An extreme high resolution Timing Counter for the MEG Upgrade

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on behalf of the MEG collaboration

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Outline

- The MEG experiment in a nutshell
- The MEG upgrade and the new Timing Counter design
- R&D work on Timing Counter single element
- Geometry, SiPMs, scintillators comparison
- The first TC prototype: towards a <30ps resolution
- Results from beam test in Beam Test Facility in Frascati
The MEG experiment in a nutshell

• Looking for cLFV $\mu \rightarrow e \gamma$ decay

• Tiny signal (current $\text{BR}(\mu \rightarrow e \gamma) < 5.7 \times 10^{-13}$) in a huge background environment

• Needs extremely high resolution on signal kinematic variables:
  • Energies (Drift chambers, liquid Xe Calorimeter)
  • Relative angles (DC, LXe)
  • Relative timing (Timing Counter, LXe)

• After 6 years of successfully data taking, it’s time for an upgrade...
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The MEG experiment upgrade

• Usage of existing infrastructure
  • cryostat, magnet, beam line, CW accelator for calibrations

• Redesign of Drift Chamber system

• Change in LXe inner face readout devices (PMT ⇒ SiPM)

• New Timing Counter design

• In a few years time schedule...
A new pixelated TC

- 2x array of 15 scintillating bars readout by PMTs arranged in a cylindrical shape

- One of the fastest TC ever: mean reso ~65ps, but some issues are present:
  - PMT operation in high magnetic field and He environment
  - Low granularity
  - Large scintillator (40x40x800 mm$^3$) bars generate uncertainty in z impact point, large multiple scattering, spread of optical photons trajectory

- Higher granularity: hundreds (~2 x 300) of small scintillator plates (typical sizes: 90x40x4 mm$^3$) read-out by Silicon PhotoMultipliers (insensitive to magnetic field, He environment)

- High single pixel resolution
- Timing resolution can be largely improved by using multiple hits information
- Thin (4mm) scintillator for less multiple scattering
- Less pile-up also with higher beam intensity
• Double side read-out with 3 SiPMs array in series connection

• Fast plastic scintillator coupled with optical cement

• Small material budget along positron trajectories: PCBs act also as framework

• Ambiguity in positron track and optical path spread inside scintillator are reduced

• Impact time and position reconstructed with sum / difference of single array time

Intensive R&D work to define the best geometry, choice of scintillator and SiPM
Multiple hits

Positron time can be measured by averaging the positron hit time of each pixels, after correcting for travel time between pixels:

\[
\sigma^2 = \frac{\sigma^2_{\text{single}}}{N_{\text{hit}}} + \frac{\sigma^2_{\text{inter pixel}}}{N_{\text{hit}}} + \sigma^2_{\text{MS}} \left( N_{\text{hit}} \right)
\]

Single hit resolution and path length contribution scale as \( N_{\text{hit}} \).

Multiple scattering effect is added at each hit

\[\sigma_{\text{single}} \approx 50\text{÷}60\text{ps}\]
\[\sigma_{\text{inter pixel}} \approx 40\text{ps}\]
\[\sigma_{\text{MS}} < 10\text{ps}\]

Expected time resolution investigated on MC simulation:

\[\langle N_{\text{hit}} \rangle = 6.6\]

Expected reso \( \sim 30\text{ps} \) with 6/7 hits
Extensive tests were led to check the best single counter configuration. Item to be fixed:

- Counter geometry (sizes of scintillator, number of SiPMs)
- Scintillator
- SiPMs
- SiPM connection
- Scintillator wrapping

We prepared several prototypes using a plastic frame (not the final one) to couple SiPM arrays to scintillator. Optical grease was used instead of cement to permit array / scintillator changes.
Single counter R&D: setup

• We use a “reference counter” (RC, 5x5x5 mm³ scintillator coupled to SiPM Hamamatsu S10362-33-050) for trigger and reference time.

• Electrons from $^{90}$Sr source (endpoint : 2.2 MeV)

• Signals from SiPMs are delayed by ~35ns cable (~7.5m) and (passively) splitted by a factor 2 (4 for RC) then pass PSI designed amplifier (G~20, BW~600MHz).

• DAQ with DRS evaluation board v4, dynamic range (-0.1, 0.9)V.

• Time resolution is defined as the sigma of the Delta T distribution

• Setup mounted in thermal chamber, tests at different temperatures are possible
Different scintillator sizes (L: 60, 90, 120 mm; H: 30, 40 mm) were tested in order to check time resolution.

Number of hits and efficiency as a function of pixel sizes has been studied on MC simulation.

The resolution is worse by increasing pixel size, but efficiency increases: best tradeoff between performance, efficiency and number of channels ($!) was found to be 90x40 mm$^2$. 
Scintillator comparison

3 kinds of plastic scintillator (BC418, BC420, BC422) with different properties were tested with a 90x30x5 mm³ pixel.

