The Low Energy Tagger for the KLOE-2 experiment

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KLOE has taken data until 2006 on the DAΦNE φ-factory at LNF
2.4 fb\(^{-1}\) have been acquired
KLOE is contributing to knowledge on
kaon physics, hadronic physics,
quantum interferometry
A new data taking campaign has been approved starting from 2010 (step-0):
- 5 fb\(^{-1}\) will be acquired
- KLOE detector will be upgraded in
  order to add “γγ physics” to its
  physics program
New sub-detectors will be added
inside KLOE in order to study these
new physics channels at the φ peak: a “tagging” system will detect scattered
beam particles which emitted a
photon at the interaction point
Present status of gamma-gamma physics

$\gamma\gamma$ physics stands for 

$$e^+ e^- \rightarrow e^+ e^- \gamma^* \gamma^* \rightarrow e^+ e^- + X$$

this process gives access to $J^{PC} = 0^{\pm+}, 2^{\pm+}$ states, not directly coupled to one photon ($J^{PC} = 1^{--}$): e.g. $\pi\pi$ ($\sigma$), $\eta$, $\eta'$, $f_0$, $a_0$

In the low-energy region, for $W_{\gamma\gamma} < 1\text{GeV}$, present experimental situation is unsatisfactory:

- small data samples and large backgrounds
  - large stat. and syst. uncertainties
- small detection efficiencies and particle ID for low-mass hadronic states
\( \gamma \gamma \) physics can be done at a \( \Phi \)-factory, on the \( \Phi \) peak:

Access to many interesting final states through photon emission from both colliding electron and positron

**TRUE, BUT...**

\( \gamma \gamma \) events acquired at the \( \Phi \) peak would suffer from \( \Phi \) decays as background

<table>
<thead>
<tr>
<th>( \gamma \gamma ) channel</th>
<th>( L = 10 \text{ fb}^{-1} )</th>
<th>Missing particle</th>
<th>Events</th>
<th>Background for:</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e^+ e^- \rightarrow e^+ e^- \pi^0 )</td>
<td>( 4 \times 10^6 )</td>
<td>( K_L )</td>
<td>( \sim 10^9 )</td>
<td>( \pi^0 \pi^0 )</td>
</tr>
<tr>
<td>( e^+ e^- \rightarrow e^+ e^- \eta )</td>
<td>( 1 \times 10^6 )</td>
<td>( K_L )</td>
<td>( \sim 2 \times 10^9 )</td>
<td>( \pi^+ \pi^- )</td>
</tr>
<tr>
<td>( e^+ e^- \rightarrow e^+ e^- \pi^+ \pi^- )</td>
<td>( 2 \times 10^6 )</td>
<td>( \pi^0 )</td>
<td>( \sim 10^9 )</td>
<td>( \pi^0 \pi^0 )</td>
</tr>
<tr>
<td>( e^+ e^- \rightarrow e^+ e^- \eta )</td>
<td>( 2 \times 10^4 )</td>
<td>( \eta )</td>
<td>( \sim 10^8 )</td>
<td>( \eta )</td>
</tr>
<tr>
<td>( \pi^0(\gamma \gamma) )</td>
<td>( \gamma )</td>
<td>( \sim 5 \times 10^8 )</td>
<td>( \pi^0 )</td>
<td></td>
</tr>
</tbody>
</table>

Tagging \( \gamma \gamma \) events by detecting \( e^+ e^- \) is mandatory to reduce backgrounds, together with \( P_T \) kinematical selection on the tagged events.
Scattered electrons escape from the KLOE detector along the DAFNE beam lines. Magnetic elements will deflect these “off-energy” particles out of vacuum tubes. A detailed description of the beam optics is necessary to track these particles and locate different escaping regions to place our taggers:

**MAD software:** nominal-energy beam simulation, no detailed off-energy tracking

**BDSIM software:** complete simulation of machine elements and bending power for off-energy particles

Agreement between the two has been checked for 510MeV electrons.
KLOE solenoid magnetic field has also been inserted into beam simulation.
Two position for tagging detectors, for two $e^+e^-$ energy ranges, have been found:
1) 160-230 MeV, 1 m away from interaction point “Low Energy Tagger” or LET
2) 425-490 MeV, 11 m away from interaction point: “High Energy Tagger” or HET
Tagging system acceptance

Depending on the energy of the emitted photons, $\gamma\gamma$ events will be tagged by the coincidence of two LET stations, one LET and one HET, or two HET

- HET-HET will only tag single-$\pi$ events
- HET-LET and LET-LET will span over the other possible decays

In order to get 5% energy resolution on the LET-LET coincidence (the most demanding one), we must reach 8% energy resolution on the single LET station

Combining all the three possible tagging combinations, we can get 500 pb$^{-1}$ of clean $\gamma\gamma$ physics during step-0
LET: a tracker or a calorimeter?

