KEK測定器開発室セミナー @ KEK, 筑波
24/November/2009

Yusuke UCHIYAMA
On behalf of MEG collaboration
Theme

• $\mu^+ \to e^+ \gamma$ search experiment, MEG started physics data taking in 2008.

In this talk, we report the detector and measurement techniques used in MEG.

Contents

• Introduction
  - Subject and purpose
• Overview of MEG
• Performance of detector
• Waveform Analysis
• Conclusion
Introduction
Subject of research

- Lepton-flavor violating muon decay: $\mu \rightarrow e \gamma$
  - cLFV: Forbidden in SM
  - Out of experimental reach with finite $\nu$ mass (BR<10^{-50})
  - Clear probe to new physics beyond SM

- $\mu \rightarrow e \gamma$ decay

Normal muon decay
(Michel decay)

Lepton flavors are conserved
Physics Motivation

• Large BR is predicted with many new Physics
  - SUSY-GUT, SUSY-seesaw ,,,
  - Possibility from just below current limit.
    • Current exp. limit : $10^{-11}$
    • ex)SU(5) SUSY-GUT: $10^{-15} \sim 10^{-13}$,
      SO(10): $10^{-13} \sim 10^{-11}$,
      SUSY-seesaw: $>10^{-14}$
    • Large $\tan \beta \to$ larger BR

• Connection to other physics
  - cLFV : $\mu$-e Conversion, $\tau$-LFV ($\tau \to l\gamma$,etc) ..
  - $g$-2, EDM
  - LHC (direct search)

\[ m_{\tilde{\mu}}^2 = \begin{pmatrix} m_{\tilde{\mu} \tilde{\mu}}^2 & m_{\tilde{\mu} \tilde{\tau}}^2 & m_{\tilde{\tau} \tilde{\tau}}^2 \\ m_{\tilde{\tau} \tilde{\tau}}^2 & m_{\tilde{\mu} \tilde{\tau}}^2 & m_{\tilde{\mu} \tilde{\mu}}^2 \end{pmatrix} \]

Mixing through slepton

J. Hisano and D. Nomura, 1998

Current exp. limit :

- SU(5) SUSY-GUT: $10^{-15} \sim 10^{-13}$,
- SO(10): $10^{-13} \sim 10^{-11}$,
- SUSY-seesaw: $>10^{-14}$
Position of the MEG Experiment

- Current experimental upper limit:
  \[ \text{Br}(\mu \rightarrow e\gamma) < 1.2 \times 10^{-11} \quad (1999, \text{MEGA@LAMPF}) \]

- Target: down to a sensitivity of \(10^{-13}\)

- In 2008, started physics data taking \(\sim 2011? \rightarrow \text{MEG upgrade ??}\)

- No other experiments (nor future program)

Other cLFV search
- \(\mu\)-e conversion
  - \(\sim 300\) times smaller BR
  - Current U.L.\(\sim 10^{-13}(\text{@PSI})\)
  - Future exp. \(\sim 10^{-16}\)
    - COMET @J-Parc
    - mu2e @Fermilab

- \(\tau\)-LFV
  - Many different modes
  - \(\text{BR} \sim O(10^{3\text{-}5}) \times \text{Br}(\mu)\)
  - Current U.L.\(\sim 10^{-7\text{-}8}\) (B-factories)
  - Future program: superB

To conduct these experiments is important independent with MEG results

To be a pioneer of coming New physics era!

- Complementary with LHC
  - Possibility of SUSY particles discovery at the beginning of LHC
\( \mu \rightarrow e \gamma \) Search

- Need a large number of muon
  - High rate experiment
  - Use positive muon (\( \mu^+ \))
    - Prevent from forming muonic atoms

- \( \mu^+ \rightarrow e^+ \gamma \) signal: a positron and a gamma
  - Clean 2 body decay
    - Both at 52.8MeV (monochromatic),
    - Back-to-back,
    - Time coincidence

- Backgrounds
  - Radiative muon decay (prompt BG)
    - Rapid decrease of phase space in signal region
    - We can control with reasonable resolutions
  - Accidental overlap of uncorrelated \( e^+ \) and \( \gamma \) (accidental BG)
    - Source of \( \gamma \): radiative decay, \( e^+ \) AIF, Bremsstrahlung, CR
Accidental Background

