Status of the GERmanium Detector Array Experiment (GERDA) at LNGS

C.M. Cattadori- INFN-Milano Bicocca
Per la collaborazione GERDA

\[ Q_{2\beta} = 2039 \text{ keV} \]
Outline

- Neutrinoless Double Beta Decay ($0\nu\beta\beta$) & $^{76}\text{Ge}$
- The design and construction of the GERDA setup.
  - The milestones
  - The Water Tank & The Cerenkov Muon veto
  - The Cryostat
  - The Ge detectors
  - The Ge detectors readout
  - The calibration system
- The first 3 months of data taking
- Preparation of GERDA Phase II
- Conclusions
Proposed by Majorana & Racah in 1937 (*Il Nuovo Cimento*).

It is forbidden in SM and requires

- Lepton number violation
- Neutrino is a Majorana particle having finite mass
- Existence of $W_R$

\[
\Delta L = 2 \quad \nu_e = \nu_e \\
\langle m_\nu \rangle \neq 0
\]
Why another experiment on $^{76}$Ge $0\nu\beta\beta$ decay?

- A debated claim @ $4.2\,\sigma$ indicate evidence of $0\nu\beta\beta$ with $T_{1/2} = 1.2 \times 10^{25}\,\text{y}$, $m_{ee}= 440\,\text{meV}$ with KK NME
- Estimated NME favorable in all the models $T_{1/2}^{0\nu} \sim 10^{27}\,\text{y}$ (for $<m_\nu> = 40\,\text{meV}$: $M_{0\nu}^{\text{nucl}} \sim 4$
- $Q_{\beta\beta} = 2039.06\pm 0.05\,\text{keV}$

$$(T_{1/2}^{0\nu})^{-1} \sim 5 \times 10^{-17}\,\text{[y}^{-1}]\,F_{0\nu}(Q,Z)\,|M_{0\nu}|^2\,m_\nu^2/m_e^2$$
GERDA: Sensitivity

 assessment E resolution: $\Delta E = 4 \text{ keV}$

 phase II

 phase I 18$\text{kg}$

 KKDC claim

~ 1 year data taking (assuming 18 kg y exposure) the KK

 claim: if true $\beta\beta$ decay GERDA will have 7 cts, above bckg of 0.5 cts $\rightarrow$ probability

 that bckg simulate signal $\sim 10^{-5}$

 Bologna, 20th September 2010

 C.M. Cattadori - XCVI Congresso SIF
GERDA: The Collaboration

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\textsuperscript{http://www.mpi-hd.mpg.de/GERDA

\textsuperscript{~ 95 physicists
\textsuperscript{17 institutions
\textsuperscript{6 countries

(Germany, Italy, Russia, Poland, Belgium, Switzerland)
Bologna, 20th September 2010 C.M. Cattadori - XCVI Congresso SIF

**Status:**
- cryo-mu-lab
- water plant Rn monitor
- control room
- water tank - rdy
- clean room – rdy
- phase I lock – under test
- GERDA bldg - rdy
- phase I array rdy (scaled:)
- FE electronics 2 version avlb
- µ veto rdy
- LAr fill: Oct/Nov 09

**Phase I Array Status:**
- Array is ready (scaled version available)
- FE electronics version 2 is available
- µ veto system is ready
- Water tank and GERDA building are ready
- Clean room and Phase I lock are under test

**LAr Fill:**
- Scheduled for October/November 2009

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*Image Description*

- **Cryostat:** Ready
- **Water Tank:** Ready
- **GERDA Building:** Ready
- **Clean Room:** Ready
- **Phase I Lock:** Under test
- **FE Electronics Version 2:** Available
- **µ Veto System:** Ready
- **LAr Fill:** Scheduled for Oct/Nov 2009

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*Diagram Details*

- Cryo-mu-lab
- Control room
- Water plant
- µ veto
- FE electronics version 2
- LAr fill timeline
- GERDA building
- Phase I array
- Water tank

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*Technical Details*

- Cryostat
- Water tank
- Clean room
- Phase I lock
- µ veto
- FE electronics version 2
- LAr fill schedule
- GERDA building
- Phase I array

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*Project Status*

- All key components are ready or under construction.
- FE electronics version 2 is available for use.
- µ veto system is operational.
- Water tank and GERDA building are completed.
- Clean room and Phase I lock are being tested.
- LAr fill is scheduled for Oct/Nov 2009.

