Test of a LYSO+APD matrix prototype for the KLOE-2 upgrade

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Talk Overview

KLOE-2 upgrade: a Crystal Calorimeter with Timing
- Physics Motivations
- Basic layout of the upgrade
- Test of single crystals+amplifiers
- Assembly of the Crystal Matrix

- Test with e-beam from 100 to 500 MeV
  - energy resolution and response
  - light yield
  - timing resolution
  - position resolution

- Conclusions and prospects
Physics Motivations

- EMC of KLOE covers up to $\theta \geq 21-22^\circ$
- Needs extension at low angles ($8^\circ$) both as veto detector or as acceptance extension for rare decay channels
- Golden channels:
  1. Working as a veto $K_S \rightarrow \gamma \gamma$
  2. Acceptance ext: $K_S \rightarrow 3\pi^0$
First design of the CCALT

- New machine layout of DAFNE --> the first quadrupoles @ 30cm from IP

- Spherical Beam pipe shape close to IP needed for Ks F.V.

- Only 20 cm of space in length available with the idea of keeping the detector also inside the constraint of quadrupole coverage in acceptance (18 degrees) to not interfere with main EMC reconstruction (and IT).

- Solution: two small barrels of 24 crystals/each with length from 10-13 cm & transversal area 1.5x1.5 to 2x2 cm^2
## Requirements for a CCALT calorimeter

- Dense, small $X_0$, $R_m$
- Extremely Fast 300-500 ps @ 20 MeV  
  (timing needed to reject accidental/machine bkg)
- **A CCALT == Crystal Calorimeter with Timing**
- Highly efficient ---> High Light Yield
- Small number of channels w photo-sensors working in B-Field  
  (0.52 kGauss)
- Energy resolution will be poor: no transversal coverage.
- Reasonable position resolution (2-3 mm at 15 cm from IP) to improve energy resolution with kinematic fitting (Ks->3p0 search)

## LYSO crystals look as a perfect match for this work:

- 27000 photons/MeV
- emission time of 40-42 ns
- $X_0 = 1.1$ cm, $R_m = 2$ cm, refraction index = 1.8
- not hygroscopic
- nice optical coupling with APD
Test of single crystals with CR

- Amplifier based on MAR8+
- X 25 amplification
- Bandwidth 1 GHz
- Prototypes not yet matched to KLOE EMC electronic chain

- Large signals with CR (40 mV) with APD@410V
- HV from CAEN (CMS-like)
- Noise few mV
- Readout by Lecroy ADC 400ns wide gate
- $\sigma(\text{ped}) = 1.5$ counts
- $MIP(\text{peak}) = 50$ Counts
- $\sigma(\text{MeV}) = 0.6$ MeV
Crystal Matrix Composition

Due to the high LYSO cost we have realized a matrix with:

- an inner core done either by 10 LYSO+APD(CCALT) or 10 PbWO/LSO +SIPM (LET) crystals
- an outer leakage recovery section done by PbWO+PM

PbWO from SICCAS

LYSO/LFS from 3 producers:
- S.Gobain
- Scionix
- Zecotek (LFS)

• 3 Lyso-SG +1 scionix
  3x(15x15x150)+15x15x130 mm3
• 1 Lyso-SG +2 Lyso-Scionix
  20x20x150 + 2x(20x20x130) mm3
• 3 LFS  20x20x130 mm3
Crystal Matrix overview

- Each APD inserted in a PVC mask and soldered to his amplifier.

- APD+amplifier inserted in a small box sustained by a PVC matrix

- Optical contact by means of Bicron optical grease

- External aluminum holder for the crystals

- Crystals wrapped in 100 µm of Tyvek apart from front and end faces. Front face kept free to insert LED for testing.

- PMs from outer matrix taken into position by external holder
From CAD to realization (in pictures)

- First Assembly of overall matrix (march 2009), waiting for arrival of APD-amplifier boards
- Test of Outer Matrix
From CAD to realization (inner matrix)
Test Beam @ BTF (4-18 april 2009)

- BTF @ LNF provides electrons to experimental area with selectable multiplicity at few tens of Hz (i.e. the Linac repetition rate)
- To select clean electrons we required OFFLINE the firing of two external finger scintillators (1x0.5x5) cm^3 which defined also the beam spot on the calorimeter.
- Due to optical cross-talk between inner and outer matrix we lost a lot of days to understand data! In the second week we turned off the outer matrix and got two days of good “e” data with KLOE daq.
Night runs with CR taken with a coincidence between two external NE110-scint counters

- Clean MIP selection
- Pedestal noise 4-5 counts with KLOE ADC chain (110 fc/count)

- MIP peak ~ 100 counts for 15x15 mm^2 crystal
  Peak precision < 1%
Response grouped by columns

\[ Q_{\text{col}} = \sum \left( \frac{Q_i}{M_i} \right) \langle M \rangle, \quad \text{where} \quad \langle M \rangle = 120 \text{ counts} \]
Energy spectra

- \( Q_{\text{tot}} = \sum (Q_i/M_i) \langle M \rangle \), where \( \langle M \rangle = 120 \) counts, \( M_i \) is the peak for MIP on channel I.