- Accidental BG limits the experiment
  - BG rate is proportional to the instant beam rate → DC beam is the best

\[ B_{\text{acc}} = R \cdot f_0^\mu \cdot f_0^e \cdot (\delta \omega / 4\pi) \cdot (2\delta t) \]

= \( N_\mu \) (DC beam)

Time overlap (Linear to time resolution)

Back to back (quadratic to angular resolution)

**e^+ BG Spectrum**

**γ BG Spectrum**

Signal

Michel e^+

Radiative decay

High rate e^+

γ energy measurement is most important

0.9  
E_\gamma (/52.8MeV)  
1

0  
E_{e^+} (/52.8MeV)  
1
Requirements for $\mu \rightarrow e\gamma$ experiment

- **High intensity DC $\mu^+$ beam**
  - $>10^7$/sec

- **High rate tolerable detectors**
  - All of $>10^7$/sec $\mu^+$ generate $e^+$
  - Pileup of $\gamma$s become a source of high energy BG

- **High resolution detectors**
  - $\gamma$ energy measurement is most important
  - Angle and time measurements are also effective
The MEG Experiment
MEG Experiment

- World's most intense DC $\mu^+$ beam @PSI (Switzerland)
- MEG detectors
  - Positron spectrometer
  - Liquid xenon $\gamma$-ray detector
- Started physics data taking in autumn 2008

~60 collaborators

- LXe $\gamma$-ray detector
- COBRA SC magnet
- Drift chambers
- Timing counters

πE5 beam line @PSI

$\mu^+$ beam

Proposal:
- Planning
- R & D
- Assembly
- E.R.
- Data taking


1st result
MEG Experiment

- World's most intense DC $\mu^+$ beam @PSI (Switzerland)
- MEG detectors
  - Positron spectrometer
  - Liquid xenon $\gamma$-ray detector
- Started physics data taking in autumn 2008

~60 collaborators
1.2MW proton Ring-Cyclotron at PSI

590MeV
Max current 2.2mA

Provides world's most intense DC muon beam

MEGA used pulsed beam
6% duty cycle
Instant intensity $2.6 \times 10^8$
average $1.3 \times 10^7$

MEG
Duty cycle 100%
Instant = ave $3 \times 10^7$ (2008)
'Surface muon' Beam Transport System

- **Surface μ**: μ produced from π at rest on the surface of prod. target
  - Extract at 175° from the primary p beam
  - Low momentum (29MeV/C) with small variance μ⁺ beam
- Through the beam transport system
  - Separate e⁺ · degrade · tune beam profile
- **3x10⁷μ⁺/sec stop on target**
  - 10mm spot size
  - 200μm polyethylene film target, placed at 20.5° slant angle from beam-axis
    - Suppression of scatter & BG VS stopping power
MEG Detector
Liquid Xenon Detector

- 900 liter liquid xenon
  - Scintillation medium
    - High light yield (75% of NaI(Tl))
    - Fast response ($\tau_{\text{decay}}=45\text{ns}$)
    - High stopping power ($X_0=2.8\text{cm}$)
    - No self-absorption
    - Uniform, no-aging
  - Challenges
    - Vacuum ultraviolet (178nm)
    - Low temperature (165K)
    - Need high purity
  - No segmentation

- Measure energy, position, time at once

- Identify pileup events
  - Light distribution
  - Time distribution
  - Waveform

Active volume $\sim 800/\Omega/4\pi = 11\%$
846 PMTs
Prototype / R&D

- Verified performance with prototype detector
  - Energy resolution @55 MeV
    - $\sigma_{up} = 1.23\%$, FWHM = 4.8\%
  - Time resolution @55 MeV
    - $\sigma_t = 65$ ps

Various R&D, obtained a lot of know-how necessary of the final detector.
Prototype / R&D

- Verified performance with prototype detector
  - Energy resolution @55MeV
    - $\sigma_{up} = 1.23\%$
  - Time resolution
    - $\sigma_t = 65$ ps

