Implementation of a Time-domain Cosmic-ray-muon Tagger for the NEXUS Low-background Cryogenic Facility

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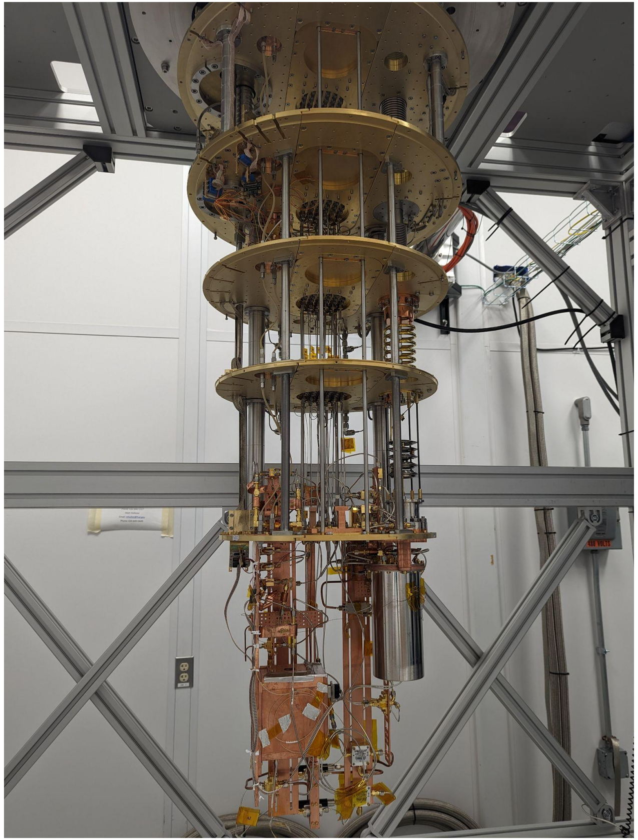
Background

- Traditional bits represent information as a binary: it is either 0 or 1.
- Quantum bits represent information as a superposition of states: a probability of existing as 0 or 1.
- Qubits encompass the technology that allows us to encode quantum information onto a physical chip.
- Storing this information can be a challenge.
- Particle collisions create correlated errors that cannot be corrected.

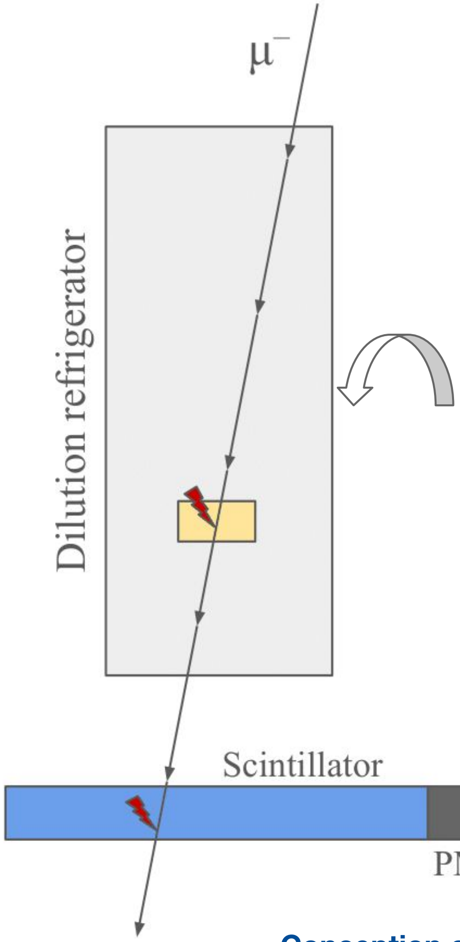


The LOUD fridge at Lab G in SiDet.

