The Mu2e calorimeter

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December 18, 2013

Outline

1. Mu2e experiment: search for $\mu \rightarrow e$ conversion
2. Mu2e Detector
3. Calorimeter and its Performance
4. Photodetector R&D

Mu2e Experiment - Search for $\mu \to e$ Conversion on Aluminum

- in the SM, fermion fields do mix, mixing is large for quarks and neutrinos
- no charged lepton mixing observed so far
- most stringent limits on Charged Lepton Flavor Violation (CLFV) come from $\mu \to e$ transitions: $\mu \to e$ conversion, $\mu \to e\gamma$, $\mu \to eee$
- coherent $\mu \to e$ conversion: $\mu^- A \to e^- A$, the nucleus left intact
- current limit (SINDRUM II, PSI, 2006) :

$$R_{\mu e}^{Au} = \frac{\Gamma(\mu^- Au \to e^- Au)}{\Gamma_{\mathrm{capture}}(\mu^- Au)} < 7 \times 10^{-13} @ 90\% CL$$

- CLFV in the SM is very small, for example, B($\mu \to e\gamma$) < 10^{-54}

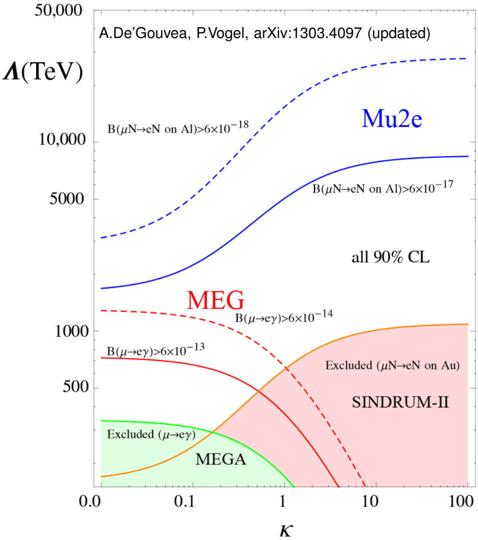
Direct CLFV searches and the new physics Mass Scale

- the CLFV lagrangian in EFT:

$$\mathcal{L}_{CLFV} = \frac{m_\mu}{(k+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \text{h.c.} +$$

$$\frac{k}{(k+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{q}_L\gamma_\mu q_L) + \text{h.c.}$$

- $k - \Lambda$ plane gives a model-independent view
- Mu2e will significantly improve the sensitivity limits for all parameter choices

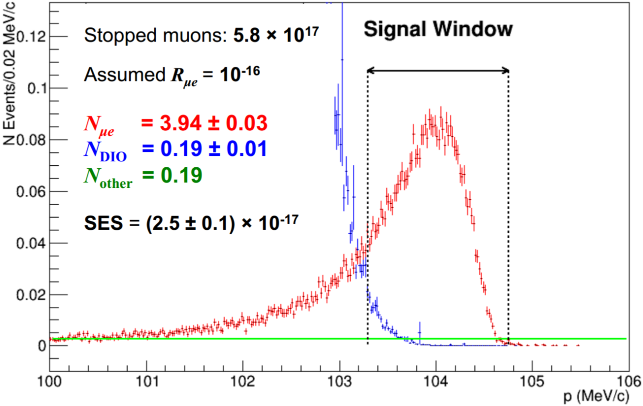


- LHC probes mass scale of ∼ 10 TeV, CLFV searches - $10^3 - 10^4$ TeV

$\mu \rightarrow e$ Conversion on Aluminum

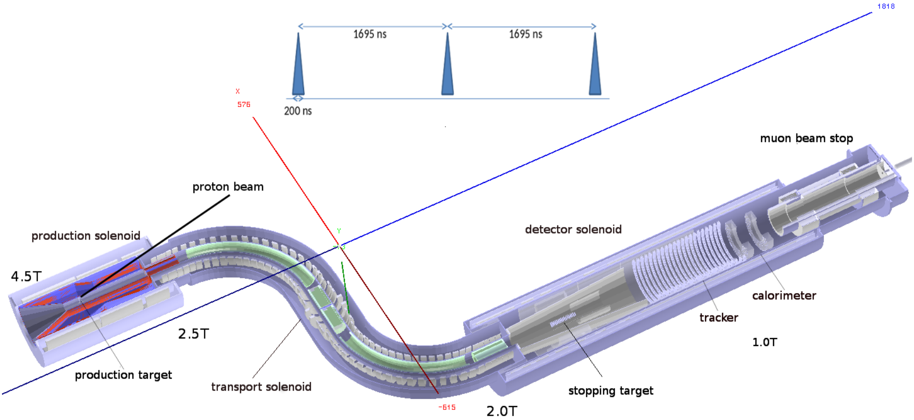
- produce high purity muon beam, stop muons in the nuclear target
- after a muon stops in the target, it gets to the s-shell of an Al atom
- then, two processes start competing:
  - muon decay-in-orbit (DIO): $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$
  - muon capture by an Al nucleus (T_{Al} = 864 ± 2 ns), followed by $\mu^- p \rightarrow n\nu$;
- conversion signature:
  - **an electron with momentum $p_e = m_\mu - E_b - E_{recoil}$, close to 105 MeV/c**
- nuclear transitions, following the capture, produce protons, neutrons, and photons creating random hits in the detector
- DIO becomes the most important irreducible background

