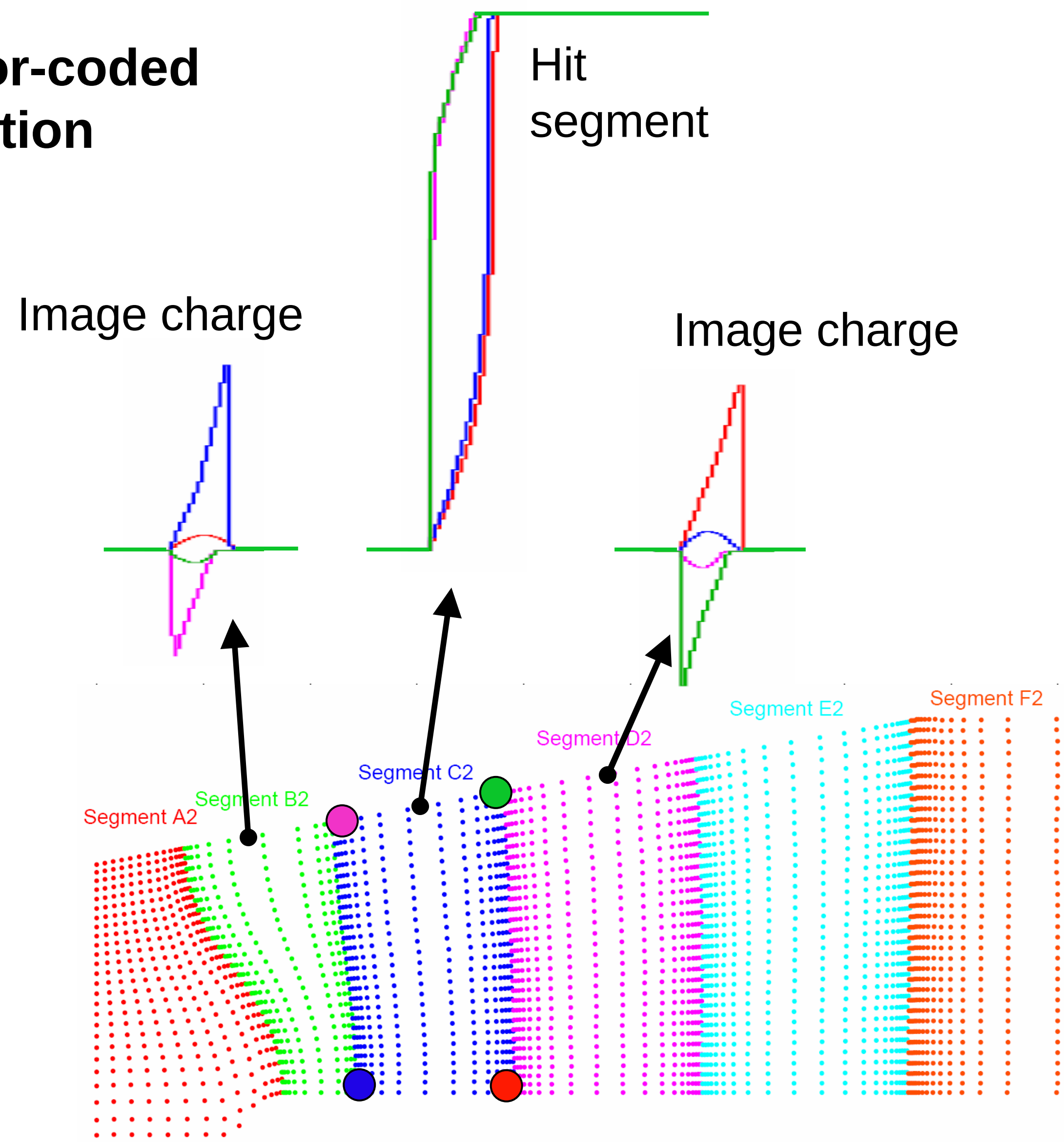
Most hit crystals have
one or two hit segments