Introduction

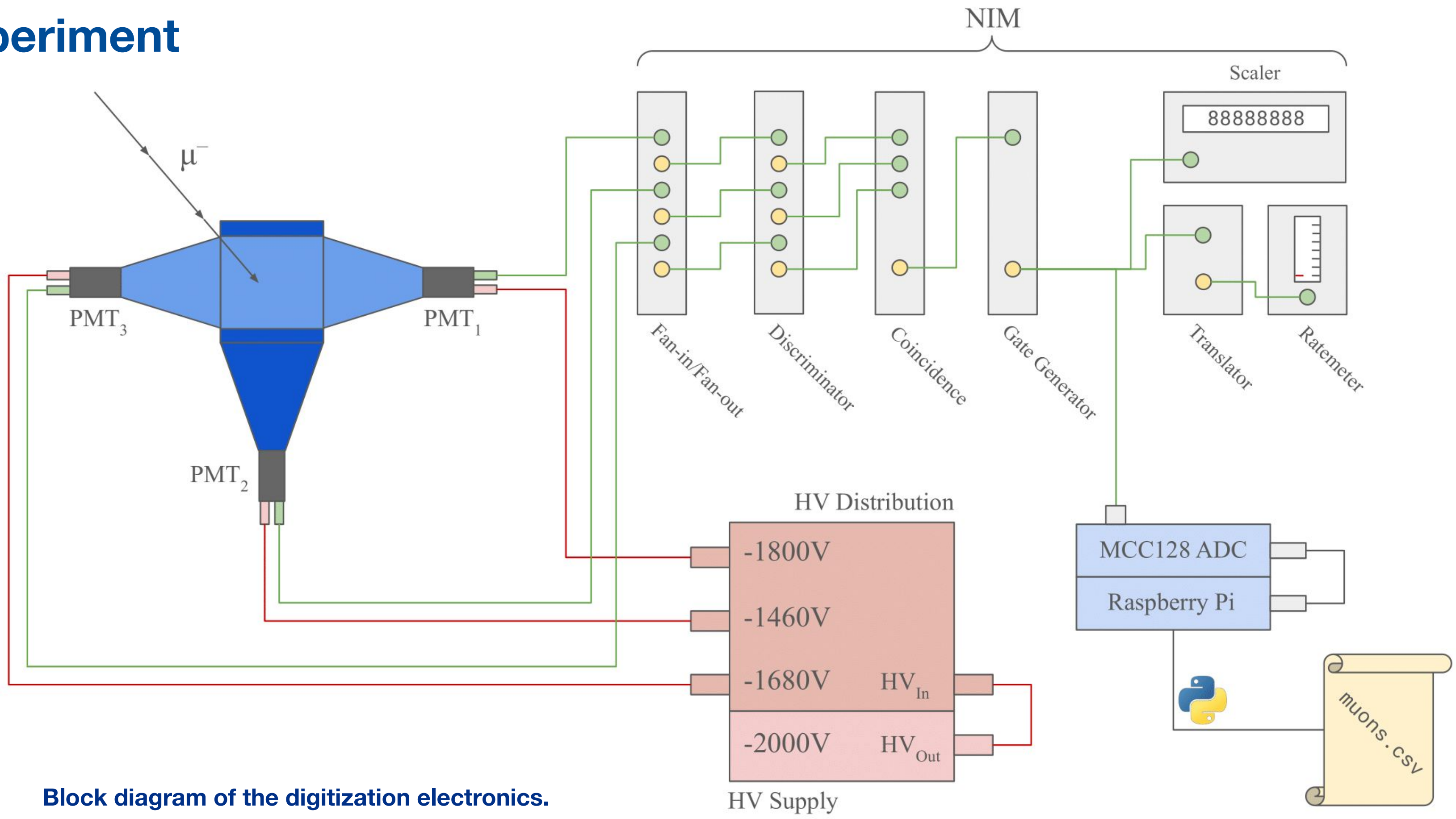
- NEXUS is a low-background facility at Fermilab for the testing and deployment of qubits and other cryogenic hardware.
- At MINOS, the rate of background radiation is approximately 500 times lower than the surface.
- Cosmic-ray muons still make it underground.
- A detector is needed to link correlated errors in qubits to an astrophysical origin.

The NEXUS lead shield.