Expected Sensitivity



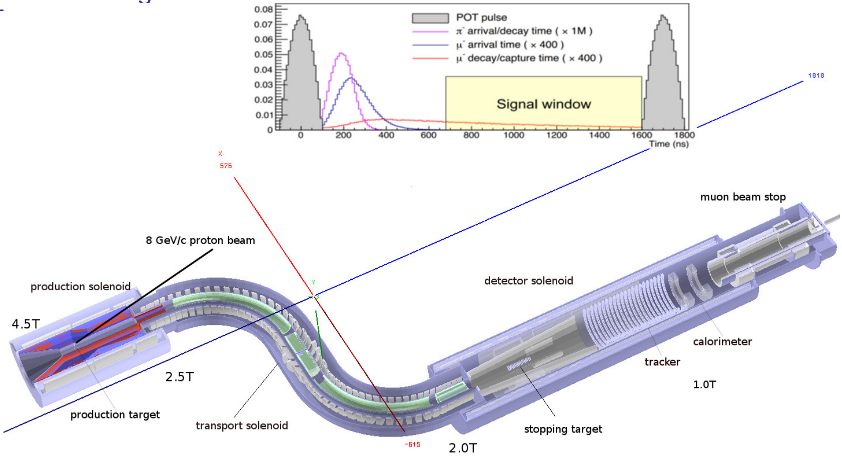
- 3 years of data taking: 3.6×10^{20} protons on target
- expected background: 0.4 ± 0.1 events (Mu2e CDR)
- expected single event sensitivity (SES) : $(2.5 \pm 0.1) \times 10^{-17}$
- an upper limit @90%CL : $2.3 \times \mathrm{SES}$

Mu2e Detector



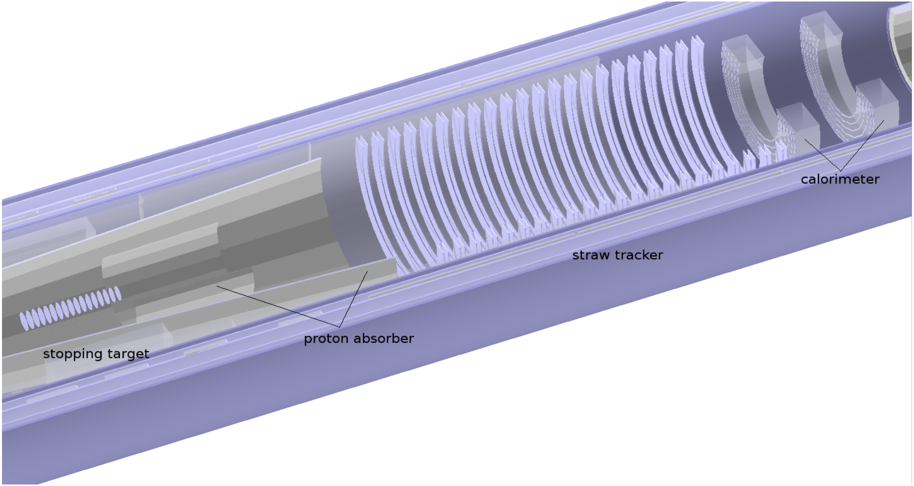
- system of magnets with graded field allows to produce $\sim 10^{10}$ stopped muons / second
- large acceptance: 1.6×10^{-3} stopped muons per proton on target

More on Timing



- to reduce prompt background down to the level $N_{exp} << 1$ event:
  - the signal window is delayed by $\sim$ 700 ns
  - proton extinction $\mathrm{N_{out\ of\ bunches}/N_{in\ bunches}}$ of 10^{-10} is required
- cosmic muon rejection at a level of 10^{-4} is needed
- after that, the background is dominated by muon interactions in the stopping target