Most hit segments have
one or two interactions



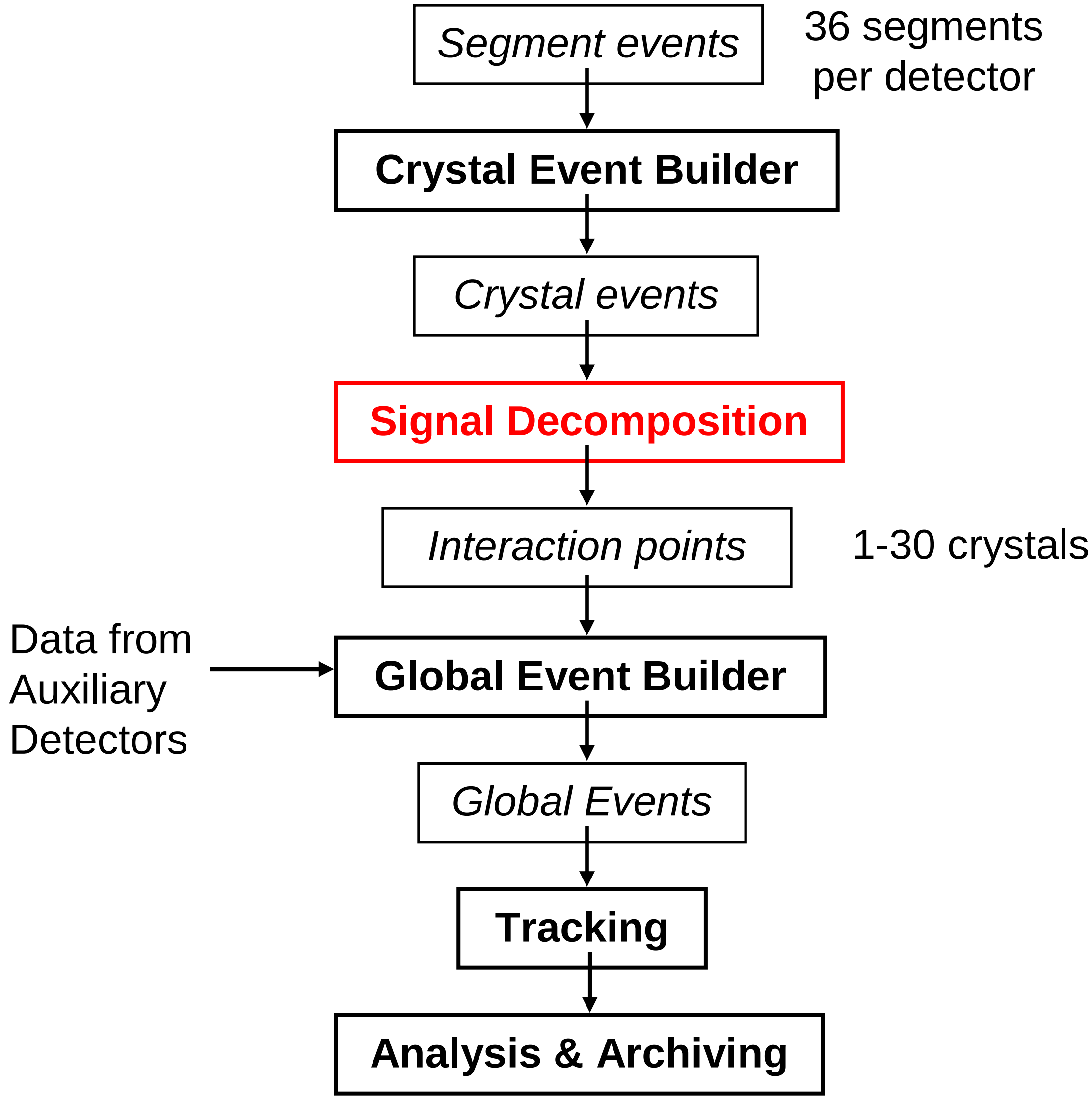
Examples of calculated signals: Sensitivity to position

Signals color-coded for position



Signal Decomposition

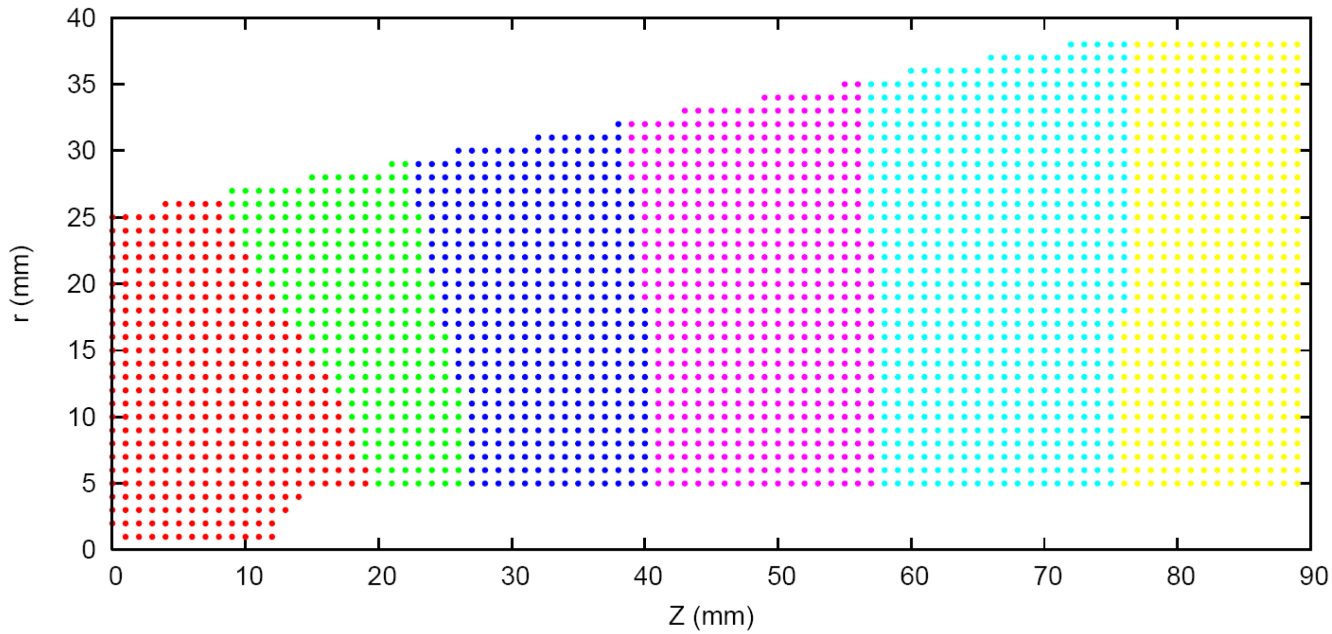
Event Building
Data Flow:



Quasi-Cylindrical Grid for GRETINA Signal Decomposition

- The old Signal Decomposition algorithm for GRETINA made use of a Cartesian grid.

Different colors show active regions for the different segments



- An irregular quasi-cylindrical grid has several important advantages:
  - The possibility to optimize the spacing of points in the grid based on separation in "Chi-squared space"
  - Reducing the number of grid points results in improved speed
  - Constructing the grid around the real segment volumes allows much better and faster constraints to be programmed into the least-squares search algorithms

Signal Decomposition

GRETINA signal decomposition algorithm

- Was the part of GRETINA that entailed the largest technological risk
- Current algorithm is a hybrid
  - *Adaptive Grid Search with Linear Least-Squares (for energies)*
  - *Non-linear Least-Squares (a.k.a. SQP)*
- Have also been developing *Singular Value Decomposition*
  - Plan to incorporate SVD into final algorithm for $N_{seg} > 2$

CPU time required goes as

Adaptive Grid Search : ~ $O(300^{n})$

Singular Value Decomp : ~ $O(n)$

Nonlinear Least-Squares : ~ $O(n + \delta n^2)$

for n interactions

Why is it hard?