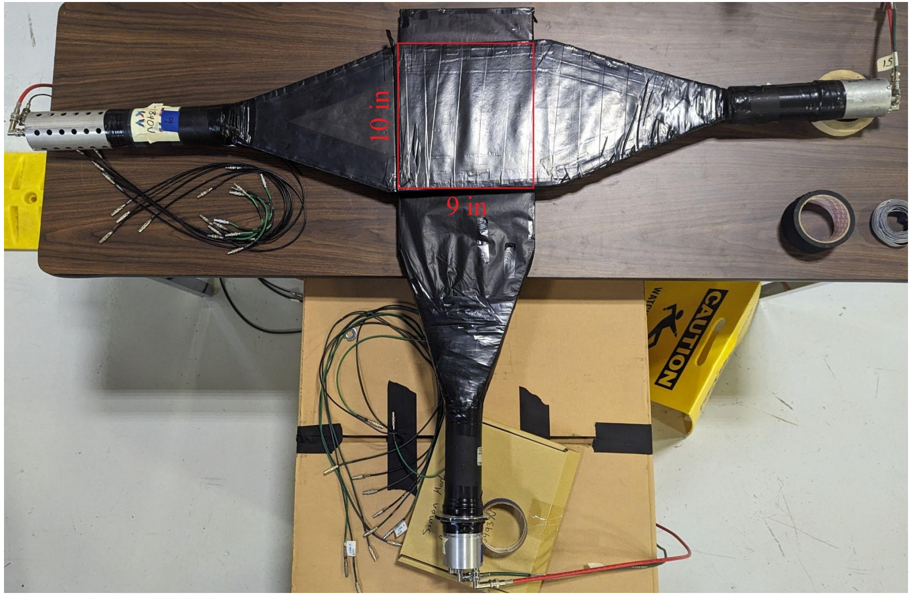
Conception of the experiment.

Experiment

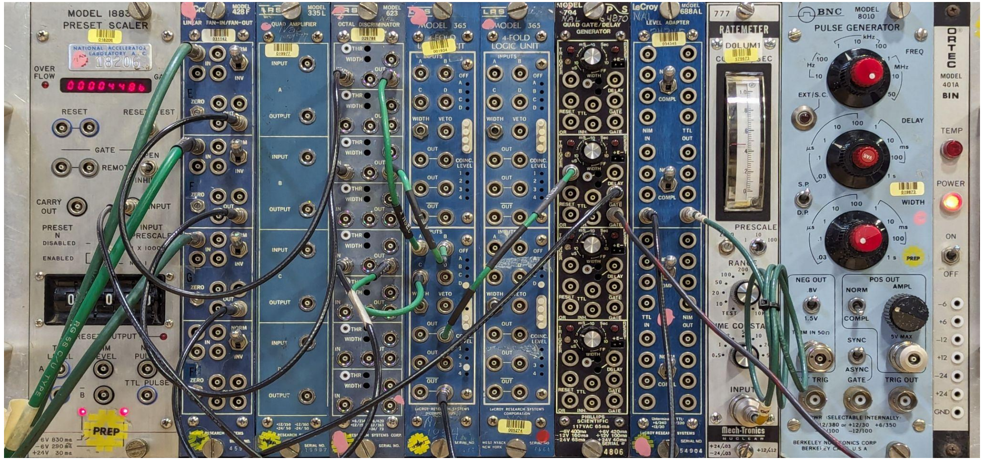


Block diagram of the digitization electronics.

