Impact of Beam Induced Backgrounds on Cosmic Ray Veto

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- Total expected Mu2e background is 0.4 events over 3 years
- Mu2e expects 1 signal-like event per day induced by cosmic rays
- Cosmic ray muons produce background through material interactions, decays and muon faking an electron
- To achieve experiment’s designed sensitivity, Cosmic Ray Veto detection efficiency is required to be $> 99.99\%$
CRV consists of 4-layer scintillating 5x2 cm² counters, read-out through wavelength-shifting fibers by 2x2 mm² SiPMs.

- CR muon detection - hits coincidence in 3/4 layers localized in time and space.
- Veto 125 ns from a signal window after a coincidence in the CRV.

- Area: 327 m²
- 86 modules of 6 lengths
- 5,504 counters
- 11,008 fibers
- 19,840 SiPMs
- 310 Front-end Boards
1. Every 1695 ns, 8 GeV protons hit production target to produce $\pi^-$
   - $\pi^-/\mu^-$ are reflected toward the transport solenoid
   - Beam intensity is 8 kW

2. Transport Solenoid delivers $\pi^-/\mu^-$ to Detector Solenoid
   - Selects particle’s momentum and charge
   - Avoids direct line of sight

3. Muons stop on the Al Stopping Target
   - 1,000 POT $\rightarrow$ 4 (2) muons reach (stop on) the target
   - Conversion electrons are measured in the tracker and calorimeter
Exploit beam bunched structure to suppress physics backgrounds
- Wait for 700 ns after proton pulse

Particle fluxes from beam interactions:
- **Damage** CRV components
- **Produce noise** in CRV, increasing DAQ rates. Noise hits in CRV fake CR muons and increase the dead-time
  - CRV ignores hits outside of the signal window
A Largest source of neutrons is PS. The source is prompt and reduced in the signal window
   - Neutrons get thermalized, captured and produce delayed gammas
B Fast neutrons, produced in the signal window, are from $\mu$-captures on beam-line and stopping target
   - Fast neutron recoil off a proton depositing energy in the counter
C High energy gammas in the Muon Beam Stop (MBS): electron brems from $\mu$-decays. Muons escaping MBS decay producing high energy electrons
- Mu2e uses detailed geometry and detector response simulation
- CRV is shielded from beam induced backgrounds by 1 yd of T-shaped concrete walls
- Upstream region is swamped with neutrons from PS
  - Neutrons captured on various materials produce gammas up to 10 MeV
- Upstream shielding consists of boron-loaded concrete
  - Neutrons captured on Boron produce lower (0.48 MeV) energy gammas
CRV shielding: Barite-loaded concrete

- Barite high-Z concrete around the stopping target shields against fast neutrons to reduce fake vetos
- Barite shielding at the middle collimator and PS corner mitigates the rad damage to SiPMs
CRV shielding: Muon stops

- 10E9 unused muons are dumped in MBS every second
- Muons stopped on low-Z polyethylene decay
- Electrons from muon decays brem. High energy gammas produce fake vetos in CRV
- Muons escaping MBS produce high energy electrons produce coincidence in CRV
Fast neutrons produce damage to SiPMs

- Rad damage is driven by PS and collimators. Requirement is $10^{10}$ n/cm$^2$

- Rad damage to scintillator and fibers is negligible
- CRV average SiPM rates is 61 kHz at 6PE
- The highest rates are in upstream (CRV-U, CRV-TS) region

![Graph showing SiPM rates for different CRV regions](image)
- Background hits in CRV fake CR muons and produce dead-time
- CRV dead-time is 13%
- Dead-time is dominated by upstream region

**Dead-time**

- CRV hit
- 3/4 coincidence
Considering enhanced shielding in upstream:
- High-Z boron-loaded concrete
- Boron-loaded poly covering the upstream portion of CRV

CRV dead-time with enhanced shielding - 4%
Cosmic ray veto is an essential component for the Mu2e experiment

- Suppress the background by 4 orders of magnitude

CRV design is challenging

- Maintain 99.99% cosmic ray veto efficiency over 3 years
- Operate in high radiation environment, and produce small dead-time to the experiment

CRV and shielding design has been modified to reduce the impact

- Further optimization is in progress

Mu2e simulation results yield the dead-time of 13%

- Expect to reduce the number with further optimizations
In order to suppress the noise from neutrons and gammas CRV design has undergone the changes

<table>
<thead>
<tr>
<th></th>
<th>Counter thickness [cm]</th>
<th>Fiber diameter [mm]</th>
<th>Counter width [cm]</th>
<th>Aluminum absorber [cm]</th>
<th>Number of layers</th>
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<tbody>
<tr>
<td>CDR</td>
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<td>10</td>
<td>0.5</td>
<td>3</td>
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<tr>
<td>TDR</td>
<td>2</td>
<td>1.4</td>
<td>5</td>
<td>1</td>
<td>4</td>
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<tr>
<td>Impact</td>
<td>Increase muon energy deposition</td>
<td>Increased light yield</td>
<td>Decrease counter rates</td>
<td>Suppress punch-throughs</td>
<td>Reduce ¾ noise rate</td>
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Sources of neutrons and gammas at CRV

- Production positions of last neutron or gamma reaching CRV
CRV dead-time in the Mu2e simulation framework is estimated

- Simulation of light production, propagation, SiPM response, digitization and reconstruction have been recently implemented
- Shielding geometry has been recently refined to the best of our knowledge

Simplified version of a coincidence finder algorithm has been implemented

- Consider reconstructed pulses above 10 PE threshold
- Localized in time (15 ns) and space (30 cm)

The total dead-time is estimated to be 12%
Sources of neutrons and gammas at CRV