Very large parameter space to search

- Average segment ~ 6000 mm^3, so for ~ 1 mm position sensitivity
  - two interactions in one segment: ~ 2 x 10^6 possible positions
  - two interactions in each of two segments: ~ 4 x 10^{12} positions
  - two interactions in each of three segments: ~ 8 x 10^{18} positions

  PLUS energy sharing, time-zero, …

Underconstrained fits, especially with > 1 interaction/segment

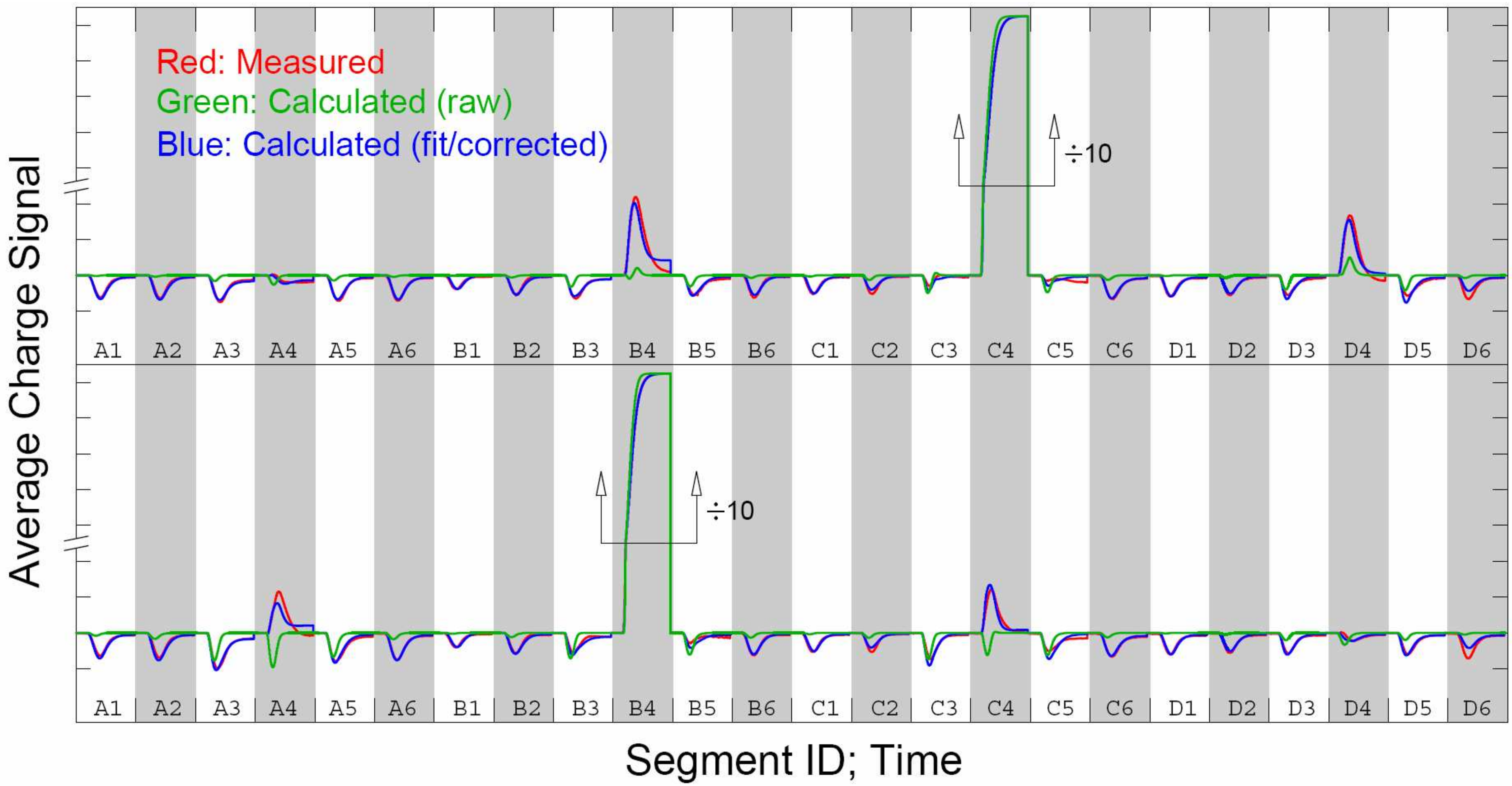
- For one segment, the signals provide only
  ~ 9 x 40 = 360 nontrivial numbers