Equipment

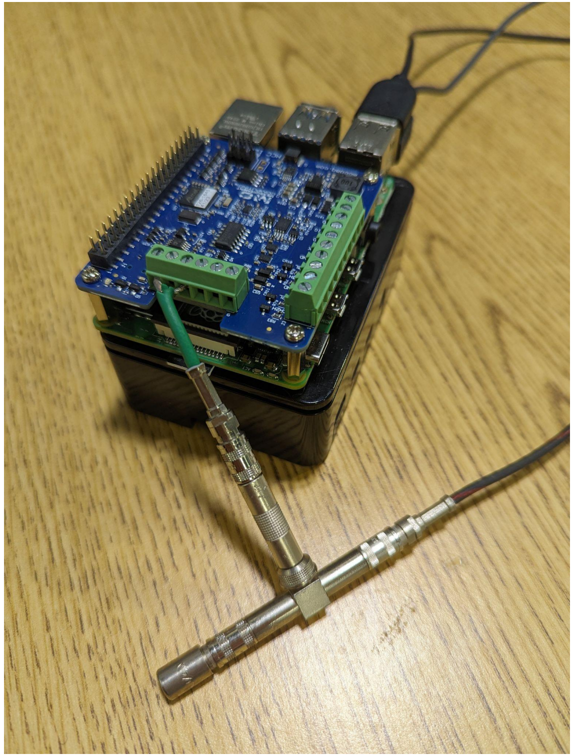


Top-down view of the scintillator paddles with the coincident surface area boxed in red.



Face-on view of the NIM modules used for detecting incident muons.

Digitization



The MCC 128 DAQ HAT used.

```python
#!/usr/bin/python
#  -*- coding: utf-8 -*-

import ntplib, daqhats, time, os, datetime
import pandas as pd
import numpy as np
from matplotlib import pyplot as plt

def continuous_read(seconds=5, log_path=None, save=True):
    t_start = time.time()
    while seconds > time.time() - t_start:
        voltage = dq.a_in_read(0)
        if (voltage < -0.4) and save:
            log = open(log_path, 'a+')
            log.write(fr'0,{time.time_ns()},0'+'\n')
            log.close()

def format_log(temp_path, log_path):
    temp_file = pd.read_csv(temp_path)
    log_file = pd.read_csv(log_path)
    times = np.delete(temp_file['t_muon'], np.argwhere(np.ediff1d(temp_file['t_muon']) <= 200*1000) + 1)
    new_log = pd.DataFrame()
    new_log['event'] = np.asarray(range(len(np.append(log_file['t_muon'], temp_file['t_muon']))))
    new_log['t_muon'] = np.append(log_file['t_muon'], pd.to_datetime(times).astype('str'))
    new_log['t_muon_ns'] = np.append(log_file['t_muon_ns'], times)
    new_log.to_csv(log_path, index=False)
    os.remove(temp_path)

def initialize_log(path):
    log = open(path, 'a+')
    log.write(fr'event,t_muon,t_muon_ns'+'\n')
    log.close()

dq = daqhats.mcc128(0)
the_date = time.gmtime()
log_path = fr'{the_date[1]:02d}_{the_date[2]:02d}_{the_date[0]:04d}.csv'
temp_path = 'temp.log'

if not os.path.exists(temp_path):
    initialize_log(temp_path)
if not os.path.exists(log_path):
    initialize_log(log_path)

continuous_read(seconds=1, save=False)
print('Beginning continuous scan...')
continuous_read(seconds=60, log_path=temp_path, save=True)
print('Continuous scan complete.')
format_log(temp_path, log_path)
```

The code file that runs to log the time a muon struck the scintillators.

Fermilab

Results

- On the surface, we measured a luminosity of 9.7425 muons per second.

$$9.7425\ \frac{\mu^-}{\text{s}} \cdot \frac{1}{9\ \text{in}} \cdot \frac{1}{10\ \text{in}} \approx 0.1083\ \frac{\mu^-}{\text{in}^2\ \text{s}} \tag{4}$$

$$0.1083\ \frac{\mu^-}{\text{in}^2\ \text{s}} \left(\frac{1\ \text{in}}{2.54\ \text{cm}}\right)^2 \frac{60\ \text{s}}{1\ \text{min}} \approx 1\ \frac{\mu^-}{\text{cm}^2 \cdot \text{min}} \tag{5}$$

- Converted to flux, this is approximately 1 muon per square centimeter per minute.
  - This is very close to theoretical.