Detector Solenoid



- the proton absorber “catches” protons coming out of the stopping target
- the calorimeter - 2 disks separated by $\sim$ 70 cm - is located behind the straw tracker
- the tracker and the calorimeter are located in a uniform field B = 1 Tesla

The Calorimeter Geometry

- geometry optimization in progress
- disk $R_{in} =\sim$ 360 mm , $R_{out} \sim$ 60-67cm, the second disk could be smaller then the first
- hexagonal BaF_2 crystals, length $\sim$ 200 mm, distance between parallel face sides $\sim$ 35 mm
- overall, about 1500 crystals
- readout: 2 1x1 cm^2 APDs per crystal
- orange circles: pipes of the calibration radioactive source system

BaF_2

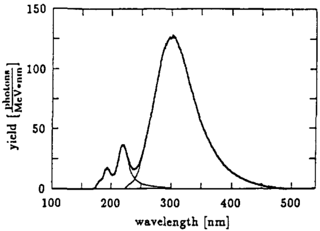
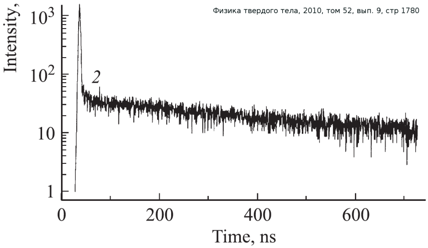


Fig. 2. BaF_2 time resolved emission spectrum. Distributions of the cross-over luminescence ($\lambda_{peak} = 220$, 195 nm; fast emissions) and self-trapped excitons ($\lambda_{peak} = 300$ nm; slow emissions) are shown [4].

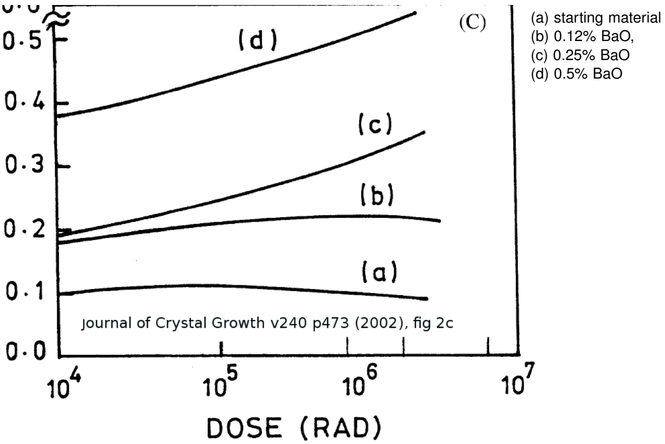


Физика твердого тела, 2010, том 52, вып. 9, стр 1780

- density : 4.89 g/cm^3, $R_{Moliere}$ = 3.1 cm, radiation length: 2.03 cm
- 2 spectral components: **220 nm, 0.9 ns (10%)** and 300 nm, 650 ns (90%)
- light yield of the fast component: about 1,800 photons/MeV
- (non-PDG) claim that the total light yield is $\sim$ 10,000 photons/MeV should be questioned
- fast component allows to work with much higher intensities
- photodetectors need to be sensitive in the UV region
- use waveform digitization to reduce sensitivity to the slow component

Radiation Hardness of BaF_2

Absorption at 200nm



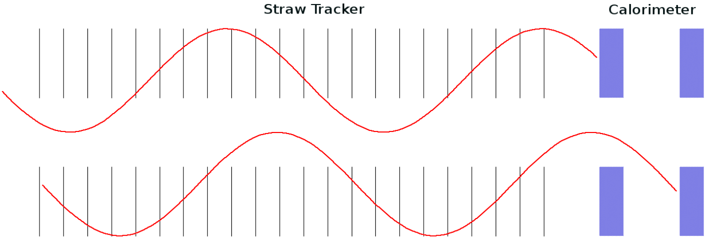
Journal of Crystal Growth v240 p473 (2002), fig 2c

- radiation hard (up to 10^7 rad), control of oxigen contamination during growth important

What defines the calorimeter performance requirements ?