<table>
<thead>
<tr>
<th>properties</th>
<th>BC418</th>
<th>BC420</th>
<th>BC422</th>
</tr>
</thead>
<tbody>
<tr>
<td>LY(%Anthracene)</td>
<td>67</td>
<td>64</td>
<td>55</td>
</tr>
<tr>
<td>Rise time (ns)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.35</td>
</tr>
<tr>
<td>Decay time (ns)</td>
<td>1.4</td>
<td>1.5</td>
<td>1.6</td>
</tr>
<tr>
<td>Wavelength (peak, nm)</td>
<td>391</td>
<td>391</td>
<td>370</td>
</tr>
<tr>
<td>Attenuation length (cm)</td>
<td>100</td>
<td>110</td>
<td>8</td>
</tr>
<tr>
<td>Resolution (ps)</td>
<td>55.8</td>
<td>57.7</td>
<td>51.2</td>
</tr>
</tbody>
</table>

Best resolution at the price of small attenuation length, but it should not be an issue for few centimeters pixels.
SiPMs: temperature dependance

A good BD vs T coefficient is needed to have stable operation.

I-V curve and BD vs Temperature coefficient fit for different SiPM:

HAM 10362-33
ADV NUV-SiPM3S-P
KET PM3350
SiPMs: bias scan

Different overvoltage ranges were scanned, due to the different I-V curves behaviour

BC422, 60x30x5mm³

Reference counter resolution was estimated to be ~35ps and it is subtracted in these plots

Best result ~44 ps with Hamamatsu (ADV: ~53ps, KET: ~70 ps)
ADV & KET show better temperature stability

We decide to check both HAM and ADV in our beam test
We checked the time resolution dependence from the impact point moving the source in different positions.

Resolution is a little bit worse near pixel edges: small (~5ps) dependence from position can be seen.
Position resolution

Light velocity in scintillator can be extracted by fitting $\Delta t$ distribution in fixed source position

Spread in reconstructed position gives 8mm resolution
Beam test @BTF, Frascati

- $e^+$ beam
- energy 48 MeV
- mean $e^+$ number per bunch: 1.9
In order to evaluate the feasibility of the multiple hits scheme, a first prototype was built.

Up to 10 counters mounted on a movable stage (x-y-θ scan)
Fixed reference counter for timing / triggering purposes
90x40x5 mm³ BC418 pixels
Charge reconstruction

e+ bunch multiplicity can be reconstructed by SiPMs charge integration
Charge reconstruction

e+ bunch multiplicity can be reconstructed by SiPMs charge integration

Landau peak for single e+ can be clearly seen by cutting over SiPM reconstructed charge
**Beam test: results**

\[ T_{\text{odd}} - T_{\text{even}} \quad \text{and} \quad T_{\text{ref}} - T_{\text{counter}} \]

- **27ps resolution with 8 pixels!**
- **RC resolution estimated to be \( \sim 35 \text{ ps} \)**
Proving multiple hit scheme

Resolution as a function of the number of hits

Mean number of hit from MC $\sim 6.6$, corresponding resolution is $\sim 30$ps

Resolution [ps]

$N_{\text{hit}}$

2 4 6 8
Multiple scattering

An estimate of the multiple scattering spread can be obtained by the width of the reconstructed position distribution, subtracting the contribution from position resolution (8mm)

Comparison between 1st and 8th counter reconstructed position
Conclusion & perspective

• An upgrade of the MEG Timing Counter, based on a system of hundreds of small pixels readout by SiPMs was presented.

• It is expected to obtain a substantial improvement in timing resolution with respect to the current MEG TC (reso ~65ps), thanks to the good single pixel resolution and the use of multiple hits average timing.

• Intensive tests were led to check the best single counter configuration, exploiting different geometries, SiPMs and scintillators.

• The best trade-off between resolution, efficiency and number of channels is currently found to be a 90x40x5 mm³ pixel.

• A small prototype, made of 10 counters was built and measured under beam at the BTF in Frascati: a preliminary resolution <30ps was obtained with 8 hits. A resolution of ~30ps is obtained with 6/7 hits (mean value from MC simulation).

• Further studies are on going: optimization of beam test analysis, new SiPMs devices...
Back-up slides
**DRS synchronization**

- **Before**
  - $\sigma = 377$ ps

- **After**
  - Time jitter among counters 23-26 ps

**Diagram:**
- Chart showing $t_{ch1} - t_{ch2}$ distribution before synchronization (spread) and after synchronization (peak).

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*MEG*
Mu-E-Gamma Collaboration

*東京大学*
The University of Tokyo
DRS synchronization

- synchronize many different channels with common clock.