Various R&D, obtained a lot of know-how necessary of the final detector

Now came back to KEK
start 2nd life
Cryostat

Inner vessel

Entrance window with honeycomb structure

2 layers of vacuum-tight cryostat
Thin window for $\gamma$ entrance face
PMT Installation

2” PMT developed for MEG
- Quartz window for VUV
- K-Cs-Sb photocathode
- Al strips on photocathode
- Metal-channel dynode
- Zener diode at last steps of Bleeder
Completed in 2007

The first ton-scale LXe detector in the world in use
Slow Control System

Preset mode

- Manual
- Pressure
- Temperature

1000L QLV valve

Flow in
Flow out

Stop

Press

Temp(in)
Temp(out)
Press

09/11/24 KEKDT P seminar/Yusuke UCHIYAMA
Positron Spectrometer

- A spectrometer efficiently measure $3 \times 10^7$ high rate $e^+$
- Measure $e^+$ momentum · emission angle · $\mu^+$ decay time & position with high resolution
“COBRA” Magnet

- Superconducting solenoid form highly gradient magnetic field
  - Center 1.27 T → edge 0.49 T

Field on beam-axis

<table>
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<tr>
<th>center</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
<th>1.0</th>
<th>1.2</th>
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<tr>
<td>m</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
<td>0.9</td>
<td>1.0</td>
<td>1.2</td>
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</table>

Step structure solenoid

Other features
- Thin coil <0.2X₀ to transmit γ-ray(85%)
- Rapid switch on/off stabilize ~30min (cooling with GM ref.)
- Two compensation coils suppress fringe field (no return yoke)
- Low B around LXe detector for PMT <50Gauss
Specially Gradient B-Field

Uniform B-field

Gradient B-field

$e^+$ quickly swept out

Same momentum $\Rightarrow$ same radius ($\text{CO}nstant \text{ Bening RA}dius$)

Enable measurement in high rate
Drift Chamber (DCH)

- 16 modules
  - Arranged concentrically (10.5° interval)
  - 2 layers per 1 module

- Chamber gas
  - He:ethane (50:50)
  - Pressure control
    - Outside He atmosphere

- Ultra low mas chamber
  - Multiple-scattering limits the performance
  - To suppress γ BG source
  - In total along e\(^+\) trajectory
    \[ \sim 2.0 \times 10^{-3} X_0 \]
DCH Design

2 layers staggered by half cell
9 drift-cells in 1 layer

Open-frame structure
Form cell only with cathode foils

12.5μm cathode foil
Vernier pattern → z reconstruction
Timing Counter

- Hit timing counter one turn after exit of DCH. Measure hit timing
- Two layers of plastic scintillator arrays
  - Outer: Scintillation bars
    - 4x4x80cm$^3$, BC404
    - 15 bars concentrically (10.5° interval)
    - Fine-mesh PMT at two ends
    - High precision time measurement
  - Inner: Scintillating fiber
    - 5x5mm$^2$
    - 128 fibers along z-dir.
    - Readout by APD
    - Hit pattern → trigger

Not used in 2008 analysis
Defects in APD readout
Data Acquisition

MIDAS system
- Frontend control
- Event building
- Logging
- Online database
- Slow control
- History monitoring
- Web interface
**Trigger**

- FPGA-FADC architecture
  - 100MHz FADC on VME boards
- MEG trigger
  - $\gamma$ energy
  - $e^+\gamma$ coincidence
  - $e^+\gamma$ direction match (back-to-back)
    - Max output PMT in LXe
    - TC hit position
- In addition, 10 trigger types are mixed in normal data taking
  - Calibration, normalization

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam rate</td>
<td>$3 \times 10^7 \text{s}^{-1}$</td>
</tr>
<tr>
<td>Fast LXe Q sum ($&gt;40\text{MeV}$)</td>
<td>$2 \times 10^3 \text{s}^{-1}$</td>
</tr>
<tr>
<td>Time coincidence</td>
<td>100s$^{-1}$</td>
</tr>
<tr>
<td>Direction match</td>
<td>10s$^{-1}$</td>
</tr>
</tbody>
</table>
Readout Electronics

- Record waveform from all sub-detectors (no ADC, TDC)
  - DRS chip (Domino Ring Sampler)
    - Up to 5GSPS, 1024cell, 8ch/chip
    - Sampling speed: 1.6GHz for LXe&TC, 500MHz for DCH
Calibration

