The Calorimeter of the Mu2e experiment

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Talk outline

• Measurement overview and experimental technique of Mu2e

• Calorimeter requirements, technical choices and design

• Calorimeter Engineering Design and Integration

• Calorimeter expected performance from Beam Test and prototypes

• Production of crystals, SiPMs, FEE and digital electronics

• Calorimeter Mechanics status

• Assembly plans and conclusions
The Mu2e Experiment

- **Mu2e** will search for the CLFV conversion of the muon into an electron after stopping it on Al nucleus \( \mu^- \text{Al} \rightarrow e^- \text{Al} \)
- Clear signature provided by the mono-energetic conversion \( e^- \) with \( E \sim M_\mu \)
- The proton beam of the Fermilab accelerator complex and the Mu2e solenoidal system produce a high intensity "pulsed" muon beam - 10 GHz of stopped \( \mu^- \)
- Goal is to reach a single event sensitivity of \(~3 \times 10^{-17}\) i.e. \(10^4\) better than Sindrum II → This requires \(10^{20}\) protons on target, \(10^{18}\) stopped muons
- Mu2e will detect and count the conversion electrons with respect to the standard muon capture.

- **Main background** is SM \( \mu^- \) decay in orbit (DIO) - softer p\(_T\) spectrum

\[
R_{\mu e} = \frac{\Gamma \left( \mu^- + N(A, Z) \rightarrow e^- + N(A, Z) \right)}{\Gamma \left( \mu^- + N(A, Z) \rightarrow \text{all muon captures} \right)}
\]

61%, Muon capture - normalization

39%, DIO – main background
Mu2e experiment: from cartoons to reality

**Production Solenoid**
- $10^{12}/s$ 8 GeV protons on Tungsten target (POT)
- Produced secondaries funneled by the graded magnetic field to TS

**Transport Solenoid**
- Pions decay to muons
- Charge and momentum selection

**Detector Solenoid**
- 10 GHz $\mu$'s stop in thin Al foils of stopping target
- Conversion electrons detected by a tracker and a calorimeter
- A surrounding cosmic ray veto detector tags Cosmic Rays
Calorimeter scope and requirements

For the $\mu \rightarrow e$ conversion search, the calorimeter adds redundancy and complementary qualities with respect to the high precision tracking system:

- Large acceptance for the mono-energetic electron candidate events
- Particle Identification capabilities with $\mu/e$ rejection of 200
- Additional “Seeds” to improve track finding at high occupancy
- A tracking independent trigger

For 100 MeV electrons @ 50 degrees impact angle:

- Provide energy resolution $\sigma_E/E$ of $O(< 10 \%)$
- Provide timing resolution $\sigma(t) < 500$ ps
- Provide position resolution < 1 cm
- Work in vacuum @ 10-4 Torr and 1 T B-Field
- Stand harsh radiation
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Technical specifications

- **Chosen Technical Solution**: High Granularity Crystal calorimeter with SiPMs readout

- 2 Disks (Annuli) geometry to improve acceptance

- Crystals with high Light Yield for time/energy resolution \( \Rightarrow \text{LY(SiPM)} > 20 \text{ pe/MeV} \)

- **2 SiPMs/preamps per crystal** for redundancy and MTTF requirement \( \Rightarrow 1 \text{ million hours/SiPM} \)

- **SiPM thermally controlled down to -10°C to reduce radiation induced leakage current**
  (factor of \( \sim 3 \) every 10 °C: 30mA \( \Rightarrow 3 \text{mA} \), 25 \( \Rightarrow -5 \text{°C} \))

- Fast signal and Digitization for Pileup and Timing \( \Rightarrow \tau \text{ of emission} < 40 \text{ ns} + \text{Fast preamps} \)

- **Crystals should withstand a TID** of 90 krad and a fluence of \( 3 \times \frac{10^{12} \text{n}_1\text{MeV}}{\text{cm}^2} \)

- **SiPM/FEE should withstand** 45 krad and a fluence of \( 1.5 \times \frac{10^{12} \text{n}_1\text{MeV}}{\text{cm}^2} \) \( \Rightarrow \text{a TID of 15 krad} \)

- **Digital electronics should withstand**: a neutron fluence of \( 3 \times 10^{11} \text{n/cm}^2 \), Charged Hadron (>20MeV) \( 10^{10}/\text{cm}^2 \)
Mu2e calorimeter design

- Two annular disks, each one with 674 un-doped CsI parallelepiped crystals with square faces:
  - Crystal dimensions (34 x 34 x 200 mm$^3$) $\sim$ 10 $X_0$
  - Inner/Outer Radius = 374/660 mm