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*Conclusion*

The project is progressing well, with all critical components ready for deployment. Further testing and commissioning are ongoing to ensure system readiness by the scheduled LAr fill date.
GERDA: a novel, ambitious approach to the background issues

GERDA goal: build a setup with a $B < 10^{-3} \, [c/kky] @ Q_{\beta\beta}$

GERDA distinctive features to reduce bckrgd of $10^{-6}$

• Ge diodes operated naked in LAr

<table>
<thead>
<tr>
<th>Activity of TI-208 ($\mu$Bq/kg)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>rock, concrete</td>
<td>3000000</td>
</tr>
<tr>
<td>stainless steel</td>
<td>~ 5000</td>
</tr>
<tr>
<td>Cu(NOSV), Pb</td>
<td>&lt;20</td>
</tr>
<tr>
<td>water, purified</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>LN2, LAr</td>
<td>~ 0</td>
</tr>
</tbody>
</table>

- XCVI Congresso SIF
GERDA milestones

- Proposed in 2004 & funded by MPG
- Approved in 2005 by LNGS with location in Hall A
- 2005 Funded by BMBF, INFN, DFG (R&D), and Russia in kind
- WT & related plants:
  - Contract signed in 2006
  - Construction in LNGS Hall A 2007-2008
  - Muon veto constructed in 2009
- Cryostat & cryogenic systems
  - Contract signed in 2007
  - Construction @ company site in 2007-2008
  - Delivered @ LNGS in 2008
  - filled with LAr in Dec ’09 & cryogenic commissioning completed
- Building
  - Constructed in 2008
- Clean room & Lock
  - Constructed in 2009> Lock tested in 2009, moved underground in 2010
- Detectors:
  - Refurbishment technology defined in 2008 after proofing long term stability in LAr
Pictures from the construction time (2007-2010)
Pictures from the construction time (2007-2010)
The main GERDA subsystems

GERDA is a composite setup. The main sub-systems are listed in the following:

- Cryostat (and relate plants)
- Water tank e $\mu$-veto (and related plants)
- Detectors insertion system (lock)
- Detectors
- Pulse readout and processing
- Calibration system
The Cryostat: design

The cooling serpentine: to sub-cool the LAr. No LAr refilling needed

- dedicated meas show that Rn in cryostat
  ~55 mBq with manifold, bellow, piping, sensors, cabling, ....

- Temp. difference suppresses exchange of LAr from neck and tank

- Rn in convective layers w/o shroud:
  30 mBq => 2 \times 10^{-3} \text{cts/(keV\cdot kg\cdot y)}

- Rn in convective layers with shroud:
  30 mBq => 1.5 \times 10^{-4} \text{cts/(keV\cdot kg\cdot y)}

- Homogenous mixing of radon in LAr:
  30 mBq => 4 \times 10^{-4} \text{cts/(keV\cdot kg\cdot y)}
The Phase I $^{enr}$Ge detectors

- 8 $^{enr}$Ge (former HdM&IGEX) + 6 $^{nat}$Ge (from GTF) p-type coaxial Ge detector available
  - mass: 1-3 kg
  - $C_{det} = 30-40$ pF
- Deployed in strings of 3 detectors each
- Mounted in low-mass Cu holders
- HV contact: on Li surface by pressure
- Readout contact: in borehole spring-loaded
- All the detectors have been tested naked in LAr and perform well ($I-V$ & $R < 3$ keV @ 1.332 MeV).
- Long term stability experimentally proved