Strongly-varying, nonlinear sensitivity

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

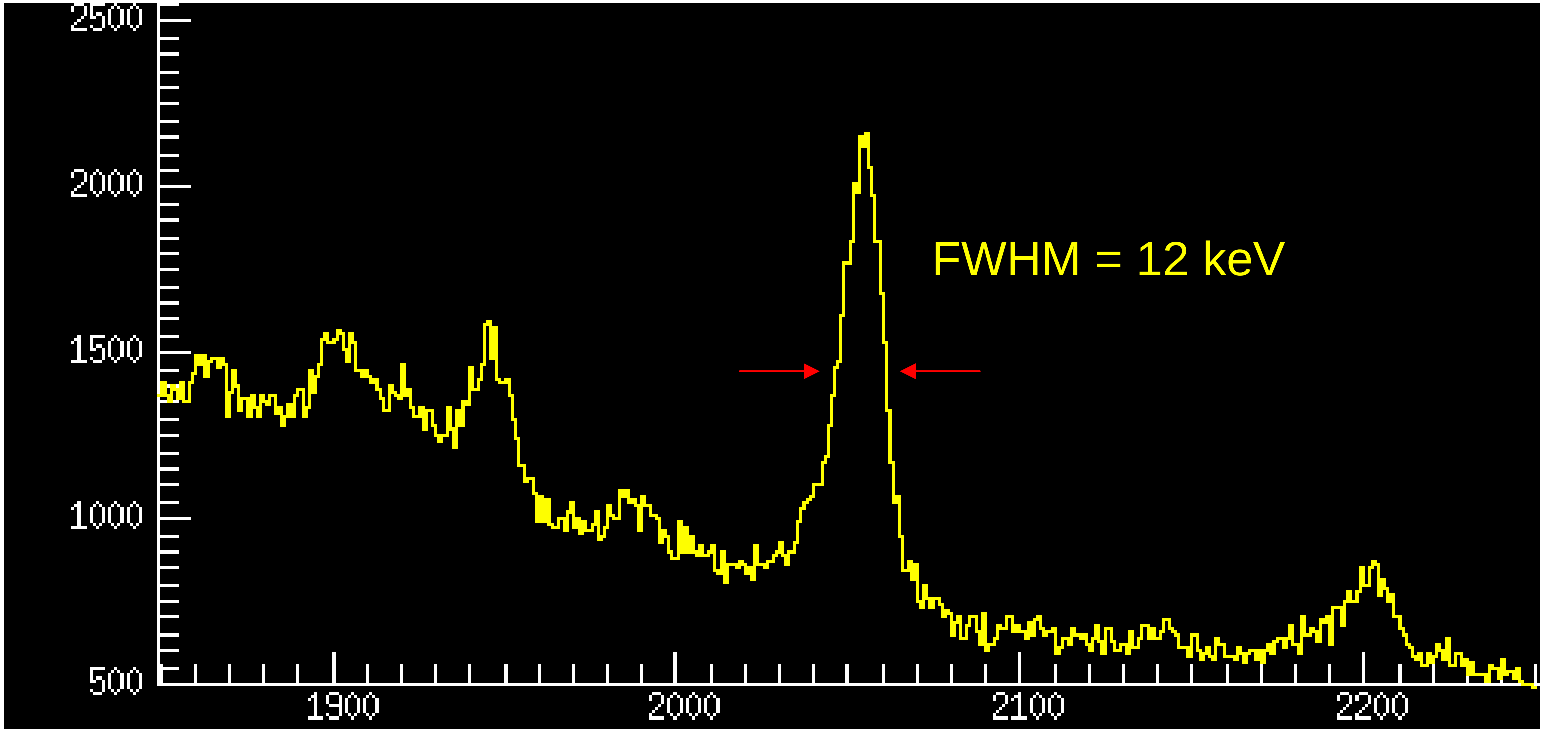
Fitting to Extract Cross-Talk Parameters

- 36 “superpulses” : averaged signals from many single-segment events (red)
- Monte-Carlo simulations used to generate corresponding calculated signals (green)
- 996 parameters fitted (integral and differential cross-talk, delays, rise times) (blue)
- Calculated response can then be applied to decomposition “basis signals”



In-Beam test

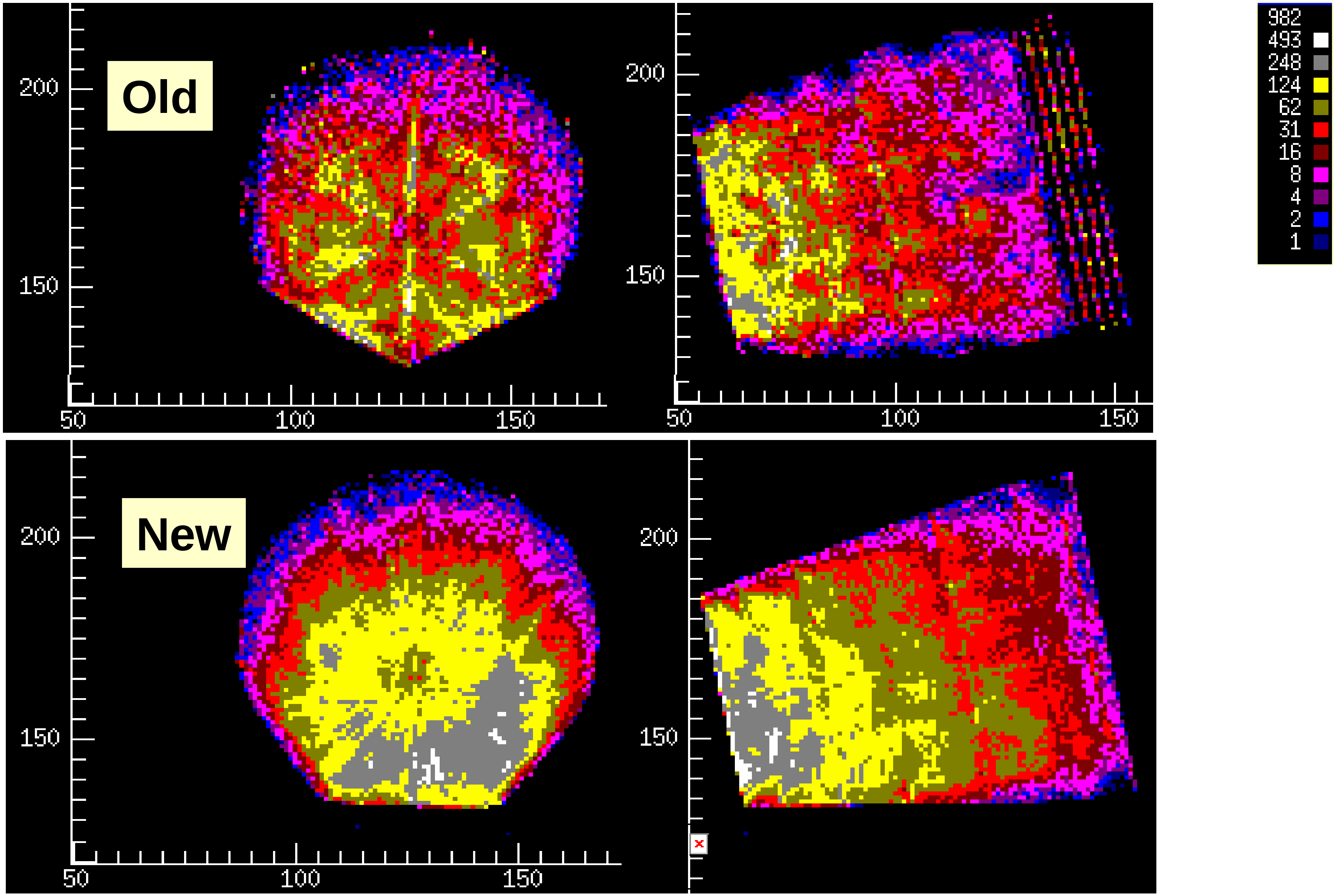
Crystal A of prototype-III triple; new grid and basis