- To equalize each channel to the same deposited energy we corrected the larger crystals with the areas' ratio:

  \[ M_i(\text{corr}) = M_i \times \frac{A_s}{A_l} \]
Fit to the spectra

\[
\frac{df}{dE} = \frac{\eta}{\sqrt{2\pi} \cdot \sigma_E \cdot s_0} \cdot e^{-\frac{1}{2} \left( \left[ \ln \left( 1 - \frac{\eta}{\sigma_E} \frac{E - E_{peak}}{s_0} \right) \right]^2 + s_0^2 \right)}
\]

\[\eta = \text{asym}, \quad \sigma = \text{FWHM}/2.35\]

Example of a gaussian fit in a region close to the peak.
Linearity and light yield

\[ \langle M \rangle = 120 \text{ Counts} \implies 1 \text{ MIP} = \frac{120}{7.5} \text{ MeV} = 16 \text{ MeV} \]

Gain vs HV from 300 to 500 (@ 410)

\[ Q(1e) = 1e \cdot \text{Gapd} \cdot \text{Gamp} = 1.6 \cdot 10^{-19} \cdot 3 \cdot 10^2 \cdot 25 = 1.2 \text{ fC} \]

1 MeV = 820 fC \implies 1 MeV = 400-700 pe
Energy resolution dependence

**GAUSSIAN FIT**

- **Nocut:**
  - $5\% \oplus 0.9\%/E(\text{GeV}) \oplus 1.6\%/\sqrt{E(\text{GeV})}$

- **Thr:** $2\text{ MeV}$
  - $5\% \oplus 1.1\%/E(\text{GeV}) \oplus 1.0\%/\sqrt{E(\text{GeV})}$

**LOGN-FIT**

- **Nocut:**
  - $5\% \oplus 0.8\%/E(\text{GeV}) \oplus 2.4\%/\sqrt{E(\text{GeV})}$

- **Thr:** $2\text{ MeV}$
  - $5\% \oplus 0.8\%/E(\text{GeV}) \oplus 2.4\%/\sqrt{E(\text{GeV})}$

- **Constant term dominated by leakage.. Fixed by MC**
- **Noise term between 0.8-1.1\%/E(\text{GeV})**
- **Stochastic term between 1--2.4%/\sqrt{(E/\text{GeV})}**
- **Few data taking points .. Instable fit.**
Detailed MC simulation in progress with Geant-4
- All dimensions respected (crystals, wrapping, APD's)
- Beam spot simulated with different dimensions (5x5 mm^2, 10x10mm^2)
- Simulation of time emission spectra OK
- Optical transportation of photons underway (... study as a function of photons-yield needed .. CPU time)
Leakage term and MC simulation

<table>
<thead>
<tr>
<th>$E_{\text{beam}}$ (MeV)</th>
<th>$E_{\text{peak}}$</th>
<th>$\sigma$</th>
<th>$\sigma/E$</th>
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<tbody>
<tr>
<td>100</td>
<td>0.9373</td>
<td>0.04594</td>
<td>4.9%</td>
</tr>
<tr>
<td>200</td>
<td>0.9206</td>
<td>0.04212</td>
<td>4.6%</td>
</tr>
<tr>
<td>300</td>
<td>0.9112</td>
<td>0.03856</td>
<td>4.2%</td>
</tr>
<tr>
<td>400</td>
<td>0.9065</td>
<td>0.03728</td>
<td>4.1%</td>
</tr>
<tr>
<td>495</td>
<td>0.9019</td>
<td>0.03502</td>
<td>3.9%</td>
</tr>
</tbody>
</table>
Consideration on noise term

Decrease of asymmetry parameter in Logn fit vs Pbeam indicate more gaussian shape due to noise..

1) $Q_{tot}$ w.o. e beam shows $\sigma$(total noise) from 4.3 to 4.9 MeV.
2) Single channels with beam $\sigma$ (ped) = 1.1-1.2 MeV --> 3.6-3.8 MeV
3) Noise twice larger than what measured in electronic lab --> coupling with KLOE EMC chain? Still under study
Position resolution measurement

- Special runs @ 500 MeV taken reading out also the BPM of BTF .. based on X-Y hodoscope of scintillating fibers (3 mm -pitch)

- Plots shown correspond to events with only 1 "electron" selected offline
Position resolution @ 500 MeV

- Position reconstruction in prototype by means of energy weighted mean of the fired crystals

\[ X_{\text{pos}} = \frac{\sum (X_i Q_i)}{Q_{\text{tot}}} \]
\[ Y_{\text{pos}} = \frac{\sum (Y_i Q_i)}{Q_{\text{tot}}} \]

Resolution 2.8 mm vs > 4.3 mm due to the pitch in agreement with expectations

\[ \sigma_y = 2.7 \text{ mm} \]
\[ \sigma_x = 2.9 \text{ mm} \]
Timing measurement at BTF

Each spill arriving from LINAC consists of many bunches separated of 200-300 ps for a total of 10 ns.