<table>
<thead>
<tr>
<th>Detector</th>
<th>Total mass (g)</th>
<th>HV (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANG 1</td>
<td>958</td>
<td>3500</td>
</tr>
<tr>
<td>ANG 2</td>
<td>2833</td>
<td>4000</td>
</tr>
<tr>
<td>ANG 3</td>
<td>2391</td>
<td>3000</td>
</tr>
<tr>
<td>ANG 4</td>
<td>2372</td>
<td>3000</td>
</tr>
<tr>
<td>ANG 5</td>
<td>2746</td>
<td>1800</td>
</tr>
<tr>
<td>RG 1</td>
<td>2110</td>
<td>4500</td>
</tr>
<tr>
<td>RG 2</td>
<td>2166</td>
<td>4000</td>
</tr>
<tr>
<td>RG 3</td>
<td>2087</td>
<td>3500</td>
</tr>
<tr>
<td>GTF 32</td>
<td>2321</td>
<td>3200</td>
</tr>
<tr>
<td>GTF 42</td>
<td>2467</td>
<td>3000</td>
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<td>GTF 44</td>
<td>2465</td>
<td>3500</td>
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<td>GTF 45</td>
<td>2332</td>
<td>1500</td>
</tr>
<tr>
<td>GTF 110</td>
<td>3046</td>
<td>3000</td>
</tr>
<tr>
<td>GTF 112</td>
<td>2965</td>
<td>2500</td>
</tr>
<tr>
<td>Prototype</td>
<td>1560</td>
<td>3000</td>
</tr>
</tbody>
</table>
The Ge detector readout: Front-end

- Cryogenic FE circuit g-ray spectrometry class. Architecture: external JFET + following amp. stage (CMOS OPAMP)

- Achieved Performances @ LN:
  - Intrinsic noise < 1 keV (< 150 e r.m.s.)
  - Rise time: 30-40 ns

- Radiopurity ($^{232}$Th) with screened components:
  - 350 µBq/PCB (3ch) for ASIC FE
  - 150 µBq/PCB (3ch) for CC2 (based on commercial CMOS OPAMP)
The Calibration System

- $^{228}$Th sources ($\gamma$-lines at 2614 keV, 2103 keV, 1592 keV, 583 keV) inserted besides detector strings
- a 20 kBq source provides an event rate in detectors of ~ 600 Hz in calibration, allowing calibration ~ 1 h

- **Ta ring**: to shield detectors when sources are in parking position
- **parasitic n-activity** of sources from ($\alpha$,n) reaction on substrate materials measured with dedicated setup
  
  $(2.7 \pm 0.5) \times 10^{-2}$ n/s for the 14 kBq source
The first three months of data taking

- GERDA started the commissioning data taking with a $^{nat}$Ge pilot string (3 detectors for a total mass of 7.62 kg of $^{nat}$Ge)
- Few technical problems related to HV → solved
- Up to now available a statistic of ~250 kg*d divided in runs taken in different configurations
- Bad news:
  - Immediately visible an $^{42}$Ar signal much larger (~ 15) than expected at the 1524 keV $\gamma$-line
- Good news:
  - No peak visible from none of the $^{238}$U (1764,2204), $^{232}$Th(2614,583 etc.), $^{40}$Kmain $\gamma$-lines
Spectra collected during 17 days with 2.3 kg $^{nat}$Ge detector in GERDA setup

$\sim 1.5 \text{ cts/(kg}^*\text{day)}$
$^{42}_{18}$Ar

$^{42}_{19}$K

\[ Q_{\beta} = 600 \text{ keV} \]

\[ 12.360 \text{ h} \]

\[ T_{1/2} = 12.36 \text{ h} \]

\[ Q = 3525.4 \text{ keV} \]

- Mostly a pure $\beta$ emitter
  - Most intense $\gamma$ ray at 1524.73 keV (18.1%)

\[ \gamma(^{42}\text{Ca}) \text{ from } ^{42}\text{K} (12.360 \text{ h}) \beta^{-} \text{ decay } \text{< for } l\gamma%\text{ multiply by 0.18089> } \]

- $312.6 (\uparrow 1.86 \text{ keV}) \text{ E2}$
- $588.87 (\uparrow <0.0021) \text{ E2}$
- $694.54 (\uparrow 0.018 4) \text{ (E1)}$
- $899.43 (\uparrow 0.265 14) \text{ M1+E2; } \delta = -0.18 2$
- $1022.78 (\uparrow 0.111 8) \text{ (E1)}$
- $1227.66 (\uparrow 0.013 6) \text{ (E2)}$
- $1524.70 (\uparrow 100) \text{ E2}$
- $1922.18 (\uparrow 0.228 22) \text{ E1(M+M2); } \delta = +0.02 7$
- $2424.09 (\uparrow 0.110 16) \text{ E2}$

