GRETINA

A. O. Macchiavelli
Lawrence Berkeley National Laboratory

Many Thanks to
I-Yang Lee, P. Fallon, M. Descovich and S. Ettenauer

SLAFNAP6
IGUAZU - ARGENTINA
October 3-7, 2005
Outline

- Introduction
- Concept of $\gamma$-ray tracking
  - Impact on spectroscopy
- Proof of principle
  - Segmented detectors
  - Electronics
  - Position reconstruction
  - In-beam results
- GRETINA
  - Design and expected performance
  - Status of the project
- Summary and conclusions
Gamma-ray spectroscopy has played a major role in the study of the atomic nucleus.

Development of new detectors and techniques have always led to discoveries of new and unexpected phenomena.
“Spectroscopic history” of $^{156}$Dy
“Effective” Energy resolution ($\delta E$), Efficiency ($\varepsilon$), Peak-to-total (P/T) Plus auxiliary devices

Weakest branch that can be resolved
Resolving power - Figure of Merit

- Resolving power

\[ \alpha (\log) \]

- Fold

\[ \frac{1}{T^f} \quad \frac{(N/No)/\varepsilon^f}{f^*} \]

\[ \alpha^* \]

\[ f^* \]
Evolution over the years
Germanium Semi-conductor Detectors

Best energy resolution

Conduction band

Valence band

Intrinsic energy resolution determined by statistics of charge carriers ~
Moving nucleus

\[ \theta \]

\[ V \pm \Delta V \]

\[ \Delta \theta_N \]

\[ \Delta \theta_D \]

\[ \gamma \text{-ray detector} \]

**Broadening of detected gamma ray energy due to:**

- Spread in speed \( \Delta V \)
- Distribution in the direction of velocity \( \Delta \theta_N \)
- Detector opening angle \( \Delta \theta_D \)

**Need accurate determination of** \( V \) **and** \( \theta \).

**Position sensitive** \( \gamma \)-ray detector and particle detector
Doppler Broadening

$^{130}\text{Te} + ^{58}\text{Ni}$ 100MeV/A 100mg/cm$^2$

- Target
- Position
- Intrinsic

$\frac{\text{FWHM}}{E\gamma}$ (%)

$\theta$ (deg.)
Compton Suppression

Improve peak-to-total ratio

Peak/Total = 20%

P/T=60%

Compton suppressor

Veto
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of modules</td>
<td>110</td>
</tr>
<tr>
<td>Ge Size</td>
<td>7cm (D) × 7.5cm (L)</td>
</tr>
<tr>
<td>Distance to Ge</td>
<td>25 cm</td>
</tr>
<tr>
<td>Peak efficiency</td>
<td>9% (1.33 MeV)</td>
</tr>
<tr>
<td>Peak/Total</td>
<td>55% (1.33 MeV)</td>
</tr>
<tr>
<td>Resolving power</td>
<td>10,000</td>
</tr>
</tbody>
</table>
Towards the “Ultimate” Ge Array

- Compton Suppressed Ge
- Ge Sphere
- Gamma Ray Tracking

\[ N = 100 \]
\[ N \Omega \varepsilon = 0.1 \]
Efficiency limited

\[ N = 1000 \text{ (summing)} \]
\[ N \Omega \varepsilon = 0.6 \]
Too many detectors

\[ N = 100 \]
\[ N \Omega \varepsilon = 0.6 \]
Segmentation
**Gamma-ray Tracking**

Pulse shape analysis in segments

⇒ 3D position of interaction points

Tracking of photon interaction points

⇒ energy and position of γ-ray

---

Gamma-ray tracking detectors

I.Y. Lee

Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

GRETA: utilizing new concepts in γ-ray detection


Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
## Advantages of $\gamma$-ray Tracking

*(In particular for Radioactive Beams)*

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>High position resolution</td>
<td>Large recoil velocity</td>
</tr>
<tr>
<td>High efficiency</td>
<td>- Fragmentation and Inverse reactions</td>
</tr>
<tr>
<td>High peak to background</td>
<td>Low beam intensity</td>
</tr>
<tr>
<td>High counting rate</td>
<td>High background rate</td>
</tr>
<tr>
<td>Background rejection</td>
<td>- Beam decay</td>
</tr>
<tr>
<td></td>
<td>- Beam impurity</td>
</tr>
</tbody>
</table>
Physics opportunities with a $4\pi$ array GRETA