- the calorimeter provides the energy and the timing measurements
- what drives the requirements to the accuracy?
- particle identification: e/μ separation, together with the tracker
- **background rejection: cosmics**
- trigger for monitoring the tracking efficiency

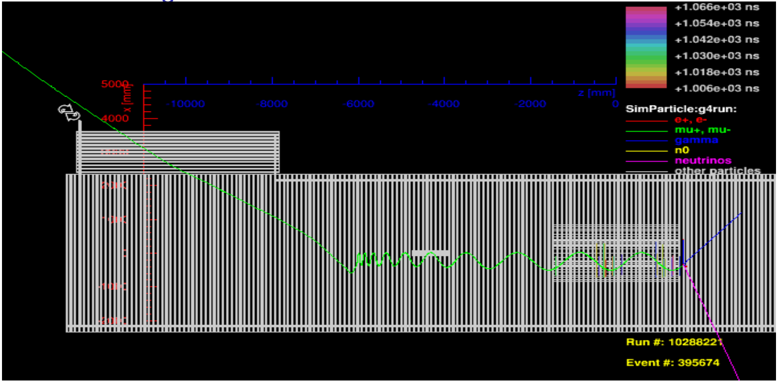
Tracker and Particle ID



- given a reconstructed 100 MeV/c track, need to tell whether it is an electron or a muon
- for a 3-m long tracker, the difference between the e/μ time-of-flight $T\mu - T_e \sim 10$ ns
- particle time, t0, is not known, but determined by the fit
- 4 possible hypotheses: electron or muon, moving downstream or upstream
- combine dE/dX and timing from the straw tubes to calculate

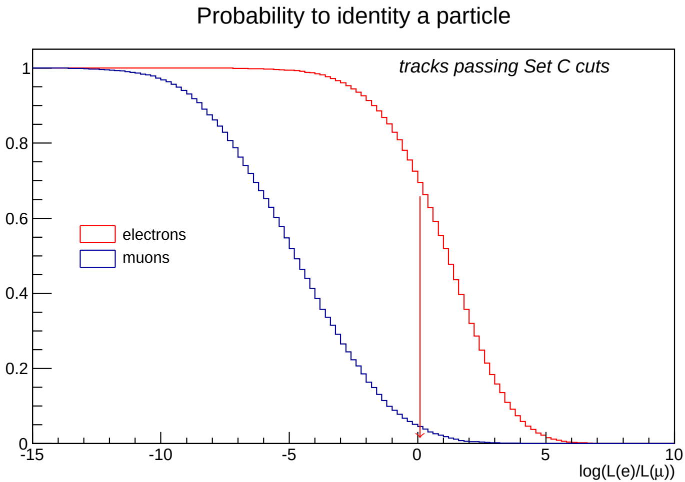
  $L_{e,\mu} \;=\; P_{e,\mu}(dE/dX) * P_{e,\mu}(time)$ and LHR = log L_e/L_μ
- for electron ID efficiency of 90%, the muon misidentification rate is about 10-15%

Cosmic Background and Particle ID



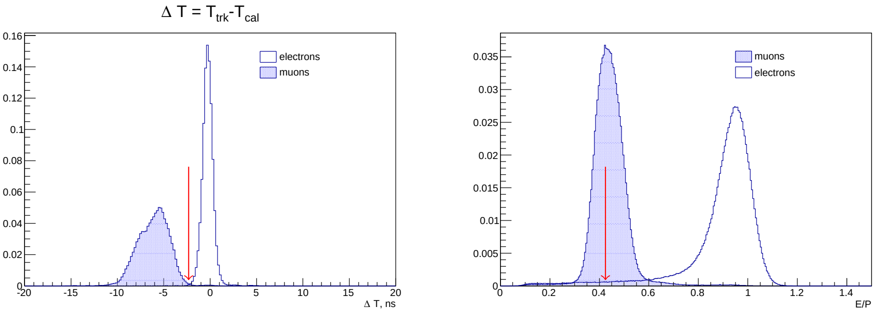
- cosmic muons produce two distinct categories of background events:
    - muons, trapped in the magnetic field
    - electrons, produced in the cosmic muon interactions
- after simulating cosmics for $\sim$ 10% of the data taking time found event shown above
- MC cosmic muon entered detector through a gap in the muon veto counters
- p = 104.4 MeV/c, $\mathbf{E_{cal} = 42}$ **MeV**
- in almost all respects looks like a signal from $\mu \rightarrow e$ conversion