- 55MeV high-energy $\gamma$ from $\pi^0$ decay
  - Evaluation of resolutions (energy, position, timing)
  - Calibrate energy scale
  - Use same beamline as $\mu^+$
  - Take some time for setup (~5days)
    - Conducted at beginning & end of physics run.
    - More BG than normal $\mu^+$ run.
- 17.6 MeV $\gamma$ from Li(p,$\gamma$)Be reaction
  - Lower energy (1/3)
  - Uniformity, light yield monitor
  - MEG dedicated p-beamline (opposite side)
  - Easy to switch (~20min)
  - 3 times per week, regular calibration
- $\mu$ Michel decay
  - Calibrate $e^+$ (DCH & TC)
- $\mu$ radiative decay
  - Time calibration
- LED, $\alpha$ source
  - PMT calibration

$\pi^{-} p \rightarrow \pi^{0} n \rightarrow \gamma \gamma n$

Tag back-to-back

Cockcroft-Walton accelerator
PMT Calibration

- LED
  - PMT gain calibration
  - Time offset calibration
- Alpha
  - PMT Q.E. calibration
  - LXe attenuation length measurement

Am source on wire

Reconstructed α event
Variation of LXe light yield

- Lower than expected
- Recover by purification
- Decrease by (possible) leak

Confirmed we can monitor light yield using several kinds of daily calibration.

We decided to continue purification during data taking (gas phase: continuously, liquid phase: intermittently (beam shutdown))

Finally, keep overall energy scale uncertainty under 0.4%

Correction of light yield
Monitor Li(p,γ)Be 17.6MeV line

Measured energy scale

Pulse shape was also changing
Xenon System

Gas phase purifier

High pressure storage tank

200W pulse-tube refrigerator

Detector

Liquid phase purifier

1000l liquid dewar

LXe Calorimeter

Liquid pump (100L/h)

Getter
Xenon System

200W pulse-tube refrigerator

Gas phase purifier

High pressure storage tank

Heat exchanger

Liquid phase purifier

1000L liquid dewar

1000L storage dewar
Xenon System: Liquefaction/Transfer

- Gas phase purifier
- High pressure storage tank
- Liquefaction
- Liquid transfer
- Detector
- Liquid phase purifier
- 1000 l liquid dewar
- LXe Calorimeter
- 200W pulse-tube refrigerator
- Cryocooler
- Cryooscillator (100W)
- GXe pump (10-50L/min)
- GXe storage tank
- Getter + Oxysorb
- Heat exchanger
- LXe Calorimeter
- Purifier
- Liquid pump (100L/h)
Xenon System: Purification System

Gas phase purification

Gas phase purifier
- GXe pump (10-50L/min)

Heat exchanger

Getter + Oxyisorb

N₂, O₂, H₂O, etc.

Liquid phase purification

Liquid phase purifier

- 200W pulse-tube refrigerator
- Cryocooler

Detector

LXe Calorimeter

O₂

H₂O

Liquid pump (100L/h)

Purifier

1000L storage dewar

1000L liquid dewar

O₂, N₂, O₂, H₂O, etc. absorption

Absorption Coefficient [m⁻¹]

Oxygen

Xe Scintillation Spectrum

Water Vapor

Wave Length [nm]
Xenon Scintillation

- De-excitation process (fast)
  - $\text{Xe} + \text{Xe}^* \rightarrow \text{Xe}_2^* \rightarrow 2\text{Xe} + \text{hv}$

- Recombination process (slow)
  - $\text{Xe}^+ + \text{Xe} \rightarrow \text{Xe}_2^+$
  - $\text{Xe}_2^+ + \text{e}^- \rightarrow \text{Xe}^{**} + \text{Xe}$
  - $\text{Xe}^{**} \rightarrow \text{Xe}^* + \text{heat}$
  - $\text{Xe} + \text{Xe}^* \rightarrow \text{Xe}_2^* \rightarrow 2\text{Xe} + \text{hv}$

Quench
- $\text{Xe}_2^* + \text{N}_2 \rightarrow 2\text{Xe} + \text{N}_2$
- $\text{O}_2
- $\text{O}_2$
  (two-body collision)

Absorption

Oxygen

Xe Scintillation Spectrum

Water Vapor

Absorption Coefficient [m$^{-1}$]

Wave Length [nm]

(a)
Light yield & pulse shape

- Further purification during shut down
  - Whole volume passed gas purification system (getter).