- Resolving power: $10^7$ vs. $10^4$
  - Cross sections down to $\sim 1$ nb
  - Most exotic nuclei
  - Heavy elements (e.g. $^{253,254}$No)
  - Drip-line physics
  - High level densities (e.g. chaos)

- Efficiency (high energy)
  (23% vs. 0.5% at $E_\gamma = 15$ MeV)
  - Shape of GDR
  - Studies of hypernuclei

- Efficiency (slow beams)
  (50% vs. 8% at $E_\gamma = 1.3$ MeV)
  - Fusion evaporation reactions

- Efficiency (fast beams)
  (50% vs. 0.5% at $E_\gamma = 1.3$ MeV)
  - Fast-beam spectroscopy with low rates - $\rightarrow$ RIA

- Angular resolution (0.2° vs. 8°)
  - N-rich exotic beams
    - Coulomb excitation
  - Fragmentation-beam spectroscopy
    - Halos
    - Evolution of shell structure
    - Transfer reactions

- Count rate per crystal
  (100 kHz vs. 10 kHz)
  - More efficient use of available beam intensity

- Linear polarization

- Background rejection by direction
Signal Generation
weighting potential

$E_x$ weighting field

V=0

V=1
\[ \Delta \Phi(r,z,\varphi) = -\rho(z)/\varepsilon \]
\[ E = -\nabla \Phi \]

\[ V = \mu(T,E,\zeta,\Theta) E \]
\[ \zeta: \text{angle between drift direction and crystal orientation} \]
\[ \Theta: \text{angle between } E \text{ and crystal orientation} \]

\[ \Delta q = q_0 \cdot E \cdot v \cdot \Delta t / U_0 \]
Technical Challenges

- Advances in detector segmentation
- Electronics development
  - Low noise high bandwidth preamplifier
  - Rapid sampling, high resolution pulse digitizer
- Signal analysis algorithm
- Tracking algorithm
- Computing power for on-line processing
Segmented Germanium Detectors

SeGA MSU

ANL - GARBO

EXOGAM
Segmented Germanium Detectors

MINIBALL

TIGRESS

AGATA

GRAPE
Prototype detectors at LBNL

GRETA: 36-fold Segmented Prototype Detector

PII

PIII

LBNL Preamplifier

Energy Resolution vs. # of Segments
Segments and segment size

![Graph showing segments and segment size](image)
Pre-Amp

Eurisys PSC823
FET IF1320
Gain 200mV/MeV
Rise Time ～40nsec
Decay Time 50μsec
Power 50mW

Performance with detector:  Energy resolution 1.15 keV Am
2.5 keV Co
Noise level 4 keV (20MHz)
Digitizer and Data Acquisition

- LBNL VME 8-channel digital signal processing boards (100 MHz - 12 bit)
- Individual or Common clock
- Programmable trigger
- FPGA Energy (P/Z)
- FPGA CFD timing
- Up to 10μsec data samples

- Acquisition rate > 8 Mbytes/sec
- Data stored to a redundant disk array (1Tbytes) over Gigabit network
- Suite of offline analysis programs
Detector characterization
At the hospital

The Doctors are in

UC Berkeley Medical Center
Singles Scan

Am source scans to determine position of segment boundaries.