Tracker-based PID



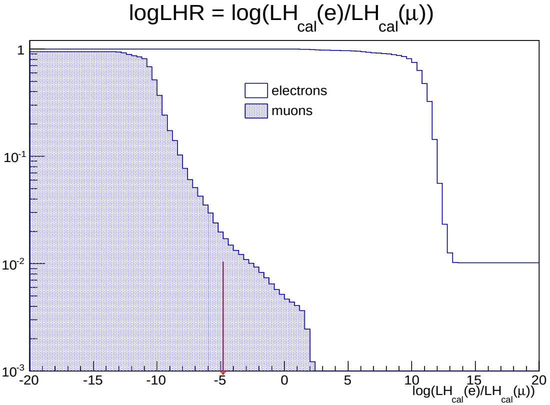
- in the tracker, the particle looked very much “electron-like”
- rejecting it based on tracking-only information ==> ∼ 30% inefficiency

Calorimeter and Particle Identification



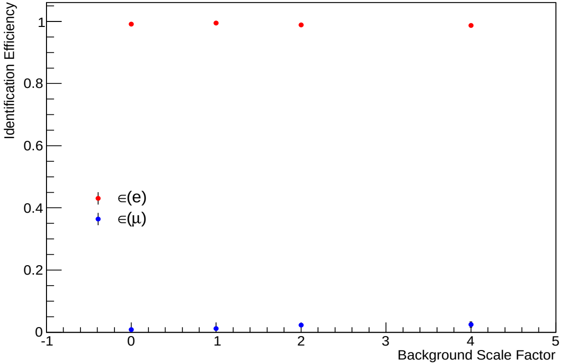
- timing of the muon track - right in between the electron and muon distributions
- plots correspond to the calorimeter resolution of $\sigma_T = 200$ ps, $\sigma_E/E = 0.05$ @ 100 MeV
- tracker resolution in $\sigma_{t_0} \sim 500$ ps
- energy deposition of the offending particle is consistent with that of a muon
- combine ΔT and E/P into a likelihood $L^{cal}_{e,\mu} = P_{e,\mu}(\Delta T) \times P_{e,\mu}(E/P)$

Calorimeter-based PID



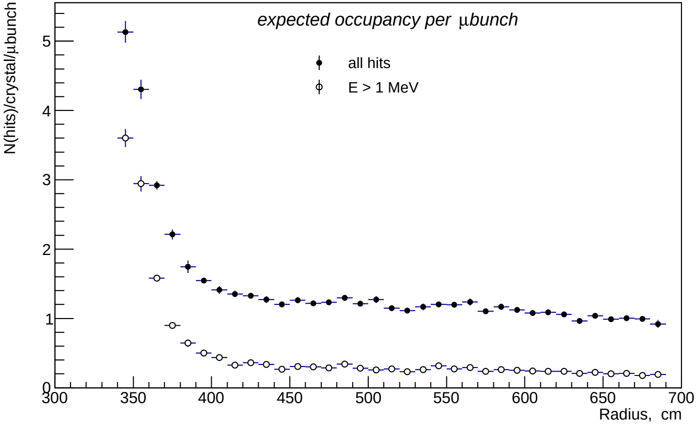
- given a particle, calculate L_e^{cal}, L_μ^{cal}, and their log ratio $log(LHR^{cal}) = \log(L_e^{cal}/L_\mu^{cal})$
- “identified electron”: log(LHR) > A, determined by the performance requirements
- keeping cosmic background at a level of 0.05 events requires muon rejection ~ 100
- **calorimeter allows to achieve muon rejection of $\sim 10^2$ for $\epsilon_{ID}^{e} > 99\%$**

Calorimeter-based Particle Identification Versus the Background Level



- data streaming DAQ: the detector is read out once every 1695 ns
- N(background hits) in the detector is proportional to N(stopped muons/μbunch)
- simulate 100 MeV/c *e* and μ with different background assumptions:
  - no background (x0); nominal background (x1); nominal background $\times 2$, $\times 4$
- **PID performance is stable up to occupancies x4 the expected one**

Expected Occupancy and Neutron Flux



- occupancy: from 3-4 hits/crystal/μbunch to 1 hit/crystal/μbunch
- flat part: neutrons and photons, raising - DIO electrons and protons
- neutron flux scaled to 1 MeV neutrons: $(0.2 - 2.2) \times 10^9$ n/year/cm^2