Time jitter among counters 23-26 ps
Amplifier

A. Stoykov (PSI)
SiPM properties

### SiPM properties

#### Selection guide

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>S10362-33 series</th>
<th>S10931 series</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective active area</td>
<td>Unit</td>
<td>-</td>
<td>1400-3000</td>
</tr>
<tr>
<td>Number of pixels</td>
<td>$x$</td>
<td>3</td>
<td>1 to 3</td>
</tr>
</tbody>
</table>

#### Absolute maximum ratings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Min</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage temperature</td>
<td>$T_{st}$</td>
<td>-40</td>
<td>$&lt;$0</td>
<td>°C</td>
</tr>
<tr>
<td>Thermal operating range</td>
<td>$T_{op}$</td>
<td>-25</td>
<td>+60</td>
<td>°C</td>
</tr>
<tr>
<td>Breakdown voltage</td>
<td>$BV$</td>
<td>100</td>
<td>350</td>
<td>V</td>
</tr>
</tbody>
</table>

**Stresses beyond those listed under “Absolute Maximum Ratings” may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated in the operational sections of the specifications is not implied. Exposure to absolute maximum-rated conditions for extended periods may affect device reliability.**

#### Electrical and optical characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Min</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral response range</td>
<td>$\lambda_{sp}$</td>
<td>400</td>
<td>800</td>
<td>nm</td>
</tr>
<tr>
<td>Peak sensitivity</td>
<td>$G_{p}$</td>
<td>0.5</td>
<td>1.0</td>
<td>%</td>
</tr>
<tr>
<td>Peak signal wavelength</td>
<td>$\lambda_{p}$</td>
<td>300</td>
<td>500</td>
<td>nm</td>
</tr>
</tbody>
</table>

#### Geometrical, electrical, and optical typical characteristics

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>ASD-NUV-SiPM35-P Family</th>
</tr>
</thead>
<tbody>
<tr>
<td>$AA$</td>
<td>Effective Area</td>
<td>3 x 3</td>
</tr>
<tr>
<td>$CS$</td>
<td>Cell Size</td>
<td>2x2</td>
</tr>
<tr>
<td>$N$</td>
<td>Cell number</td>
<td>3600</td>
</tr>
<tr>
<td>$I_{sp}$</td>
<td>Spectral response range</td>
<td>300 to 500</td>
</tr>
<tr>
<td>$G_{p}$</td>
<td>Peak sensitivity</td>
<td>0.5</td>
</tr>
<tr>
<td>$BV_{th}$</td>
<td>Breakdown voltage</td>
<td>27 to 35</td>
</tr>
<tr>
<td>$BV_{mm}$</td>
<td>Breakdown voltage stability</td>
<td>25</td>
</tr>
</tbody>
</table>

#### KETEK Silicon Photomultiplier

- New state-of-the-art sensor for the detection of ultra-low level light

**Features**

- Single photon counting
- High photon detection efficiency
- Optimized for blue light
- High gain and excellent timing properties
- Low dark count rate and low crosstalk probability especially for trench type
- Huge bias voltage range of stable operation
- Extremely low temperature coefficient

**Geometrical Data**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Sensor Area</td>
<td>3.0 ± 3.0 mm²</td>
</tr>
<tr>
<td>Micropixel Size</td>
<td>50 x 50 µm²</td>
</tr>
<tr>
<td>Number of Pixels</td>
<td>3600</td>
</tr>
<tr>
<td>Geometrical Efficiency</td>
<td>70%</td>
</tr>
</tbody>
</table>

**Spectral Properties**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Range</td>
<td>400 to 800 nm</td>
</tr>
<tr>
<td>Peak Wavelength</td>
<td>420 nm</td>
</tr>
<tr>
<td>$P_{d}$ at 420 nm</td>
<td>$\geq$ 50%</td>
</tr>
<tr>
<td>Gain $M$</td>
<td>$\geq 2.0 $</td>
</tr>
<tr>
<td>Temp. Coefficient</td>
<td>$\leq 2.5$</td>
</tr>
<tr>
<td>Dark Rate</td>
<td>$\leq 0.65$</td>
</tr>
<tr>
<td>Crosstalk</td>
<td>$\leq 35$</td>
</tr>
</tbody>
</table>

**Electrical Properties**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breakdown Voltage</td>
<td>27 V</td>
</tr>
<tr>
<td>Operation Voltage</td>
<td>25 %</td>
</tr>
</tbody>
</table>
Series vs parallel

Resolution vs Overvoltage: Hamamatsu

Resolution vs Overvoltage: Hamamatsu Parallel
Wrapping comparison

No reflector

σ_{ave} = 45.1 ps

Teflon tape

σ_{ave} = 47.4 ps

Al Mylar

σ_{ave} = 43.5 ps

3M radiant mirror

σ_{ave} = 42.3 ps

Measured resolution map

BC422 (30×60×4.5mm³) 6×SiPMs