114$\mu$Ci Am source (60keV)
Vertical and horizontal collimators (2mm) to define x,y and z
Automatic scan on pre-determined x,y,z pattern.
1min per point
Singles Scan

Deviation from nominal values

dX = 0.1 +/- 0.1 mm

dY = 0.2 +/- 0.1 mm

\[ d\alpha = 0 +/- 1 \text{ deg} \]
Crystal Orientation

Gate on Am

Energy central contact

Drift Time [ns]

Angle

(110)

(100)

215

230

245
Coincidence Scans

Pulse shape measurement using a prompt coincidence requirement between GRETINA and Clover(s)

1mCi $^{137}$Cs source
Vertical and slit collimators to define 90 deg scattering
500nsec overlap
Coincidence trigger ~ 200 events/day
Coincidence Scans

- Clover
- 2 crystals

\[ E_{\text{clover}} + E_A = 662 \text{keV} \]
Pulse Shapes

~ 200 events

Δx = 5mm
Pulse Shapes

Signals in Segment B4

Measurement at small radius
\( x=14, \ y=4.5, \ \Delta z=1.5 \ \text{mm} \)

Measurement at large radius
\( x=22, \ y=4.5, \ \Delta z=1.5 \ \text{mm} \)

Calculation in center
Calculation w. averaging

I.) \( \Delta x=8\text{mm} \)

\( \Rightarrow \Delta (\text{B3-ampl.})=35\% \)

II.) Amplitude spread

\( \Rightarrow 1.5\text{mm}^3 \text{ collimator} \)
A γ-ray tracking algorithm for the GRETA spectrometer


Lawrence Berkeley National Laboratory, University of California, Berkeley, CA 94720, USA
First step – cluster finding

Any two points with $\theta < \theta_p$ are grouped into the same cluster.
Second step – Tracking of Compton scattering interaction points

Problem: $3! = 6$ possible sequences

Assume: $E_\gamma = E_{e_1} + E_{e_2} + E_{e_3}$; $\gamma$-ray from the source

Sequence with the minimum $\chi^2 < \chi^2_{\text{max}}$

- Correct scattering sequence
- Rejects Compton and wrong direction
Fig. 1. The $\chi^2$ distributions for full energy events and Compton events from tracking 10,000 simulated gamma rays with an energy of 1.2 MeV. These gamma rays are emitted from the center of a spherical shell with an inner radius of 12 cm and an outer radius of 21 cm. Results are shown for position resolutions of 1 and 3 mm, respectively.

Fig. 2. Trade off between efficiency and peak-to-total ratio for a 1.2 MeV gamma ray from the simulations shown in Fig. 1. The diamond indicates result for a detector with infinite position resolution, the solid and dashed lines represent the results for position resolution of 1 and 3 mm, respectively.
Let’s put it all together
Full analysis of simulated and experimental data

- GEANT
- Signal calculation
  - Detector geometry
  - X Y Z E
- Signal analysis
  - Electric field
  - Drift velocity
  - Electronics response
  - Signals
- Tracking
  - Spectra → Efficiency, P/T
  - Imaging
  - X Y Z E

• $E_\gamma=0.662$ MeV ($^{137}$Cs), source distance= 12cm

• Signal analysis (least square method)
  • up to 4 segments and 2 interactions per segment (98% of all events)

• For single interaction per segment
  • position determination <1.5 mm success rate ~80%

• For two interactions per segment
  • position determination < 1.5 mm success rate ~70%
  • minimum separation 2 mm

• Compared data and simulation with and without tracking
$^{137}$Cs source

Tracking

Simulation

P/T $\sim$ 38%
Relative Eff $\sim$ 0.67

Data

P/T $\sim$ 31%
Relative Eff $\sim$ 0.62

P/T no tracking $\sim$ 16%
“Battle” conditions

In-beam measurement of the position resolution of a highly segmented coaxial germanium detector

M. Descovich\textsuperscript{a,}\textsuperscript{*}, I.Y. Lee\textsuperscript{a}, P. Fallon\textsuperscript{a}, M. Cromaz\textsuperscript{a}, A.O. Macchiavelli\textsuperscript{a}, D.C. Radford\textsuperscript{b}, K. Vetter\textsuperscript{c}, R.M. Clark\textsuperscript{a}, M.A. Deleplanque\textsuperscript{a}, F.S. Stephens\textsuperscript{a}, D. Ward\textsuperscript{a}