Waveform

Decay time

09/11/24 KEKDTP seminar/Yusuke UCHIYAMA
DCH Discharge Problem

- DCH frequently discharged
  - Inside magnet is filled with pure-He.
  - DCH-outside is exposed in He atmosphere. (HV line)

- It happened also in 2007 engineering run.
  - Repaired in maintenance period
  - At the beginning of 2008, every chamber could be operated
  - We thought we could fix the problem ...

- In 2008, after a few months
  - Gradually some chambers starts to discharge again.

- Finally, out of 32 planes
  - 18 planes were operational
  - Only 12 planes worked at nominal voltage

Degradation of $e^+$ measurement (efficiency • resolution)
Solution for the Discharge problem

- Exhaustively investigated weak points for all HV connections.
- HV soldering spot on PCB and HV via on PCB are suspicious.
- Discharge was reproduced at Lab. test finally after many trial.

Solutions
- New design of PCB
  - Separate layers for HV and GND completely
    - (3 → 4 layers)
- Potting HV soldering spot with epoxy
After modification

- Two chambers with new HV PCB into “Aquarium” to see long term operation with He/Ethane inside and pure-He outside and nominal HV
- 16 chambers are mounted on the support structure inside the “He cabin”. Signal check with nominal HV

Stable operation for ~7 months
Reconstruction & Performance

In 2008
Gamma energy I

- **Reconstruction**
  - Sum of PMT outputs
  - Correction of non-uniformity (collection efficiency)
    - Use 17.6MeV $\gamma$ from Li(p,$\gamma$)Be reaction
      - It illuminate the detector uniformly.
  - Treatment of shallow events
    - Low resolution at shallow part
      - Shower escape
      - Large variation of photon collection, Photon leakage
      - Saturation of signal (dyn.range of elec.)
    - But want to use for statistics.
    - Recovered saturation using waveform
    - Correct photon collection efficiency by calculating solid angle

$\varepsilon \sim 30\%$ recover

Detector entrance face

Energy response map (before corr.)

In front of a PMT  intermediate
Gamma energy II

- Recover of pileup events
  - Not discard pileup events, but use with unfolding.
  - Improve efficiency

- ID pileup → reconstruct energy using region without pileup → replace PMT outputs for pileup region with estimated charge → then normal reconstruction

\( \varepsilon \sim 8\% \) gain
Gamma energy II

- Recover of pileup events
  - Not discard pileup events, but use with unfolding.
  - Improve efficiency

- ID pileup → reconstruct energy using region without pileup → replace PMT outputs for pileup region with estimated charge → then normal reconstruction

\[ \varepsilon \sim 8\% \text{ gain} \]
Gamma energy III

- $\pi^0$ 55MeV

- Evaluate energy resolution as a response to 55MeV
- Evaluate res for all over the entrance face
- Average res (averaged over the event distri. in MEG run)

\[ \sigma_{up} = 2.0\% \text{ for deep}(>2\text{cm}), \ 3.0\% \text{ (1~2cm)}, \ 4.2\% \text{ (0~1cm)} \]

Determine energy scale
Gamma energy IV

- Using $\gamma$ spectrum of $\mu$ decay (side-band)
  - Check those correction, resolution and energy scale

Fit spectrum with the expected one from MC
- Parameters
  - Energy scale
  - Resolution
  - Fraction of pileup

Well consistent $\rightarrow$ validation of analysis
Positron Tracking: pattern recognition

Select hits with time and z info.