Background at $Q_{\beta \beta}$ by:

- $\beta$, bremsstrahlung from $\beta$ and 2424 keV $\gamma$-ray
$^{42}\text{Ar}$: expected values and possible origin

- $^{42}\text{Ar}$ is mainly generated by $^{40}\text{Ar}(\alpha, 2p)^{42}\text{Ar}$ reaction in atmosphere and fall-out from atmospheric nuclear explosions.

<table>
<thead>
<tr>
<th>Measurements of upper concentration limits of $^{42}\text{Ar}$ in Ar</th>
<th>[$\mu$Bq/LAR]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992 Arpesella et al. LNGS internal report 92/27: 1.2×10^{-18} atoms 42/40 =</td>
<td>16800</td>
</tr>
<tr>
<td>1995 Cennini et al. (ICARUS 3H) NIM A 356,526-529: 4×10^{-18} atoms 42/40 =</td>
<td>56000</td>
</tr>
<tr>
<td>1998 Ashitkov V.D.et al. NIM A 416, 179-181: 6×10^{-21} atoms 42/40 =</td>
<td>84</td>
</tr>
<tr>
<td>1999 Ashitkov V.D. et al. Nucl. Phys. (Proc Suppl.) 70,233: 5×10^{-21} g/g =</td>
<td>70</td>
</tr>
<tr>
<td>2003 Ashitkov V.D. et al. arXiv:nucl-ex/0309001: 4.3×10^{-21} g/g =</td>
<td>60</td>
</tr>
<tr>
<td>2004 Ruben Saakyan thesis: 4.3×10^{-21} atoms 42/40 =</td>
<td>60</td>
</tr>
</tbody>
</table>

Liquid Ar ionization chamber to measure $^{100}\text{Mo}$ (306 g enriched and 138 g natural) 113 d and 13 d

- Energy spectrum of single electron events full dynamic range

- 55 kg LAR

- <0.094 c/(kg*d) in GERDA meas. geometry
Simulated $^{42}$Ar spectrum in GERDA geometry (detectors surrounded by homogeneous LAr bath)

$^{42}$K total spectrum (3 detectors) for $^{42}$Ar/$^{40}$Ar = $4.3 \times 10^{-21}$ g/g

- $< C_{rate} @ 1524$ keV $0.094$ (cts/kg*d)
- $C_{rate} @ Q_{\beta\beta} < 1.7 \times 10^{-3}$ (cts/keV*kg*y)

- From $\beta$s (3.5 MeV) entering in the detector where there is no dead layer or passing through it
- Hard bremsstrahlung of 3.5 MeV $\beta$s in LAr
Possible explanations and actions

- The reference $^{42}\text{Ar}$ conc. measurements are wrong (of a large factor $\rightarrow$ unlikely)
- The $^{42}\text{Ar}$ concentration in atmosphere has large variations, and the GERDA LAr has a particularly high concentration of $^{42}\text{Ar}$
  - $\rightarrow$ measure in two independent setups (GERDA & LARGE).
- The $^{42}\text{K}^+$, which is produced positively charged in the $^{42}\text{Ar} \beta$ decay, is not uniformly distributed around the detectors: $^{42}\text{K}^+$ (lifetime in LAr unknown) is drifted towards the detectors holder (GNDed surfaces) and detector borehole, by the detector bias $E_{\text{field}}$ dispersed in LAr (detectors are naked!):
  - indications of this mechanism comes from (Cts@Peak)/(Cts above peak) ratio
- $\rightarrow$ Perform a series of runs placing the metallic surfaces around the detectors (shroud and mini-shroud) at various potentials and measure the cts rate: $\rightarrow$ results encouraging, already achieved a relevant reducing factor. Continue on this road!
The mini-shroud

- A Cu mini-shroud has been inserted,
  - to close field lines onto a surface few cm away from the detector (not onto detector holders)
  - To prevent ions sucked from the LAr bath to reach the detector
- The detector string is inside the mini-shroud
- Significant $^{42}$K signal reduction
- No bkgrd increase
The Next steps

