Silicon Photomultipliers for the decay tunnel instrumentation of the ENUBET neutrino beam

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Neutrino beam for precision physics

The next generation of short baseline experiments should rely on:

• a direct measurement of the fluxes
• a narrow band beam → energy known a priori from beam width
• a beam covering the region of interest from sub- to multi-GeV

ENUBET project

Goal: demonstrate the technical feasibility and physics performance of a neutrino beam where lepton production at large angles is monitored at single particle level exploiting the Ke3 decay.

Two aims:

• Design/simulate the layout of the hadronic beamline
• Build/test a demonstrator of the instrumented decay tunnel

Recognized in the CERN Neutrino Platform as ENUBET/NP06
A high precision narrow band $\nu$ beam

**CHALLENGES:**

The decay tunnel is a harsh environment:
- particle rates: $> 200$ kHz/cm$^2$
- instrumented region: $\sim 50$ m
- backgrounds: pions from $K^+$ decays
  $\rightarrow$ need to veto 98–99% of them
- significant spread in the initial direction

**REQUIREMENTS:**

**$e^+$ tagger:**
- longitudinal sampling
- homogeneity
  $\rightarrow$ integrated light-readout
- Separate $e^+$, $\pi^+$, $\mu$ (PID)

**Photon veto:**
- photon identification capabilities
- precise timing of the particles ($< 1$ ns)
- exploit 1 mip – 2 mip separation
The integrated fluence to achieve 1% of statistical error on $\nu_e$ CC depends on the position of the calorimeter with respect to the axis of secondary beam at the entrance of the decay tunnel.

ENUBET @ 1 m distance (lifetime - integrated):
- non ionizing fluence: $1.8 \times 10^{11}$ n/cm$^2$ 1-MeV eq.
- ionizing dose: 0.06 kGy
The Tagger/Photon Veto technology

Compact shashlik calorimeter
Ultra Compact Module (UCM):

1) compact calorimeter with longitudinal segmentation
2) integrated γ-veto

- longitudinal (~4 X₀) segmentation.
- 3x3x1.5 cm³ Fe + 3x3x0.5 cm³ scint. modules
- SiPM embedded in the bulk of the calorimeter

Separate e⁻, π⁺, μ

Photon Veto Rings (t₀ layer):

3 x 3 cm² pads of plastic scintillator readout by SiPM
Factory Parameters:
- Active Area: 1 x 1 mm$^2$ (match with WLS fiber $\varnothing = 1$ mm$^2$)
- Cell pitch: < 25 $\mu$m
- Breakdown Voltage @T$_{\text{ROOM}}$: ~ 28V

Tests:
- Exposure to fast neutrons @ Irradiation Test Facility of Laboratori Nazionali di Legnaro (LNL)
- Measure the response to MIP and electrons @ CERN T9 beamline
Irradiation tests @ LNL

Van der Graaf accelerator (Vmax = 7 MV)

Protons on Beryllium target: \[ p (5 \text{ MeV}) + ^9\text{Be} \rightarrow n + X \]

Irradiated sample inside an experimental area: external shield of concrete, inner layer of water as neutron moderator.
Neutron Yield assessment


Expected fluxes on irradiated samples evaluated from:


• real time monitoring of proton current to the target (current integrator)

• Neutron backscattering on the shielding estimated with FLUKA 2011 → negligible contribution
Irradiated samples

3 PCB Boards - Each Board hosts:
- 9 SiPM - parallel connection
- Passive components
- Signal routing to front-end
- Readout through a decoupling capacitor
  no amplification

SiPM tested: cell pitch 12, 15, 20 \( \mu \text{m} \)

1 PCB Board equipped with:
- 1 SiPM - 12 \( \mu \text{m} \) cell pitch
- Readout with Advansid amplifier
  (ASD-EP-EB-N) removed during exposure time
Irradiation Procedure

• All PCB boards irradiated with:
  • minimum dose: $1.8 \times 10^6$ n/cm$^2$;
  • maximum dose: $1.7 \times 10^{11}$ n/cm$^2$;

• During irradiation SiPM are:
  • not biased
  • temperature monitored (two LM 35 sensors – Arduino One board)
    • maximum increase + 10 °C w.r.t $T_{Env}$
    • time to reach room temperature after irradiation: 15-30 min.

• After each irradiation run:
  • I-V curve recorded (Keythley 485 Picoammeter);
  • darkCurrent and p.e. sensitivity measured (Rohde & Schwarz RTO 1024 oscilloscope).
FBK - RGB-HD sensors shows after irradiation:
- minor changes in the breakdown voltage
- dark current increases by more than two orders of magnitude
Sensitivity to single photo electron

Single SiPM PCB 12 \( \mu m \) cell, 1 mm\(^2\)

sensitivity lost at fluence \( \geq 3 \times 10^9 \) n/cm\(^2\)
TB @ CERN - T9 beamline

- Particle beam composition:
  - Electrons;
  - Muons;
  - Pions;

- Momentum selected in the range 1 - 5 GeV → covering the whole ENUBET energy range;

SiPM after irradiation were stored @ 25 °C for three months
Strip detectors used to select particles hitting the UCM front face (fiducial area 2x2 cm²) and crossing it.