Energy from 0 to 500 MeV

at LET position the off-energy leptons show no correlation between energy, escape position and emission angle:

a calorimeter is necessary to measure their energy (for HET is different)
Space and environmental constraints

Placing the LET inside KLOE detector imposes many tight constraints:

- **available space limits the active volume** of the calorimeter → high density (low $X_0$)
- presence of KLOE B-field: **magnetic-insensitive photodetectors**

Electrons and positrons escape from the beam pipe with $11^\circ$ angle
**Which scintillator?**

Active volume: homogeneous crystal calorimeter with $X_0 \sim 1$ cm ($\sim 15 X_0$ in $\sim 15$ cm)

Energy range is limited: 160-230 MeV $\rightarrow$ at least 2 photoelectrons/MeV needed to get 5% resolution (stochastic term). “Fast” scintillating time for bunch crossing correlation

**Two candidates** on the market: PbWO$_4$ and LYSO(Ce)

<table>
<thead>
<tr>
<th>Parameter: $\rho$</th>
<th>MP</th>
<th>$X_0^s$</th>
<th>$R_M^s$</th>
<th>$dE/dx$</th>
<th>$\lambda_I^s$</th>
<th>$\tau_{decay}$</th>
<th>$\lambda_{max}$</th>
<th>$n^\frac{1}{2}$</th>
<th>Relative output$^\dagger$</th>
<th>Hygroscopic?</th>
<th>$d(LY)/dT$</th>
<th>Hygroscopic?</th>
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</thead>
<tbody>
<tr>
<td>Units: g/cm$^3$</td>
<td>°C</td>
<td>cm</td>
<td>cm</td>
<td>MeV/cm</td>
<td>cm</td>
<td>ns</td>
<td>nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>%/°C$^\downarrow$</td>
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<tr>
<td>NaI(Tl)</td>
<td>3.67</td>
<td>651</td>
<td>2.59</td>
<td>4.13</td>
<td>4.8</td>
<td>42.9</td>
<td>230</td>
<td>410</td>
<td>1.85</td>
<td>100</td>
<td>yes</td>
<td>−0.2</td>
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<td>BGO</td>
<td>7.13</td>
<td>1050</td>
<td>1.12</td>
<td>2.23</td>
<td>9.0</td>
<td>22.8</td>
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<td>480</td>
<td>2.15</td>
<td>21</td>
<td>no</td>
<td>−0.9</td>
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<tr>
<td>BaF$_2$</td>
<td>4.89</td>
<td>1280</td>
<td>2.03</td>
<td>3.10</td>
<td>6.6</td>
<td>30.7</td>
<td>630$^s$</td>
<td>300$^s$</td>
<td>1.50</td>
<td>36$^s$</td>
<td>no</td>
<td>−1.3$^s$</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.9$^f$</td>
<td>220$^f$</td>
<td>3.4$^f$</td>
<td></td>
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<td></td>
<td>1300</td>
<td>560</td>
<td>1.79</td>
<td>165</td>
<td>slight</td>
<td>0.3</td>
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<tr>
<td>CsI(Tl)</td>
<td>4.51</td>
<td>621</td>
<td>1.86</td>
<td>3.57</td>
<td>5.6</td>
<td>39.3</td>
<td>35$^s$</td>
<td>420$^s$</td>
<td>1.95</td>
<td>3.6$^s$</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>6$^f$</td>
<td>310$^f$</td>
<td>1.1$^f$</td>
<td></td>
<td></td>
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<tr>
<td>PbWO$_4$</td>
<td>8.3</td>
<td>1123</td>
<td>0.89</td>
<td>2.00</td>
<td>10.2</td>
<td>20.7</td>
<td>30$^s$</td>
<td>425$^s$</td>
<td>2.20</td>
<td>0.083$^s$</td>
<td>no</td>
<td>−2.7</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10$^f$</td>
<td>420$^f$</td>
<td>0.99$^f$</td>
<td></td>
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<tr>
<td>LSO(Ce)</td>
<td>7.40</td>
<td>2050</td>
<td>1.14</td>
<td>2.07</td>
<td>9.6</td>
<td>20.9</td>
<td>40</td>
<td>420</td>
<td>1.82</td>
<td>83</td>
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<tr>
<td>GSO(Ce)</td>
<td>6.71</td>
<td>1950</td>
<td>1.38</td>
<td>2.23</td>
<td>8.9</td>
<td>22.2</td>
<td>600$^s$</td>
<td>430</td>
<td>1.85</td>
<td>3$^s$</td>
<td>no</td>
<td>−0.1</td>
</tr>
</tbody>
</table>
Photosensor choice: Silicon Photomultipliers

- **KLOE** field \(=0.5T\) in the LET placement region → magnetic insensitive photosensor
- \(O(10^2)\) photoelectrons expected: high gain necessary

**SiPM (Silicon Photomultipliers) could be the solution**

SiPM (a.k.a. G-APD or MPPC) are arrays of very small Avalanche Photodiodes (APDs) operated in geiger mode, parallel-connected via individual quenching resistors. The sum of the “digital” signals of each G-APD, one for each photoelectron, makes the device analog again.