In the next months our activity will follow this scheme:

- Complete the measurements devoted to understand the $^{42}$Ar signal and pursue mitigation actions.
- Installation of the 3-string arm.
- Test of 3-string arm with mockup & capacitors.
- Optimization of noise in the underground setup (grounding, tests with FE+ capacitors and detector mockup).
- Deploy the enrGe detectors.
The preparation of GERDA Phase II: \textit{enr}Ge processing

on 30 April 2010

- 36.6 kg >50 Ohm material produced. 97\% of the 37.5 kg available \textit{enr}Ge is now 6N material.

- The integrated exposure has been about 5.2 days including the transport from Geel.

- All the material is packed in two boxes and is underground in the Rammelsberg mine.
PHASE II Detectors allowing enhanced PSD: Choice of BEGe as reference type

- Applying PSA cuts and requiring 90% survival probability for the $^{232}$Th DEP (mostly Single Site Events $\rightarrow 0\nu\beta\beta$-like)

- 12% survival of the $\gamma$-line $^{212}$Bi line (mostly Multi-Site Events $\rightarrow \gamma$-bgd like)

- Segmented & BEGe show similar PSD performances, but BEGe simplest readout and cabling $\rightarrow$ benefit for setup radiopurity

- 3 $^{nat}$Ge + 2$^{dep}$ Ge BEGe detectors tested so far: all of them excellent $En\ Res < 2.0\ keV \ @ \ 1.332\ MeV$
### PSD: comparison of results from all the BEGe tested in GERDA

<table>
<thead>
<tr>
<th>Dim.sns</th>
<th>Contact dim [mm]</th>
<th>Mass [g]</th>
<th>$V_{depl}$ [V]</th>
<th>Compton @Qbb</th>
<th>DEP 1592 keV</th>
<th>FEP 1621 keV</th>
<th>SEP 2103 keV</th>
<th>FEP 2614 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>81 x 32 Hd</td>
<td>15</td>
<td>868</td>
<td>4000</td>
<td>39 ± 2</td>
<td>90 ± 1.6</td>
<td>9.5 ± 1.5</td>
<td>5.8 ± 0.6</td>
<td>7.7 ± 0.7</td>
</tr>
<tr>
<td>70 x 32 LNGS</td>
<td>15</td>
<td>632</td>
<td>3000</td>
<td>37.5 ± 0.5</td>
<td>90 ± 0.6</td>
<td>11.5 ± 0.1</td>
<td>6.2 ± 0.4</td>
<td>6.4 ± 0.1</td>
</tr>
<tr>
<td>60 x 26 Geel</td>
<td>15</td>
<td>390</td>
<td>3000</td>
<td>45 ± 2</td>
<td>90 ± 3</td>
<td>18 ± 3</td>
<td>6.8 ± 1.7</td>
<td>14 ± 3</td>
</tr>
<tr>
<td>80 x 30 Geel</td>
<td>15</td>
<td>825</td>
<td>3500</td>
<td>49 ± 2</td>
<td>90 ± 3</td>
<td>29 ± 2</td>
<td>23 ± 2</td>
<td>Not avlbl</td>
</tr>
<tr>
<td>74 x 33 Depl CC</td>
<td>9</td>
<td>752</td>
<td>3500</td>
<td>38.3 ± 0.3</td>
<td>90 ± 1.1</td>
<td>10 ± 0.6</td>
<td>5.4 ± 0.3</td>
<td>8.3 ± 0.1</td>
</tr>
<tr>
<td>74 x 32 Depl DD</td>
<td>22</td>
<td>~750</td>
<td>3500</td>
<td>39.8 ± 0.3</td>
<td>90 ± 1.1</td>
<td>11.3 ± 0.6</td>
<td>5.8 ± 0.4</td>
<td>8.8 ± 0.1</td>
</tr>
</tbody>
</table>
Phase II: The recentest results with bare BEGe (80 x 40 mm) & cold FE in LARGE setup (@GDL): long term stability proved