Clustering, connecting

Find track candidates
Positron Tracking: Kalman Filter

- Reconstruct $e^+$ trajectory by track fitting with Kalman-filter.
- Extrapolate the track up/down to timing counter / target.
- Reconstruct momentum · emission angle · vertex on target.
- Reconstruct ToF to timing counter.
Positron momentum

- Evaluate momentum response (resolution) by fitting kinematical edge (52.8 MeV) of Michel spectrum

- Response function: triple Gaussian
  - Core = 374 keV (60%)
  - Tail = 1.06 MeV (33%)
  , 2.00 MeV (7%)

\[
P(E) = (P_{\text{theo}}(E) \times P_{\text{acc}}(E)) \otimes P_{\text{res}}(E)
\]
Positron emission angle

- Evaluate angular resolution using 2 turn events
  - See difference of angle between reconstruction with each turn

\[ \sigma_{\theta} = 18 \text{ mrad} \]
\[ \sigma_{\phi} = 10 \text{ mrad} \]

\[ \sigma_{\theta} = 1.45 \text{ deg.} \sqrt{2} \approx 18 \text{ mrad.} \]
\[ \sigma_{\phi} = 0.81 \text{ deg.} \sqrt{2} \approx 10 \text{ mrad.} \]
Muon decay vertex

- Reconstruct μ decay vertex as a point crossing e\(^+\) track and target plane
- Evaluate resolution with
  - Using holes on target
  - Using 2 turn events

\[ \sigma_x = 4.5\, \text{mm} \]
\[ \sigma_y = 3.2\, \text{mm} \]
**Gamma position**

- **Reconstruction**: *Fit with solid angle*
- **Evaluate resolution**
  - $\pi^0$ run with Pb bricks
  - Shadow of slits gives resolution and bias
  - Results
    - $\sigma_{xy} = 4.5 \sim 5\text{mm}$, bias (RMS) = 0.7mm
    - Compared with MC:
      - Reduce systematic.
      - 1.8mm worse than MC
    - QE uncertainty
- **Detailed study with MC**
  - Take in the difference with data
  - Resolution variation by the relative position to PMT
  - Shape of the response
    - Double Gaussian

\[ \sigma_{xy} \sim 5\text{mm} \]

(position dependent)
Opening Angle

- Not possible to reconstruct direction of gamma
  - Direction of the line b/w μ vertex and γ interaction point
- Combined resolution: $\sigma_{\theta_{e\gamma}} = 20.6$ mrad, $\sigma_{\phi_{e\gamma}} = 13.9$ mrad
Gamma timing I

- Reconstruction
  - Subtract scinti photon propagation time from PMT hit time.
  - Combine a lot of measurement by different PMTs (~150 PMTs) ($\chi^2$ fit).

- $\pi^0 \rightarrow \gamma \gamma$
  - Time difference b/w the reference counter
  - Results
    - Gaussian
    - $\sigma_t = 78\text{ps} @ 55\text{MeV}, \ 61\text{ps} @ 83\text{MeV}$
    - Better resolution at December (high light yield).
      - $\sigma_t = 68\text{ps} @ 55\text{MeV}$

$\sigma_t = 80\text{ps} @ 52.8\text{MeV}$
(This value is not used directly.)

Energy dependence

![Graph showing energy dependence](image-url)
Gamma timing II

- Correction by $\mu$ radiative decay
  - Change of pulse shape as improvement of purity
  - Observed drift of t0

Low intensity RD run
- 24h /1week
- Better S/N, better precision of t0

Stability after the correction $<20$ ps
**Time resolution**

- $t_{e\gamma}$: time difference b/w $e^+$ and $\gamma$ time on target
  - $e^+$: TC measurement, subtract ToF from track length
  - $\gamma$: LXe interaction time, subtract ToF
- Observe RD peak in normal data taking
  - Correct small dependence of $\gamma$ energy

$$\sigma t_{e\gamma} = 148 \pm 17 \text{ ps}$$
Gamma efficiency

- Detection efficiency
  - $\pi^0 2\gamma$: NaI single trigger
  - MC
  - $\mu$ data single spectrum
  - Calculate position dependent efficiency with MC
  - Multiply with $e^+$ event distribution
  - In analysis region of $46 < E_\gamma < 60$ MeV
    - $\varepsilon_{\text{det}} = 66\%$

- Analysis efficiency
  - Inefficiency (pileup, CR cut)
    - 9%

$$\varepsilon_\gamma = (60 \pm 3)\%$$
**Positron efficiency**

- $e^+\text{ detection efficiency}$
  
  - $\varepsilon_{e^+} = \varepsilon_{DCH} \times A_{DCH-TC}$
  
  - $\varepsilon_{DCH}$: tracking efficiency
  - $A_{DCH-TC}$: DCH-TC matching probability. Make inefficiency if $e^+$ interacts with material and annihilates or changes its direction largely.