Derived average effective position resolution: σ_x = 2.1 mm in 3D

Comparison – Old Basis and Code vs. New

Distribution of deduced interactions points throughout the crystal



Signal Decomposition

Linear Least-Squares

For two interactions of energies e_i, e_j at locations i and j, the calculated signal is $C_{kt} = (e_i s_{ikt} + e_j s_{jkt})$ where k is the segment and t the time step. s_{ikt} is the basis signal calculated at point i.

If the observed signal is O_{kt}

$$\chi^2 = \sum_{kt} \frac{(O_{kt} - C_{kt})^2}{\sigma_{kt}^2} = \frac{\sum_{kt}(O_{kt} - e_i s_{ikt} - e_j s_{jkt})^2}{\sigma^2} \quad (1)$$

where $\sigma_{kt} = \sigma$ is the uncertainty (noise) in O_{kt}, assumed independent of k, t.

We want a minimum in χ^2, *i.e.*

$$\frac{\partial \chi^2}{\partial e_i} = \frac{\partial \chi^2}{\partial e_i} = 0 \quad (2)$$

$$\frac{\partial \chi^2}{\partial e_i} = \frac{2\sum_{kt}(O_{kt} s_{ikt} - e_i s_{ikt}^2 - e_j s_{ikt} s_{jkt})}{\sigma^2} = 0 \quad (3)$$

Signal Decomposition

Thus we get two equations in two unknowns:

$$\sum_{kt} O_{kt} s_{ikt} - e_i \sum_{kt} s_{ikt}^2 - e_j \sum_{kt} s_{ikt} s_{jkt} = 0 \tag{4}$$

$$\sum_{kt} O_{kt} s_{jkt} - e_j \sum_{kt} s_{jkt}^2 - e_i \sum_{kt} s_{ikt} s_{jkt} = 0 \tag{5}$$

We can *precalculate*

$$\sum_{kt} s_{ikt}^2$$

and

$$\sum_{kt} s_{ikt} s_{jkt}$$

once for all events, and

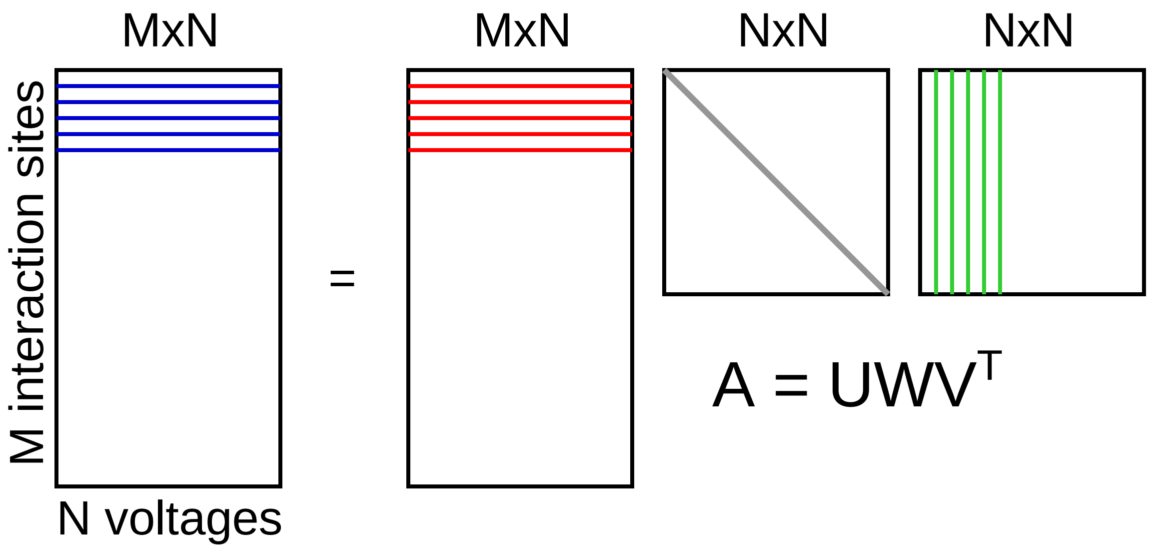
$$\sum_{kt} O_{kt} s_{jkt}$$

once per event.