LAr scintillation light readout implemented
Conclusions

- The construction of the GERDA setup at LNGS is completed since spring 2010.
- All the recommendations of the safety review have been implemented.
- Commissioning started in June 2010 with a pilot string of 3 \(^{nat}\text{Ge}\) detector.
- Performances not as good as in September 2009 tests (\(R = 5-7\) keV @ 2614 keV) dominated by EM disturbances.
- Available a statistic of \(\sim 250\) kg\(\cdot\)d.
- A concentration of \(^{42}\text{Ar}\) a factor \(\sim 15\) larger than expected (from measurements available in literature) is observed.
- Actions are ongoing to understand the origin of the extra \(^{42}\text{Ar}\) signal and to mitigate its impact on the detector background index.
- Still no background visible from U, Th and K (B of the setup matches the design).
- Run with \(^{enr}\text{Ge}\) will then follows (time schedule depends on the outcome of the ongoing commissioning).
- The BEGe detectors have been chosen as reference detectors for the GERDA PHASE II. We are defining and negotiating the contract with Canberra to produce the \(^{enr}\text{Detectors for GERDA Phase II. The x-tal pulling and diode production will start spring 2011.}\)
EXTRA slides
Signature of $0\nu\beta\beta$ decay and sensitivity on $T_{1/2}^{0\nu}$

\[ \varepsilon = \text{detection efficiency} \]
\[ a = \beta\beta \text{ isotope fraction} \rightarrow \text{enrichment} \]
\[ M = \text{mass of detector in kg} \]
\[ T = \text{data taking time [y]} \]
\[ B = \text{background index in cts/(keV kg y)} \]
\[ R = \text{energy resolution at } Q_{\beta\beta} \text{ [keV]} \]

With bck

\[ T_{1/2}^{0\nu} \propto a\varepsilon \sqrt{\frac{MT}{BR}} \]

\[ T_{1/2}^{0\nu} \propto a\varepsilon MT \quad \text{Bck free} \]
0νββ rate and the effective neutrino mass

0νββ rate ~ (effective Majorana neutrino mass)²

\[ < m_ν > \geq \sqrt{m_1^2 + \Delta m_{\text{atm}}^2} \left| U_{e1}^{L} \right|^2 e^{i\phi_2} + \left| U_{e2}^{L} \right|^2 e^{i\phi_3} \]

\[ < m_ν > \geq m_1 \left| U_{e1}^{L} \right|^2 + \left| U_{e2}^{L} \right|^2 e^{i\phi_2} \left( 1 + \frac{\Delta m_{\text{solar}}^2}{2m_1} \right) \]

\[ \Delta m_{\text{atm}}^2 = m_3^2 - (m_2^2 + m_1^2)/2 \]

Rate is the quantity measured in ββ experiments

\[ (T_{1/2}^{0ν})^{-1} \sim 5 \times 10^{-17} \text{ [y}^{-1} \text{]} \]

\[ F_{0ν}(Q,Z) |M_{0ν}|^2 m_ν^2/m_e^2 \]

\[ \text{From Vissani, Strumia hep-ph/0606054v2} \]

Bologna, 20th September 2010

C.M. Cattadori - XCVI Congresso SIF
Germanium detectors are an established technology.

Feasible to scale up experiment by subsequently adding more detectors → GERDA staged approach (Phase I + Phase II)

Ge density = 5.3 g cm$^{-3}$ → compact setup

Source = detector → high efficiency!

High intrinsic purity and energy resolution $O(0.1\%-0.2\%)$ allowing understanding of background sources and geometry.

$^{76}$Ge is an appealing $0\nu\beta\beta$ candidate

$^{76}$Ge isotopic abundance = 7.44 %, but enrichment of $^{76}$Ge possible at centrifuge up to >80% (reasonable cost)

Low Atomic Weight (1 kg of $^{76}$Ge = 13.1 Moles = $7.9 \times 10^{24}$ nuclei)
The Ge detectors performances achieved so far in LAr in summer 2009 tests (first commissioning)

Clean glove box (N2/hepa) with commissioning lock

2.9 keV (FWHM) @ 1.3 MeV

Best resolution achieved in setup: 2.7 keV (FWHM)