Calorimeter Calibrations

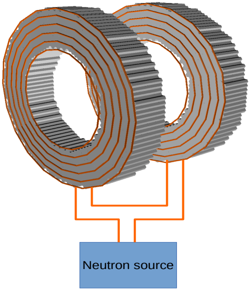
- FEE charge injection, LED pulser
- radioactive source calibration: idea and equipment come from BaBar
- pump short-lived gamma-radioactive fluid through thin tubes positioned in front of the crystals
  - neutrons: $d + t \rightarrow n\,(14.2\ MeV)\ +^4 He$
  - activate fluid (fuorinert by 3M)

$$^{19}F + n \rightarrow ^{16}N + \alpha$$

$$^{16}N \rightarrow\ ^{16}O^* + \beta \qquad (\tau = 10\ sec)$$

$$^{16}O^* \rightarrow\ ^{16}O + \gamma \qquad (E = 6.13\ MeV)$$

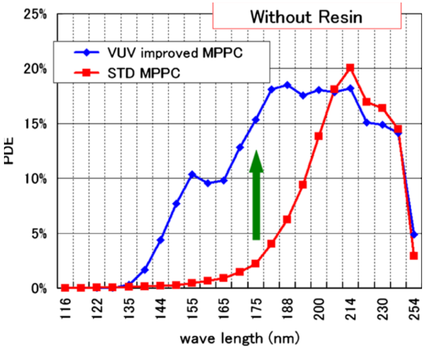
  - pump activated fluid through the system
- highest readily available photon energy for the source calibration
- higher energies: cosmics, DIO electrons

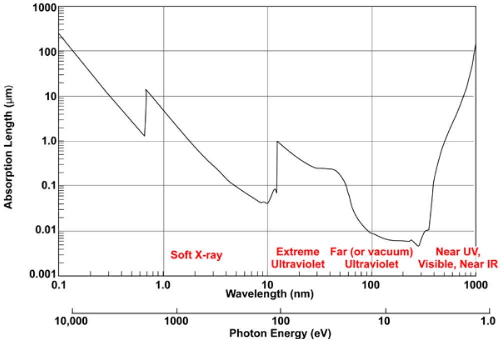


How does one read the BaF_2 Scintillations? UV-sensitive Photodetectors

- the area where an R&D is required to make the final choice
- fast BaF_2 scintillations: $\lambda \sim 200$ nm , far UV
- currently, a lot of activity in the area of UV-sensitive photodetectors
- option #1 : UV-sensitive APD's (Hamamatsu)
- Mu2e has a small sample of UV-sensitive SiPMs, initial testing in progress
- our Italian collaborators have a standing order for 1x1 cm^2 UV-sensitive APDs
- also want to investigate solutions which could have long-term advantages

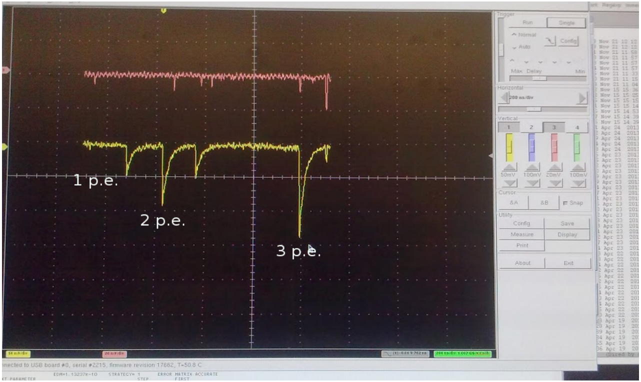
UV-sensitive SiPMs and APDs





- Si absorption length for $\lambda \sim 200 - 300$ nm is less than 10 nm
- Hamamatsu: extend MPPC sensitivity into the UV region by removing the protective layer
- PDE 15-20% at 200 nm
- new photodetectors are being tested by several collaborations
- baseline option for MEG ($\mu \to e\gamma$) LXe calorimeter readout

SiPM Characterization with the Digitizer-based Readout



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nected to USB board #0, serial #2215, firmware revision 17662, T=50.8 C
          EDM=1.13237e-10    STRATEGY= 1         ERROR MATRIX ACCURATE
KT PARAMETER                           STEP            FIRST
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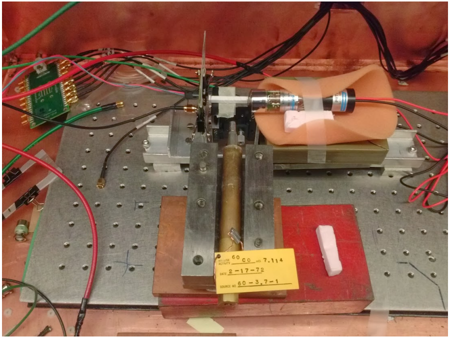
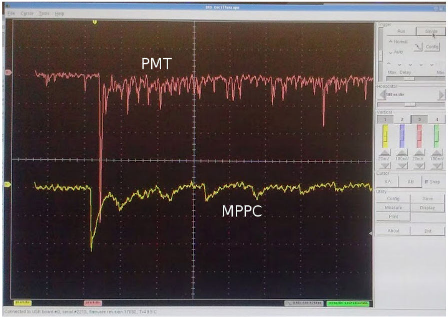
- use the DRS4 evaluation board to digitize signals from SiPM
- set electronic gain to 10^2, discriminator threshold below 0.5 p.e.
- screenshot: the electric charge quantizes! estimate noise and gain
  - digitization window 1 μsec ==> noise $(4 \pm 2) \times 10^6$
  - SiPM internal gain: $G \sim 1.5 \times 10^6$