Singular Value Decomposition

Very roughly:

- The full signal -vs.- grid position matrix can be decomposed into the product of three matrices, one of which contains the correlations (eigenvalues).



$$A = UWV^T$$

Singular Value Decomposition

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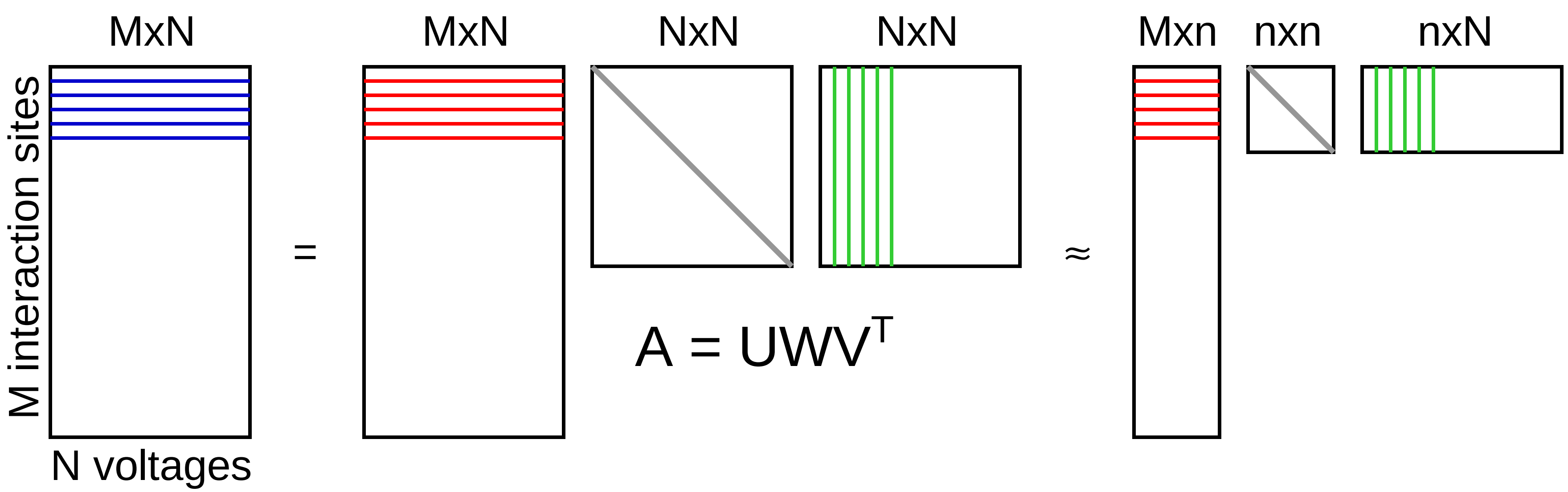
- By neglecting the small eigenvalues, the length of the signal vectors (and hence computation with them) can be greatly reduced.



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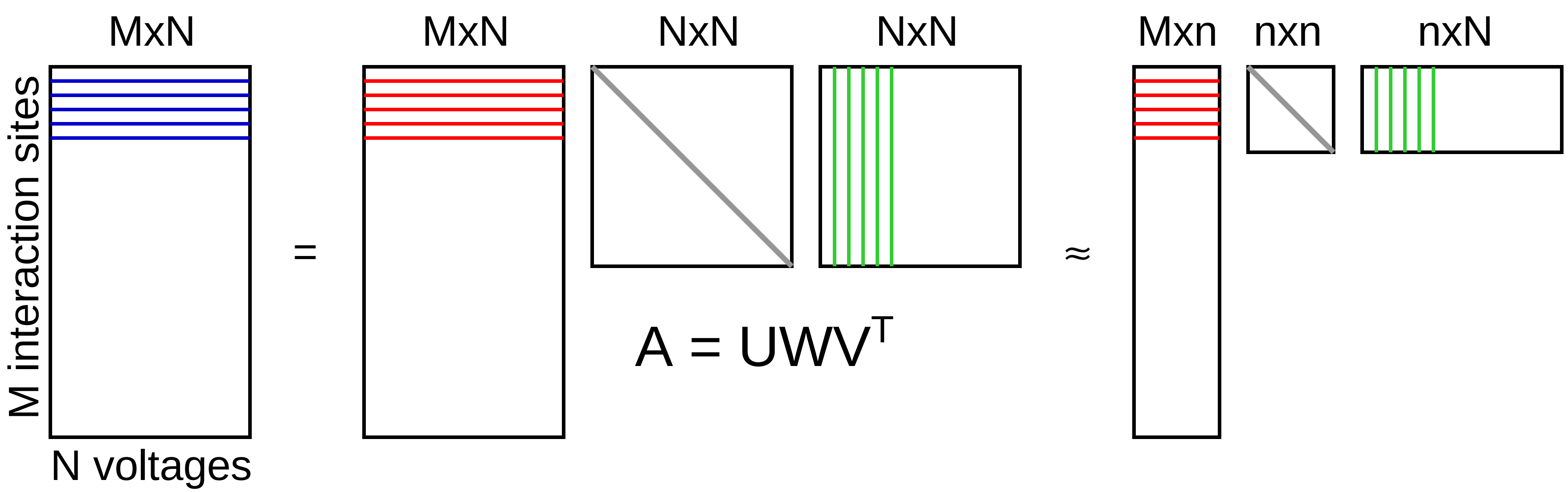
- The more eigenvalues kept, the higher the quality of the fit.



Singular Value Decomposition

Very roughly:

- The full signal -vs.- grid position matrix can be decomposed into the product of three matrices, one of which contains the correlations (eigenvalues).
- By neglecting the small eigenvalues, the length of the signal vectors (and hence computation with them) can be greatly reduced.
- The more eigenvalues kept, the higher the quality of the fit.
- Measured signals can be compressed the same way as, and then compared to, the calculated library signals.
- Different similarity measures can be used to emphasize different aspects.