\textsuperscript{a}Lawrence Berkeley National Laboratory, Nuclear Science Division, Berkeley, CA 94720, USA
\textsuperscript{b}Oak Ridge National Laboratory, Nuclear Science Division, Oak Ridge, TN 37830, USA
\textsuperscript{c}Lawrence Livermore National Laboratory, Glenn T. Seaborg Institute, Livermore, CA 94550, USA
In-beam Test of PII and PIII

Experimental measurement of position resolution
Doppler broadening related to $\Delta r$
Maximize Doppler effect

- $^{82}\text{Se} + ^{12}\text{C} @ 385 \text{ MeV}$
- $^{90}\text{Zr}$ nuclei ($\beta \sim 8.9\%$)
- 2055 keV ($10^+ \rightarrow 8^+$) in $^{90}\text{Zr}$
- Target-detector @ 4 cm
- Beam-detector @ 90°
Digitized pulse shapes have been analyzed to extract energy and position of individual $\gamma$-ray interactions (signal decomposition).

The position of the 1st interaction was used to correct for Doppler shift.

Doppler shift:

$$E_\gamma = E^0_\gamma \frac{\sqrt{1-\beta^2}}{1-\cos \theta}$$
Comparison between the observed signals and a linear contribution of pre-calculated basis signals:

\[ Q(t) = E_i q_i(t) + E_j q_j(t) + \ldots \]
From simulations, 14.5 keV FWHM

\[ \sigma = 2.4 \text{ mm (RMS in 3D)} \]
Results from PIII

**Single segment**
- Correct for central contact
- Correct for segment contact
- FWHM 28 keV

**Two segment**
- Correct for the first interaction
- FWHM 14 keV
- FWHM 18 keV

*Results from PIII*
G R E T I N A  =  1/4 of 4π
“First stage of GRETA”

But not “Little GRETA”

Gamma Ray Energy Tracking In beam Nuclear Array
12 pentagons and …

<table>
<thead>
<tr>
<th>Number of hexagons</th>
<th>Number of different hexagonal shapes</th>
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<tbody>
<tr>
<td>80</td>
<td>2 (20, 60)</td>
</tr>
<tr>
<td>110</td>
<td>3 (20, 30, 60)</td>
</tr>
<tr>
<td>120</td>
<td>2 (60, 60)</td>
</tr>
<tr>
<td>150</td>
<td>3 (30, 60, 60)</td>
</tr>
<tr>
<td>180</td>
<td>3 (60, 60, 60)</td>
</tr>
<tr>
<td>200</td>
<td>4 (20, 60, 60, 60)</td>
</tr>
</tbody>
</table>
$4\pi$ Simulations GEANT4

Quad

Triplet

E. Farnea and D. Bazzacco - Padova
GRETINA

- 7 quad modules + 1 triplet (31 crystals)
- Cost of $17M
- Construction period from 2005 - 2010
Data Acquisition System

- Local Trigger Module
- Signal Digitizers
- Readout Computer
- 2.2 MB/s
- 66 MB/s

- Global Trigger Module
- 30 Crystals

- Aux. Det. Trigger
- Aux. Det. Data

- Network Switch

- Processing Farm
  - 75 dual Processors
  - 6.9 MB/s

- Workstations, Servers
  - 2.3 MB/s + Aux. Data

- Data Storage
How does nuclear shell structure and collectivity evolve in exotic neutron-rich nuclei?

What is the influence of increasing charge on the dynamics and structure of the heaviest nuclei?

How do the collective degrees of freedom and shell structure evolve with excitation energy and angular momentum?

What are the characteristics of Giant Resonances built on excited states and loosely bound nuclei?
Performance

Relative to a $4\pi$ array
solid angle $\sim 0.8$, position resolution $\sim 2\text{mm}$
n-rich nuclei from fragmentation reactions

$^{30}\text{Mg} \ (\text{pn}) \rightarrow ^{30}\text{Na} \ (100 \text{ MeV/u})$

$v/c=0.43$

charge exchange reaction

Gamma-gamma coincidence

NSCL data SeGA

(E. Rodriguez-Vieitez et al.)
High spin states from fusion reactions

\[ ^{64}\text{Ni} \left( ^{48}\text{Ca}, 4n \right) ^{108}\text{Cd}, \text{Gammasphere} \]

\[ v/c = 0.04 \]

\[ \text{Simulation GS, } \varepsilon = 0.09 \]