Electrons selection:
- Signals required in both Cherenkov Counters;

MIP-like particle (muons and not interaction pions) selection:
- No signals in Cherenkov counters and signals in muon catchers;
UCM Under Test

2 UCMs equipped with both irradiated and not irradiated boards:

• **Prototype 16B:**
  - 5 iron slabs (3x3x1.5 cm$^3$) interleaved with
  - 5 scintillator tiles (3x3x0.5 cm$^3$)
  - EJ-200 + WLS Kuraray Y11
  - ~50 p.e. for a MIP crossing the unit
  (from lab. Test with C.R.)

• **Prototype 17UA:**
  - 5 iron slabs (3x3x1.5 cm$^3$) interleaved with
  - 5 scintillator tiles (3x3x1.35 cm$^3$)
  - Uniplast Injection Molded + WLS Kuraray Y11
  - ~85 p.e. for a MIP crossing the unit
  (from lab. Test with C.R.)
UCM 16B - Not Irradiated PCB

- SiPM overvoltage: \( \sim 9\) V
- MIP signal is separated from dark noise
  - it can be employed to monitor changes in UCM response over time and equalize the response
- Electrons well separated from MIP particles
UCM 16B Irradiated board

- SiPM overvoltage: ~ 9 V
- MIP is NOT separated from dark noise after irradiation
- Electrons separated from dark noise
UCM 17UA Irradiated PCB

- SiPM overvoltage: $\sim 9$ V
- MIP is still visible after irradiation
- Electrons separated from dark noise
Phothon Veto SiPM - SenSL 30020 J

**Factory Parameters:**
- Active Area: 3 x 3 mm² (match with 2 WLS fibers Ø = 1 mm²)
- Cell pitch: 20 µm
- Breakdown Voltage @T_{ROOM}: ~ 24V

**Tests:**
- SiPM characterization with laser pulses (Picosecond Laser λ = 405 nm)
- Measure the response to MIP an exploit 1-2 mip separation @ CERN T9 beamline
Laser test $V_{\text{overvoltage}} = +3\, V$

\begin{align*}
\text{PKA} & \quad \text{h} \\
\text{Smaller} & \quad 1622 \\
\text{Mean} & \quad 0.1433 \\
\text{RMS} & \quad 0.68144 \\
\text{P} & \quad 127.4 \pm 123 \\
\text{Prob} & \quad 0.3746 \\
\text{G0} & \quad \text{peak constant pedestal} \quad 3.926 \pm 0.079 \\
\text{G0} & \quad \text{peak value} \quad 0.005494 \pm 0.0000591 \\
\text{sig} & \quad \text{peak total signal} \quad -0.000102 \pm 0.000072 \\
\text{C1} & \quad \text{1st pixel} \quad 0.81094 \pm 0.00058 \\
\text{C1} & \quad \text{std deviation of the 1st pixel} \quad 0.0006172 \pm 0.000 \\
\text{Peak Amplitude (V)} & \quad \text{total} \quad 7.927 \pm 0.080 \\
\end{align*}
Material:
• Scintillator: EJ 204 3x3x0.5 cm³
• TiO₂ painting: EJ / 510 reflective coating
• 2 WLS fibers - BCF 92 - 40 cm
• Optical Glue: EJ - 500

Results:
• Collection efficiency: > 95%
• Time resolution: ~400 ps
• 1 mip / 2 mip separation

Custom Optical Connector

\[ \pi^- + p \rightarrow n + \pi^0 (\rightarrow \gamma \gamma) \]
Profiting of t0 design new UCM configuration is under investigation:

- WLS fibers from scintillator sides are bundled to single SiPM reading 10 fibers (1 UVC)
- Fibers are connected with a custom optical connector;
- 40 cm WLS fibers allow for
  - reducing neutron flux impinging on SiPM
  - MIP signal preserved for entire life-time of ENUBET
  - better accessibility (replacement is possible)
  - reproducibility in WLS-SiPM connection;
Neutron reduction lateral readout

- 30 cm of borathed polyethylene in front of SiPM
- FLUKA Simulation (proton 400 GeV)
- Reduction Factor ~18 averaging over the spectrum
Conclusions (1/2)

ENUBET aims:
• at monitoring lepton production at large angles (single particle level).

CHALLENGE
the decay tunnel is a harsh environment (particle rate > 200 kHz /cm²)
→ lifetime integrate non ionizing fluence $1.8 \times 10^{11}$ n/cm² 1-MeV eq.

FBK - SiPM + UCM integration:
• Irradiation tests @ LNL → RGB-HD sensors shows after irradiation:
  • minor changes in the breakdown voltage
  • dark Current increases by more than two orders of magnitude
• Test @ T9 – CERN beamline:
  • MIP is NOT separated from dark noise after irradiation for standard UCM
  → it can be preserved by increasing the scintillator thickness

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Conclusions (2/2)

**Photon Veto:**

- SiPM SenSL 30020J $\rightarrow \sigma_t \sim 70$ ps with laser $\lambda \sim 400$ nm
- Test @ T9 - CERN beamline
  - $\sigma_t \sim 400$ ps (matching requirement < 1 ns)
  - 1 mip / 2 mip separation (matching requirement $e^+ / e^- e^+$ separation)

**UCM modified with $t_0$ - like design allow for:**

- **reducing neutron flux impinging on SiPM** $\rightarrow$ MIP signal preserved for entire life-time of ENUBET
- better accessibility (replacement is possible)
- reproducibility in WLS-SiPM connection

Backup slides
Standard UCM
The tagger demonstrator

- Length ~3m → allow the containment of shallow angle particles in realistic conditions
- Fraction of $\phi$
- Due by 2021