Dot Product

$$x.y = \sum_{i=1}^{N} x_i y_i$$

Cosine

$$\cos(\theta_{xy}) = \frac{x.y}{|x||y|}$$

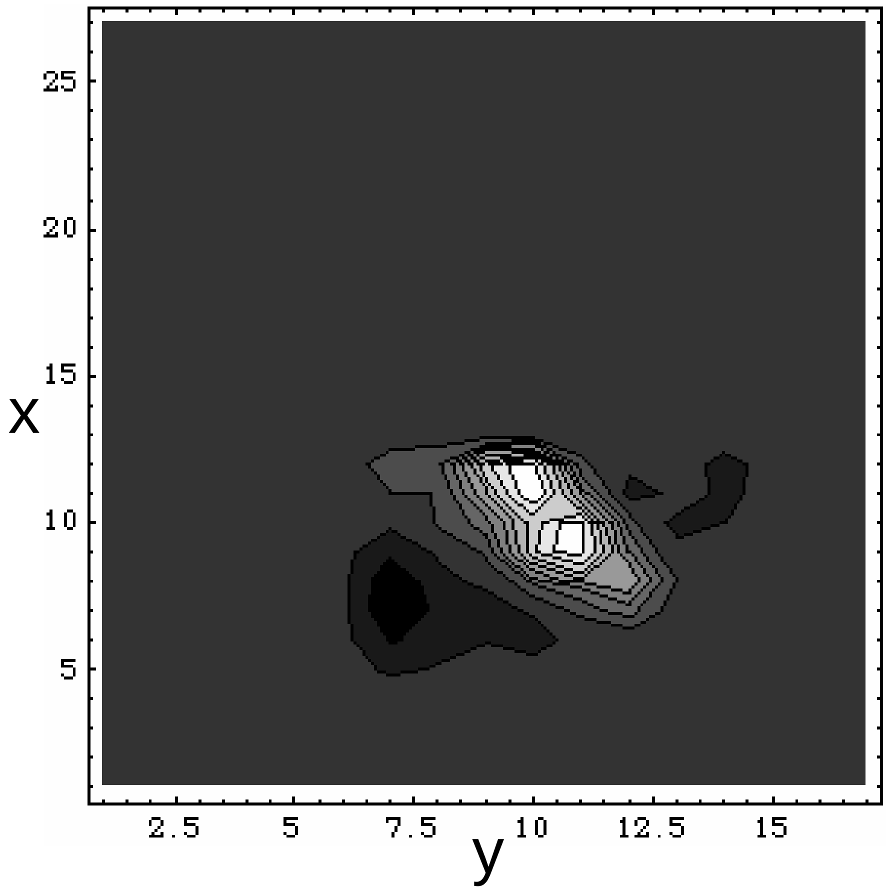
Euclidean Distance

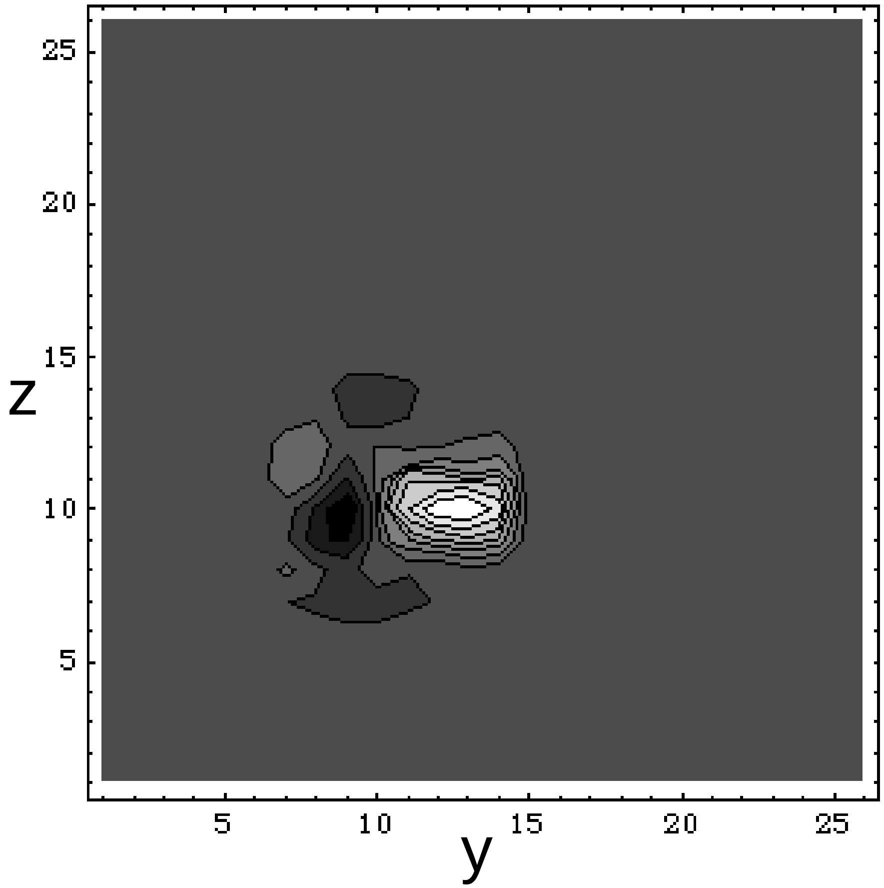
$$euclid(x, y) = \sqrt{\sum_{i=1}^{N} (x_i - y_i)^2}$$

New SVD Results

2D projections of SVD amplitudes

Interaction sites at (13,9,11) and (8,11,11)





Signal Decomposition

Adaptive grid search fitting:

Energies e_i and e_j are constrained, such that $0.1(e_i+e_j) \leq e_i \leq 0.9(e_i+e_j)$

Once the best pair of positions (lowest χ^2) is found, then all neighbor pairs are examined on the finer (1x1x1 mm) grid. This is 26x26 = 676 pairs. If any of them are better, the procedure is repeated.

For this later procedure, the summed signal-products cannot be precalculated.

Finally, nonlinear least-squares (SQP) can be used to interpolate off the grid. This improves the fit ~ 50% of the time.