Advantages with respect to their parents (APD) and grandparents (PIN diodes):

- **high gain** \((10^6\) w.r.t. PIN, \(10^4\) w.r.t. APD)
- **thin** (no fake signals due to leaking shower particles reaching photosensor)
- **no avalanche fluctuations** from excess noise factor (geiger mode)
- **low bias voltage** (70V or less)
SiPM front-end electronics

The front end electronics has been custom designed to satisfy the detector requirements and to be compatible with the KLOE Electromagnetic Calorimeter (EmC) readout chain. Main requirements:

- very stable, low noise power supply for the SiPMs,
- working voltage setting and monitor for each SiPM channel,
- low noise, good linearity, low power consumption preamplifier.

Power module:

- main switching power supply: 90V, 10 parallel channels
- Control: - SiPM working voltage setting via control current
  - SiPM working voltage monitor

FEE:

- on board voltage regulator:
  - high stability, low noise, distributed regulation
  - adjustable in the range 60-80 V with 5 mV precision
  - 0.002 % load regulation
  - 0.02% long term stability
  - 10μV RMS output noise (10Hz-10kHz)
  - 2mA supplied current

- transimpedance preamplifier
  - Low noise, low power consumption
  - 2 transistor configuration with bootstrap technique
  - 24 mW power consumption
  - 2 μV/√Hz noise

High packing factor: 10X20 mm² board
We coupled this front-end electronics to Hamamatsu SiPM (MPPC) S10362-33-050C with **3600 pixels, 3x3 mm² active area**
A complete Monte Carlo simulation with GEANT4 is being used to model the LET detectors. Simulations for energy resolution, with respect to calorimeter dimensions and placement, will be used to validate test-beam data and choose the final design for the calorimeter.

 Deposited (black)  Detected (blue)

 Deposited and detected energy in one LET detector, averaged over the impinging off-energy beam particles.

 Shower containment (upper) and expected resolution (lower) with respect to length.
Different mechanical supports have been realized to couple the SiPMs to crystals in different configurations for cosmic rays, LED pulsing and e⁻ test beams.
Test beam campaign at LNF-BTF

- **Electron beam tests have been made, and are still ongoing**, at the Frascati Beam Test Facility BTF with “single” electrons of energy ranging from 150 to 500 MeV (lower energy tests ongoing in these days)
- First tests: PbWO vs. LYSO (single crystals with single SiPM):
  - 20x20x130 mm³ crystals
  - 3x3 mm² SiPM (light collection on end face reduced by 45 times)

![Graph showing light yield for PbWO and LYSO with and without optical grease.](image)

- LYSO **without optical grease, with optic attenuator**
- PbWO **with optical grease**

Light Yeld for PbWO showed too poor for our pourposes
LYSO is instead promising as for light yeld and emission time
**Ongoing test beam**

- An array of **14 SiPM** is now mounted on a crystal matrix of **60x55x130 mm³**, made of both **LYSO** and **PbWO**, to test its energy resolution, linearity, timing capabilities.
- Amplifier gain has been lowered from 20 to 2
- Last but not least, the coupling between this detector prototype and the **KLOE EMC DAQ chain** is being tested

**Preliminary results are very promising:**

Scan along the crystal front faces, across one “crack”

Timing performance of a single LYSO crystal: **400ps time resolution**
Test beam preliminary results

Energy resolution has been evaluated by summing over 2/3 of the crystals (PbWO crystals are being calibrated) so lateral leakage is still high

Stochastic term= 2.8%/√E consistent with ~2 PE/MeV as expected from gain and amplification

Uncorrelated noise contributes with 0.7%/E, other test-beam setup-driven noise contributions are being investigated

Constant term is consistent with what expected from leakage

The output signal is proportional to the number of fired cells as long as the number of photons in a pulse ($N_{\text{photon}}$) times the photodetection efficiency PDE is significantly smaller than the number of cells $N_{\text{total}}$:

$$A \approx N_{\text{fired cells}} = N_{\text{total}} \cdot \left(1 - e^{-\frac{N_{\text{photon}} \cdot PDE}{N_{\text{total}}}}\right)$$

2 or more photons in 1 cell look exactly like 1 single photon.

When 50% of the cells fire the deviation from linearity is 20%.

Very good linearity: SiPM pixels not saturated $\Rightarrow < 1000$ p.e. @ 500 MeV
Mechanical integration is now aiming at defining the dimensions of the LET stations, their exact placement around the beam pipe and within the space allocated for CCALt in step-1. A combined light pulsing-radioactive source calibration is being designed to monitor detector gain. Temperature sensors will be placed close to SiPMs to monitor temperature variations, and eventually correct bias voltage.
Conclusions

By these test-beam results we will finalize the design of the LET stations:

- crystals will be wrapped by Tyvek™ to increase LYSO light yield
- we will use 3x3mm², 14400 pixel Hamamatsu MPPC to increase photoelectron statistics without SiPM pixel saturation
  → 4 times photoelectrons available, 35% photon detection efficiency, lower temperature dependance of gain and dark count
  → we can expect to stay within 7% total energy resolution in the LET energy acceptance

Final design will be ready before summer,

and then...

LET... there be light!