- Each crystal is read out by two large area UV extended (silicone resin window) SiPM's (14x20 mm$^2$) coupled in air with 2mm gap
  - PDE=30% @ CsI emission peak =315 nm. Gain $\sim$1.7x10$^6$
  - Tyvek+Tedlar wrapping (LY$\uparrow$ and cross talk$\downarrow$)

- SiPM glued on copper holders for heat dissipation/cooling and connected to FEE

- Digital electronics at 200 Mspses on-board custom crates

- Radioactive source (a la Babar) and green laser systems provide absolute calibration and monitoring capability

**Operate with very high reliability in vacuum, magnetic field and be resilient to radiation harsh environment**
Exploded view of components

- Outer monolithic stepped Al supporting cylinder with integrated cradle and stands
- Inner carbon fiber stepped cylinder
- PEEK back plate, housing Read Out Units
  - Embedded copper cooling lines
- Read Out Units, ROU’s, composed of
  - Copper holders
  - Glued SiPm
  - FEE cards
  - Faraday cages
  - Fibers needle
- Carbon fiber front plate integrating the source calibration pipes
- Array of 674 Tyvek wrapped crystals
- 10 Read out/service electronics crates (6-8 boards each)
- Cabling and pipes

See A. Saputi’s poster for Mech. Engineering details
Module-0 test beam

A Module-0 (51 crystals + 102 SiPMs + 102 FEE) was built to resemble the final design. Calorimeter performances fulfillment have been checked testing it with e-beams in Frascati. The energy and timing resolution obtained for 100 MeV electron is well in agreement with the Mu2e requirements.

- Single particle selection
- Mips equalization and time scale
- LightYield/SiPM =30 pe/MeV
- Excellent Data-Mc agreement
- 5.4% (7.3%) resolution @100 MeV for 0° (50°)
- $\sigma_T \sim 100$ ps

_results fully comply with our requirements
* Green light for Production of components*
Procurement of Crystals and SiPMs

- Production of 1500 CsI crystals and 4000 Mu2e SiPMs started in 2018
- $^{22}$Na QA test at SIDET (FNAL) + irradiation tests at Caltech, HZDR, FNG, Calliope

**Crystals**

- Two producers (SICCAS, St. Gobain)
- QA of optical (LY, LRU, F/T, RIN) and mechanical dimensions
  - St. Gobain failed to match our specs.
  - Final production back to SICCAS
- OK with irradiation tests
- ~8 % had specification failure

**SiPMs**

- Producer: HAMAMATSU
- 6 individual 6x6 mm$^2$ 50 µm px MPPCs (Hamamatsu) paralleled series (2/3 Ci)
- All 6 cells/SiPM tested, measuring $V_{br}$ $I_{dark}$ Gain x PDE
- Irradiation with ~1x10$^{12}$ neutrons/cm$^2$ and (MTTF) test on 5 SiPMs/batch

**Completed end of 2020**

- Completed in 2019

25/05/22  F. Happacher  Pisa Meeting 2022
Due to the pandemics, we moved the gluing operation from FNAL to INFN (+ 1 year delay)

- All copper holders produced (1500 pieces)
- Faraday cages produced
- All SiPM’s glued
- FEE produced, 2500/3500 tested
- Readout units under assembly 500/1500 done

see E. Sanzani’s poster for details on ROU’s assembly and tests
Signal processing chain overview

- 2700 readout channels
- Fully custom readout chain (from SiPM to DAQ)

**2700 Read-Out Units**
- FEE consists in trans-impedance preamp, shaper and HV regulator

10 DAQ crates/disk housing:

- 140 custom **Mezzanine Boards**
  - Slow-control distribution for HV/LV setting

- 140 custom **DIRAC digitizer board**
  - Signal digitization @ 200 Msps w/ 12-bit flash ADC
  - Sampling optimized for signal reconstruction and pileup handling
  - PolarFire rad-hard FPGA
  - VTRX 10 Gbps optical link to Detector Control System

See F. Spinella’s poster on electronics
Calorimeter Vertical Slice Test (VST) with cosmics

- 20 ch MB+ DIRAC V2 boards used for full Vertical Slice Test
- **Data collected in vacuum, at low T**
- **Test of cooling system**
- Stable operation and reconstruction
- Data taking of CR events triggered with external scintillators

Cosmic Ray Tagger
(See R. Gargiulo’s poster)

- Two sets of 8 (1.6 m long) Scint Counters with SiPM readouts integrated with FEE readout + mech support
- The CRT allows to test the dependence of response and resolution along the crystal axis for Module-0 and will provide an external trigger during calorimeter assembly and commissioning at SIDET (FNAL)
VST: summary of results

- T0-calibration done with iterative “alignment” method (residual better than 10 ps)
  - Cell mean time resolution w/ MIPs ≈ 210 ps

Sigma distribution for the pedestal

T0-finder

left-right time difference

mean time difference between 2 crystals w/ 2D ToF

3 parameters template generated from data to fit time and charge

400 mV/MIP

200 keV Noise
Calibration Tools - Source and laser

- Neutrons from a DT generator irradiate a fluorine rich fluid (Fluorinert) that is then piped to the front face of the disks.