When using as TDC start the Gate from Linac we get a 10 ns wide distribution. To eliminate this we offline correct.

For the arrival time provided by the Two finger scintillators limiting the Beam spot.

Jitter of the start: $\sigma(\Delta T)/\sqrt{2}$

KLOE TDC -- 53 ps/Count

$\sigma_{\text{trig}} = 245 \text{ ps @ 500 MeV}$

$= 265 \text{ ps @ 100 MeV}$
Calorimeter timing single cells

Central Cell
No Slewing corrected

Central cell
Slewing corrected

\[ \sigma = 275 \text{ ps} \]

\[ \sigma = 345 \text{ ps} \]
Calorimeter timing clusters

- $T_{clu} = \sum (T_i - T_0) Q_i / Q_{tot}$
- Assuming all channels calibrated with 53 ps/Count!
- $\sigma(T_{clu}) = 250 (49)$ ps at 500 MeV, 291 (120) ps at 100 MeV without (with) correction for trigger jitter
- Consistency with cr/single crystal measurements in progress

<table>
<thead>
<tr>
<th>Energy</th>
<th>Mean (MeV) ± Error</th>
<th>Sigma (ps) ± Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 MeV</td>
<td>10.75 ± 0.1650</td>
<td>5.524 ± 0.1506</td>
</tr>
<tr>
<td>500 MeV</td>
<td>18.54 ± 0.6701E-04</td>
<td>4.710 ± 0.5048E-04</td>
</tr>
</tbody>
</table>

![Graphs showing distributions of the timing clusters for 100 MeV and 500 MeV electrons]
Conclusions

- We are designing a Crystal Calorimeter with timing for KLOE-2 upgrade (2011-2012)
- First prototype has been built and tested with CR and e-beam
- High Light Yield observed
- Energy resolution dominated by leakage at higher energy
  - k/E component too high w.r.t. lab measurement of noise
  - stochastic term between 1-2%/√(E/GeV)
- Position resolution 2.8 mm @ 500 MeV as expected
- Timing resolution 250-300 ps from 100 to 500 MeV without correcting for trigger jitter.
  - Already satisfies detector requirement.

- Next Plans (fall 2009)
  - identify /correct noise term
  - make a test with outer matrix functioning
  - longer data taking for single crystals certification
  - reduce time jitter of the trigger
• Additional material
Response to LED vs time
Response to MIP vs time
Example of MIP fitting @ test lab

\[ \chi^2/\text{ndf} = 3285/12 \]
- Constant: 7790
- Mean: 231.5
- Sigma: 1.562

\[ \chi^2/\text{ndf} = 20.27/13 \]
- Constant: 296.6
- Mean: 261.8
- Sigma: 5.585
Example of LED fitting @test lab
The main constraint comes from accidental background:
- simulation of new optics suggest a x 5 increase of Touschek background rate: from 5 MhZ in EMC to 15 MhZ with screens around inner quads
- to play conservative we want to be able to keep up a rate of 0.5 MhZ/channel.
- A prompt time window of 2 ns -->
  makes Pacci = 1ns * 0.5 Mhz = 1% ---> negligible
- WE NEED A CALORIMETER with 300-500 ps time resolution @ 20 MeV
- CCALT
Example of LED signal
KLOE-2

BGO
em: 480 nm
ex: 304 nm

LSO
em: 402 nm
ex: 358 nm

BaF$_2$
X-ray luminescence
Peaks: 220 nm, 300 nm
em: 410 nm
ex: 348 nm

NaI(Tl)
em: 410 nm
ex: 348 nm

PWO
em: 424 nm
ex: 310 nm

LYSO
em: 402 nm
ex: 358 nm

CeF$_3$
em: 301 nm
ex: 265 nm

CsI(Tl)
em: 540 nm
ex: 322 nm

Wavelength (nm)

Intensity (a.u.)

Transmittance (%)
## LYSO vs LFS

<table>
<thead>
<tr>
<th></th>
<th>LYSO</th>
<th>LFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>7.1</td>
<td>7.2 - 7.3</td>
</tr>
<tr>
<td>Attenuation length (cm)</td>
<td>1.2</td>
<td>1.12</td>
</tr>
<tr>
<td>Decay constant (ns)</td>
<td>41</td>
<td>35 - 36</td>
</tr>
<tr>
<td>Max emission (nm)</td>
<td>420</td>
<td>435 - 438</td>
</tr>
<tr>
<td>Light yield (relative NaI)</td>
<td>75</td>
<td>80 - 85</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>8</td>
<td>9 - 12</td>
</tr>
<tr>
<td>Hygroscopic</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.81</td>
<td>1.78</td>
</tr>
</tbody>
</table>