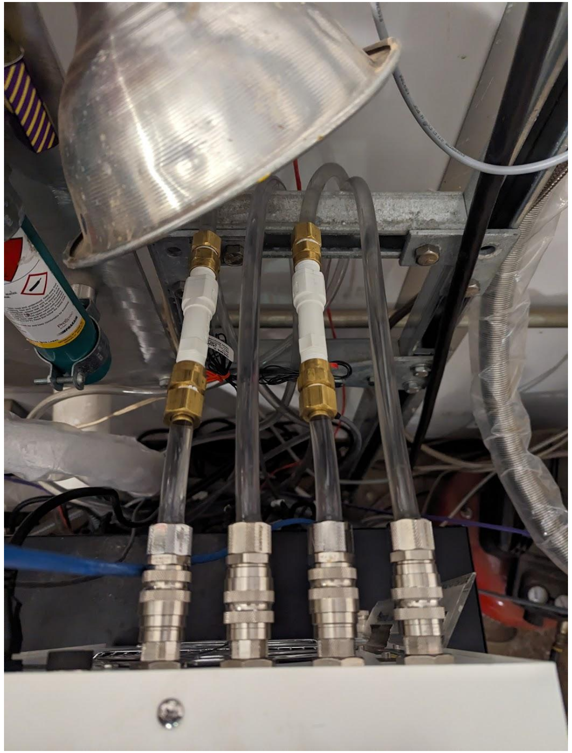
Summary

- The muon detector has been assembled and calibrated at the surface level in Lab G.

- We have measured a surface-level flux of muons within ~1% of the theoretically expected value.

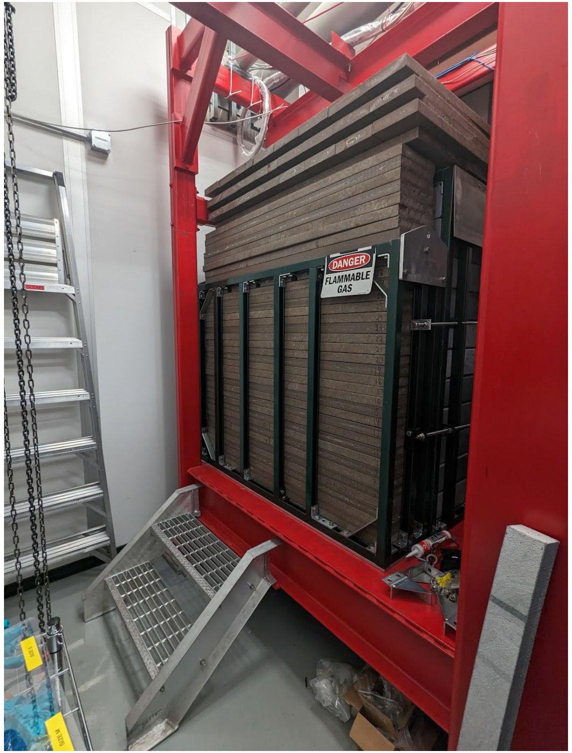
- I will deploy the detector at NEXUS in the coming months.

Supplemental



Fluorinert coolant tubing.

D-D generator control rack.



Neutron shield reassembled.

Supplemental

Table 1. Hardware used in the Experiment

Quantity	Manufacturer	Model	Description
1	Ortec	401A	NIM Bin
1	Jorway	1883	Visual Scaler and Preset Pulse Generator
1	LRS	335L	6x Quad-channel Linear Amplifier
1	LRS	428F	Linear Quad-channel Fan-in/Fan-out
1	LRS	623	Custom-threshold Octal Discriminator
2	LRS	365	Quad-channel Arbitrary-coincidence Unit
1	Phillips	794	Quad-channel Gate/Delay Generator
1	LRS	688AL	Bi-directional NIM-TTL Logic Translator
1	MTN	777	1Hz–1Mhz Visual Ratemeter
1	BNC	8010	Arbitrary Logic Pulse Generator
1	Power Designs	HV1547	High-Voltage Power Supply
1	Fermi	11X2562SIC	High-Voltage Zener Divider
1	MCC	128	Analog-to-Digital Voltage Sampler
1	CanaKit	Raspberry Pi - 8GB	Python Watchdog Script Executor
4			High-Voltage Cable
17			LEMO Signal Cable

NOTE—Abbreviations used in the text are as follows: BNC/Berkeley Nucleonics Corporation. Fermi/Fermilab. LRS/Lecroy/Lecroy Research Systems. MCC/Measurement Computing Corporation. MTN/Mech-Tronics Nuclear. Phillips/Phillips Scientific.