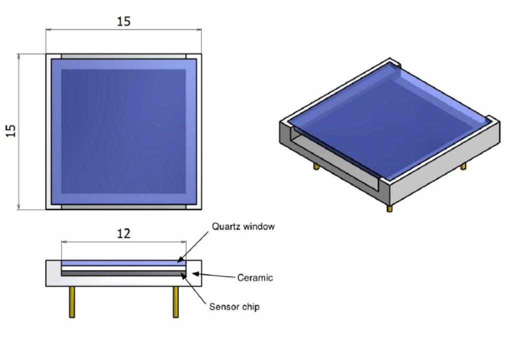
Reading BaF_2 with the UV-sensitive SiPMs (very preliminary)





- read a 5x5x40mm^3 BaF_2 crystal with the UV-sensitive MPPC and 5800Q PMT
- crystal wrapped in teflon
- amplifiers - Philips 776
- MPPC is unprotected, no direct contact with the crystal
- observe signals consistent with the expectations, analysis of the data in progress

Protecting the UV-sensitive Photodetectors

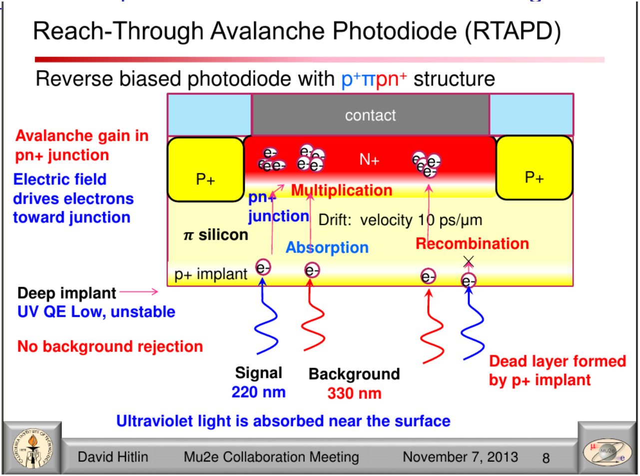


- UV-MPPCs do not have any protective coating, sensitive to operational conditions
- shown: protection design by MEG, Mu2e orders UV-APD with very similar protective layer
- Mu2e detector will run in vacuum, moisture should not be an issue
- at 100 MeV will have enough light, the energy resolution should not be affected

Thinking Forward

- BaF_2 calorimeter should be able to operate at beam intensities of x10 Mu2e
- additional requirements to photodetectors / electronics:
  - reduce the intrinsic photodetector pulse width down to $\sim$ 1 ns
  - suppress the slow component (waveform-based readout helps)
- suppression of the slow component:
  - doping BaF_2 with rare-earth elements
  - **solar-blind photodetectors** , sensitive at 200 nm, but not in the visible part
- want the photodetector sensitive area to match that of the crystal
- various technologies, not at the production level yet, some - very close
- discuss two options:
  - delta-doped silicon APDs with antireflective coating
  - MCP-based photodetectors with UV-sensitive photocathodes

UV-sensitive Delta-doped APDs with antireflective coating



Reach-Through Avalanche Photodiode (RTAPD)