- $\varepsilon_{e^+}$ decreased gradually during the run
  - DCH discharge problem

- Expectation (full DCH): ~40% ($= 80 \times 50$)

![Spectrometer Efficiency Graph](image)
Waveform Analysis
Domino Ring Sampler

- Switched Capacitor Arrays
  - High speed sampling
  - Low power consumption
  - Low cost
  - High channel density
  - No precise timing

- FADC

- Inverter “Domino” ring chain

- 0.2-2 ns

- “Time stretcher” GHz → MHz

- FADC 33 MHz

- Waveform stored

09/11/24 KEK-DTP seminar/Yusuke UCHIYAMA
General purpose VPC board built at PSI

- 32 channels input
- 40 MHz
- 12 bit FADC
- USB adapter board

Version 3

Version 2
Calibration

- Non-linear response in amplitude & time
  - Measure response to reference voltages
  - Measure response to sine wave
    - Not constant sampling intervals (but fixed over time)

- Synchronization among chip by a reference clock
  - Trigger system distributes a global reference clock (20MHz)
  - Each chip digitizes the clock
  - Clock analysis (offline)
    - Global synchronization
    - Event-by-event time calibration

Synchronization precision
\( \sigma \approx 40 \) psec
What is the merits?

- Pileup identification
- Particle identification (PSD)
- Noise
  - Can investigate noise (online oscilloscope)
  - Event-by-event baseline subtraction
  - Additional noise reduction
- Precise waveform analysis in offline
  - Digital filter
  - Various timing algorithms
  - Fitting waveform
Online Display

Re-binned
For data size reduction

Raw waveform

Fitting

Baseline

Frequency spectrum

Digital filter

Differential

Baseline

Spectrum MAG
Charge Integration

- Use high-pass filter
  - Remove low freq noise
  - Make pulse sharp
    - Narrow integration window
    - Low noise
    - Robust to pileup

![Graph showing original waveform, template fit, integration area (50ns), and after optimized high-pass FIR filter]
Time Extraction

- digital constant fraction
  - Eliminate time-walk effect
  - Parameter adjustable
  - Interpolate sample points
  - Linear or cubic

- Template fitting
  - Maximal usage of sample points
  - Robust to noise
Coherent noise subtraction

- Estimate coherent noise using baseline region
Coherent noise subtraction

- Coherent noise subtraction using no hit channel

Signal from drift chamber
Cross talk removal

Signal from timing counter

subtract

Hit

Hit
Pulse Shape Discrimination

- PSD by
  - Q/A, pulse width, decay time
Digitizer upgrade

- DRS2 → DRS4
  - Many modifications are applied from the experience with DRS2
    - DRS2 have been used since 2004
  - Replaced all DRS2 with DRS4 in September
  - But not yet full performance
    - Eliminate temperature drift
    - Linearity improve (upto 1 V)
    - Differential input
    - Timing accuracy (?)
    - Double cell (twice sampling speed or twice window)
  - It takes longer than expected to install
    - Completely new system
    - Several problems to debug
Conclusion

- MEG実験は2008年秋、物理データ取得を開始。RUN2008ではMEG最初の3ヶ月分のデータをとった。
- 3 ton LXe detector の実用化に世界初成功。安定に運転している。
- SCAを用いた高速波形取得。波形解析手法を開発。
- 検出器の解析手法を確立。
  - RUN2008を一通り解析し結果を出した。
    - RUN2008のsensitivity : 1.3 x 10-11
    - 実際のデータからのupper limit : Br(μ→eγ) < 3.0 x 10-11 @90% C.L. (preliminary)
- 今年はこの4倍の統計をためる。(11月頭から物理ラン再開)
  - これに応じてsensitivityの向上
  - sensitivityの詳細は今年の検出器の性能に依存する(現在、校正・評価中)が性能向上も見込めるため今年も統計で制限されるだろう。

Thank you.