Signal Decomposition

Some numbers for adaptive grid search:

~35000 grid points in 1/6 crystal (one column, 1x1x1 mm)

2x2x2mm (slices 1-3) or 3x3x3 mm (slices 4-6) coarse grid gives
N ≤ 600 course grid points *per segment.*

For two interactions in one segment, have $N(N-1)/2 \leq 1.8 \times 10^5$ pairs of points for grid search. This takes ~ 3 ms/cpu to run through.

But $(N(N-1)/2)^2 \sim 3.2 \times 10^{10}$ combinations for two interactions in each of 2 segments; totally unfeasible!

Limit N to only 64 points; then $(N(N-1)/2)^2 \sim 4 \times 10^6$

-- this may be okay. But 4 unknowns will require matrix inversion.

But $(N(N-1)/2)^3 \sim 8 \times 10^9$ combinations for two interactions in each of 3 segments; still impossible.

Signal Decomposition

Remaining To-Do List

- Improve understanding of charge carrier mobilities
- Allow for occasional three interactions per segment
- Incorporate Singular Value Decomposition

  e.g. SVD $\rightarrow$ least-squares

  SVD $\rightarrow$ grid search $\rightarrow$ least-squares
- Develop better metrics and examine failure modes in detail
- Try to determine basis signals directly from observed calibration source signals, either collimated or uncollimated

Acknowledgements

Karin Lagergren (ORNL / UTK)

- Signal calculation code in C
- Optimized pseudo-cylindrical grid

I-Yang Lee

- Original signal calculation code

M. Cromaz, A. Machiavelli, P. Fallon, M. Descovich, J. Pavan, …

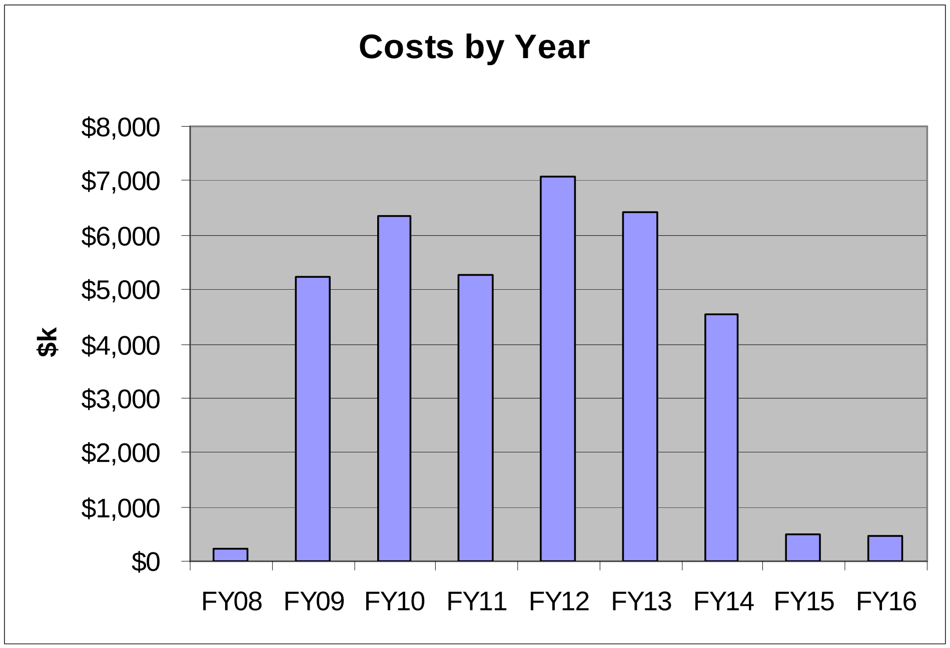
- In-beam data analysis, simulations, electric field calculations, etc.

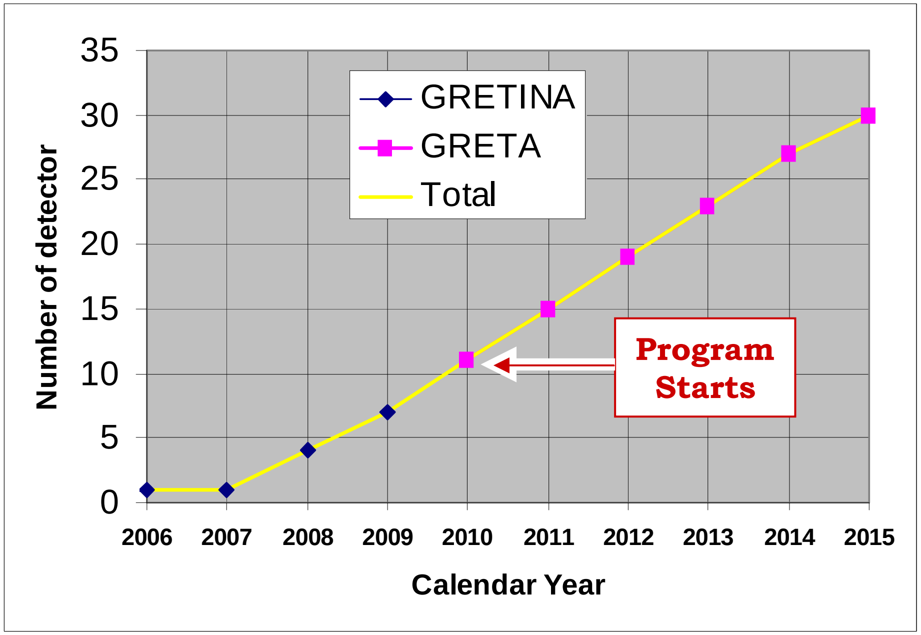
Tech-X Corp, especially Isidoros Doxas

- SVD development

GRETA Cost and Schedule

Start FY08, complete FY16





- As fast as allowed by detector production schedule.
- No gap between GRETINA and GRETA
- Physics program to start 2011 with continued growth of capabilities.
- Match FRIB schedule, GRETA will be ready when FRIB starts
- Competing European project AGATA plan to be completed in 2016