Reverse biased photodiode with $p^+\pi p n^+$ structure

Avalanche gain in pn+ junction

Electric field drives electrons toward junction

Deep implant

UV QE Low, unstable

No background rejection

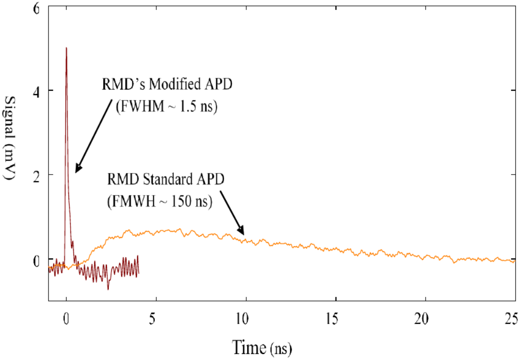
Dead layer formed by p+ implant

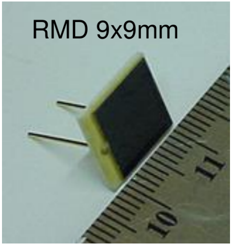
Ultraviolet light is absorbed near the surface

David Hitlin Mu2e Collaboration Meeting November 7, 2013 8

- delta-doping - creation of a very thin, a few nanometers, doped layer
- Doping with boron avoids potential well on the surface (MBE) ==> 50% @ 220nm
- thin drift region ==> radiation tolerant, reduced noise
- ALD-based antireflective coating: QE(300 nm) < 1%

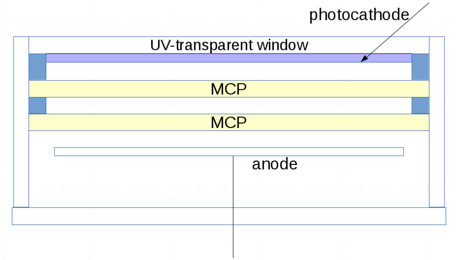
UV-sensitive Delta-doped APDs with antireflective coating





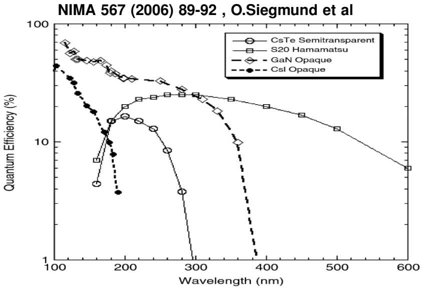
- the modified APDs produce dramatically shorter pulses
- Mu2e Caltech group in collaboration with JPL and RMD is pursuing this effort

MCP-based photodetectors



- vacuum photodetector, 2 amplification stages, gain per stage $\sim 10^3$, total gain - $10^6 - 10^7$
- HV $\sim$ 1 kV, typical for PMTs
- large area, fast signals (1 ns)
- LAPPD MCPs: borosilicate glass activated using Atomic Layer Deposition (ALD)
- radiation hardness improved, compared to the lead glass MCPs
- ALD activation also improves gain uniformity
- stable performance up to $Q \sim$ 2-3 C/cm^2
- the photodetector can match the crystal size

What to use as a UV-sensitive photocathode? - GaN !



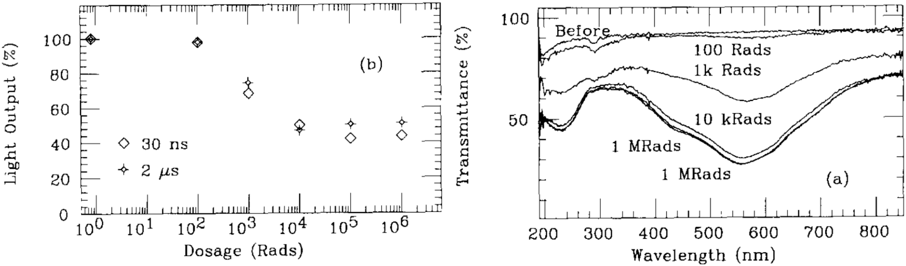
- photocathodes with high QE, based on (Al)GaN , are known for a long time
- GaN - wide-band semiconductor (3.4 eV), solar blind, radiation hard
- deposition technologies exist - MBE, MOCVD
- QE $\sim$ 25% in transmission mode reported by many groups
- at Argonne, a production facility for MCP-based photodetectors is being assembled
- an joint R&D effort with LAPPD could produce results on a very short time scale

Summary

- Mu2e calorimeter makes the experiment significanlty more robust
- significantly improves the particle ID
- **critical for rejecting the residual cosmic background**
- choice of BaF2 should allows the calorimeter to be used at high beam intensities
- expect to learn a lot from an R&D on UV-sensitive, fast photodetectors next year
- big part of this R&D is rather generic - it is an R&D on ultra fast crystal calorimeters

Backup

Radiation Hardness of BaF_2



- 1993: BaF_2 is affected by the radiation, however the damage stops at 50% after 10Krad
- radiation hard (up to 10^7 rad), control of oxigen contamination during growth important