- The following reaction gives rise to 6.13 MeV photons:

\[
^{19}_F + n \rightarrow ^{16}N + \alpha
\]

\[
^{16}_N \rightarrow ^{16}O^* + \beta \quad t_{1/2} = 7 \text{ s}
\]

\[
^{16}O^* \rightarrow ^{16}O + \gamma (6.13 \text{ MeV})
\]

- The produced $\gamma$'s uniformly shines the crystals.

- Few minutes of data taking to calibrate each crystal at O(1%).

- A pulsed, 530 nm, green laser illuminates all crystals through a distribution system based on optical fibers and integration spheres.

- Monitor gain variation at level of 0.5%.

- Determine T0’s at level of 100 ps.

- Stability at level of few %, monitored with PIN Diodes at laser source. Used at low rate in off-spill gates.

In-situ calibration with crossing MIPs, DIO’s and other physics processes.
mechanical parts procurement

Front Panel CF with embedded source pipe

Crates

Carbon Fiber Inner Ring

Front Plate: CF+Al Honeycomb+ Source Al Tubing

Calorimeter Feet

Aluminum Outer ring

FEE plate
Status of the mechanics

- Design and integration of the components within the envelope
- Outer ring construction  ✅
- Back plate construction  ✅
- Front plate with source incorporated under assembly  ❓

30/07/21

E. Diociaiuti | EPS - HEP 2021

Apartment from the source tubing integration on the front plate, all calorimeter mechanical parts have been produced.

In progress: routing test of FEE-MB cables from FEE plate to the crates.

Shipment to FNAL of all large mechanical parts in progress for the downstream disk.
Conclusions

- The Mu2e CsI+SiPM Calorimeter shows excellent energy (< 7 %) and timing (< 200 ps) resolution @100 MeV as tested with electrons beams

- The most demanding requirements are to operate in a 1 T field, in vacuum and in a rad-hard environment:
  - SiPM’s work under neutron irradiation but eventually need to be cooled down to -10 °C
  - Engineering of cooling and calorimeter mechanics has been challenging

- Production of crystals, SiPMs and FEE completed

- Production of mechanical parts almost completed+ dry FIT ongoing

- Successful VST carried out with excellent results on timing and energy calibration
  - Production of Digital electronics underway as planned

- Shipments of material from INFN to FNAL is in ongoing as we talk

- Assembly room at FNAL being completed
  - We plan to start outgassing components in June
  - We plan to begin crystal stacking this summer
  - to be ready to move in the Mu2e building by the end of 2023

25/05/22
Calorimeter Integration in the Muon Beam line

The Calorimeter design is already fully integrated in the Mu2e detector train

Disks can move apart for servicing
The straw tube tracker

- dual ended TDC/ADC readout large Radii
- ~21000 straw tubes, 5 mm diameter
- Spiral wound
- Walls: 12 µm Mylar + 3 µm epoxy + 200 Å Au + 500 Å Al
- 25 µm Au-plated W sense wire
- 33 - 117 cm in length
- 80/20 Ar/CO₂ with HV < 1500 V

\[ \sigma_p < 115 \text{ keV} @ 105 \text{ MeV} \]

Tracker not sensitive to particles with \( p_T < 80 \text{ MeV/c} \) (beam flash and most of DIOs)
Parts procurement status

- Pure CsI Crystals all procured, LY response and dimensionally tested and Tyvek wrapped
- Hamamatsu SiPM’s all procured and tested for gain, MTTF and irradiation
- FEE boards being produced and calibrated + integrated to SiPM
- ROU’s being assembled
- Mezzanine boards being produced
- Digitizer boards prototypes received, production planned

Mechanical parts

- Outer Al support rings ready, one at FNAL, one at LNF for Dry run
- FEE plates ready, being shipped
- Feet ready
- Carbon Fiber Inner Ring ready and being shipped, Source plate under construction
- SiPM+FEE copper holder and Faraday cages in our hands
- HV/LV+ Digitizer crates are ready, being shipped
- Outgassing station assembled and ready
In Situ Cosmic Ray calibration

Calibration trigger for commissioning, 20Hz. (Docdb # 36767)

**Procedure for Energy calibration based on MIPs**

**Procedure for Timing Calibration based on crossing time alignment**

With few iterations from ns to O(10 ps) T0’s corrections

Resolution at 250ps/MIP
Particle identification and Pattern Recognition

Stopping Target
Straw Tracker
Crystal Calorimeter

particles with hits within +/-50 ns of signal electron $t_{\text{mean}}$