3-fold, \( I = 10^{-4} \)

\[ \text{Simulation GS} \]

3-fold, \( I = 10^{-3} \)

\[ \text{Simulation GRETA, } \varepsilon = 0.25 \]

4-fold, \( I = 10^{-5} \)
<table>
<thead>
<tr>
<th>Decision</th>
<th>Description</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD0</td>
<td>Mission need</td>
<td>Aug. 2003</td>
</tr>
<tr>
<td>CD1</td>
<td>Preliminary Baseline Range</td>
<td>Feb. 2004</td>
</tr>
<tr>
<td>CD2A/CD3A</td>
<td>Performance Baseline range for long lead time items</td>
<td>June 2005</td>
</tr>
<tr>
<td>CD4</td>
<td>Start of Operation</td>
<td>May 2010</td>
</tr>
</tbody>
</table>
Collaborating Institutions

• **Argonne National Laboratory**
  – Trigger system
  – Slow control software

• **Michigan State University**
  – Detector testing

• **Oak Ridge National Laboratory**
  – Liquid nitrogen supply system
  – Data acquisition

• **Washington University**
  – Target chamber
Working Groups

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

http://grfs1.lbl.gov/
http://radware.phy.ornl.gov/greta/join.html
Large arrays of Ge detectors such as Gammasphere and Euroball had a large impact in nuclear structure research in the last decade.

A $4\pi$ Gamma-Ray Tracking Array appears as the next frontier and was identified as a new initiative by the nuclear structure communities in Europe and USA.

GRETINA has just received CD2/3A approval from DOE.

With the AGATA demonstrator, first realization of a tracking device and offers a very compelling physics case.

We look forward to an exciting research program.

Important applications in many fields.
Why imaging gamma-rays?

- **High energy astrophysics**
  - Correlate the detected photon to the source object as known from more precise observations in other wavelengths

- **Biomedical research**
  - Precise localization of radioactive tracers in the body
  - Cancer diagnosis
  - Molecular targeted radiation therapy
  - Monitor changes in the tracer distribution -> dynamical studies

- **National security**
  - Nuclear non-proliferation/ nuclear counter terrorism
  - Contraband detection
  - Stockpile stewardship
  - Nuclear waste monitoring and management

- **Industrial non-destructive assessments**
  - Determination of the material density distribution between the source and detector
Compton gamma-ray imaging

- Gamma rays interact several times with detector via Compton interaction (e.g. until it is stopped by the photo-electrical effect).
- Measuring positions and energies of individual interactions enables to determine pathway of gamma ray in detector (tracking).
- Energies and positions of first two interactions define cone of incident angles (electron path is not measured).
- Cones are projected on plane or sphere (one circle per event) for 2D or into cube (one cone per event) for 3D imaging.

\[
\cos \theta = 1 - \frac{E_1 m_0 c^2}{E_\gamma (E_\gamma - E_1)}
\]

\[
E_\gamma = E_1 + E_2 + E_3 + E_4
\]
$4\pi$ gamma-ray imaging

K. Vetter et al.
Finally, to conclude, a word about the future ...
"The future isn’t what it used to be."
Arthur C. Clarke

"Prediction is very difficult, especially about the future."
Niels Bohr

Shrinking budgets
Limited resources
Need to find new opportunities
March 15, 2001

Rod Clark
Lawrence Berkeley National Laboratory
1 Cyclotron Road
Mailstop 88-221
Berkeley, CA 94720

Dear Rod:

Thank you for taking the time out of your busy schedule to show our group around the Lab and answer our questions. It was a treat to tour the Gammasphere and Cyclotron. More importantly, the day was extremely informative and has everyone excited about embarking upon the film.

With a little luck, there’ll be a large green man in all of our futures.

All the best,

Gale Anne Hurd
However, with
Radioactive Beam Facilities and
Gamma Ray Tracking Arrays

My Forecast

Sunny & Warm
THE END
Signal Generation

- **Electric field**
  \[ \vec{E} = \vec{\nabla} V \]
  \[ \nabla^2 V = \rho \quad \rho: \text{impurity concentration} \]
  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
**Signal Generation**

- **Trajectory**: for electrons and holes

\[ \vec{v} = \vec{v}(\vec{E}) \]

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

- **Induced charge** (S. Ramo, 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

\[ \Delta Q_k = q \left( V_k(\vec{x}_2) - V_k(\vec{x}_1) \right) \]
Energy Resolution

Measurements using the digitizer board

Crystal A

- Am 60keV
- 60Co 1173keV
- 60Co 1332keV

FWHM (keV)

2.55 keV

1.28 keV
Noise level at high-frequency

\[ \sigma \text{ (keV)} \]

Segment number

3.5 keV
Three-dimensional position sensitivity in two-dimensionally segmented HP-Ge detectors

K. Vetter\textsuperscript{a,\textcopyright}, A. Kuhn\textsuperscript{a}, M.A. Deleplanque\textsuperscript{a}, I.Y. Lee\textsuperscript{a}, F.S. Stephens\textsuperscript{a}, G.J. Schmid\textsuperscript{b}, D. Beckedahl\textsuperscript{b}, J.J. Blair\textsuperscript{c}, R.M. Clark\textsuperscript{a}, M. Cromaz\textsuperscript{d}, R.M. Diamond\textsuperscript{d}, P. Fallon\textsuperscript{d}, G.J. Lane\textsuperscript{d}, J.E. Kammeraad\textsuperscript{b}, A.O. Macchiavelli\textsuperscript{a}, C.E. Svensson\textsuperscript{a}

\textsuperscript{a}Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
\textsuperscript{b}Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
\textsuperscript{c}Bechtel Nevada, North Las Vegas, NV 89130-4134, USA
Signal decomposition

- Calculate signal in each segment for interactions on a grid → base signals

- Decompose the composite signal into a linear combination of base signals

- Interpolate to improve position resolution
Results

150 keV < \( E_{\gamma} \) < 5 MeV : Compton Effect dominant

“Compton Tracking”

Cluster generation ➔ Tracking ➔ Split/Add/Split-add

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>Peak-to Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{GRETA 1mm} )</td>
<td>( \text{GRETA 1mm} )</td>
</tr>
<tr>
<td>( \text{GRETA 2mm} )</td>
<td>( \text{GRETA 2mm} )</td>
</tr>
<tr>
<td>( \text{Gammasphere} )</td>
<td>( \text{Gammasphere} )</td>
</tr>
</tbody>
</table>

Angle in degrees

- Tracking efficiency about 50%

\( E_{\gamma} > 5 \text{ MeV} \) : Pair Production dominant

“Pair Tracking”

First hit recognition ➔ Tracking

- Tracking efficiency about 50%
$^{152}\text{Eu full analysis}$

Gain in peak/total vs. efficiency
Neutron damage

Effects of neutron damage on the performance of large volume segmented germanium detectors


Lawrence Berkeley National Laboratory, Nuclear Science Division, 1 Cyclotron Road, MS 88RO192, Berkeley, CA 94720, USA
Fast neutrons damage the Ge structure and create hole-traps. Reduction of charge collection efficiency. Signal loss depends on the interaction position. Hole-trapping has been introduced in the calculation through attenuation length $\lambda$ [T. Raudorf, R. Pehl, NIM A255 (1987)]. $\lambda \sim 1/\phi$ and depends on bias, detector temperature, crystal type.

\[ n = n_0 \cdot \exp\left(-\frac{r - r'}{\lambda_h}\right) \]

For GRETINA: $\phi = 10^{10}$ n/cm$^2 \Rightarrow \lambda = 10$ cm

$\phi = 10^9$ n/cm$^2 \Rightarrow \lambda = 100$ cm
Degradation in E resolution occurs for $\lambda < 100$ cm, before correction and for $\lambda < 30$ cm, after correction, but only for $\lambda < 17$ cm position resolution becomes worse than 1 mm (achievable limit).

A measurable effect of neutron damage on position resolution is never reached before annealing is required!