Mu2e Solenoid Capture System: Radiation and Heat Shield Optimization using MARS15

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Fermilab

Solenoid Capture Workshop
Brookhaven National Laboratory
29–30 November 2010
Outline

• Mu2e Experiment at Fermilab

• Production Solenoid Shield Constraints
  – SC in radiation field: quench stability & heat loads
  – Aluminum resistance and lifetime at cryo temperatures
  – Cost

• Shielding Material/Cost Optimization

• Tungsten Mass/Geometry Optimization

• Conclusions
What is $\mu e$ Conversion?

Muon converts to electron in the presence of a nucleus, coherent conversion:
1) neutrinos are not emitted
2) nucleus remains intact
3) signature – 105 MeV monoenergetic electron

$$\mu^- N \rightarrow e^- N$$

\[
R_{\mu e} = \frac{\Gamma(\mu^- + (A, Z) \rightarrow e^- + (A, Z))}{\Gamma(\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z - 1))}
\]

\[
R_{\mu e} < 6 \times 10^{-17} @ 90\% CL
\]

Best limit: $6 \times 10^{-13}$ (90% C.L.) from SINDRUM II

Search for Charged Lepton Flavor Violation, rate in SM $< 10^{-51}$

Explanation: SUSY, extra dimensions, leptoquarks, second Higgs doublet etc.
Mu2e Collaboration

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V. Pronskikh, Mu2e Capture Solenoid
Mu2e experimental setup

Proton beam:
- 8 GeV on Au target
- 25 kW (2E13 p/s)
- \( \sigma_x = \sigma_y = 1 \) mm

Production solenoid SC coils:
- 5 Tesla
- \( D = 167 \) cm
Simulations

- MARS is a Monte Carlo code for inclusive and exclusive simulation of three-dimensional hadronic and electromagnetic cascades, muon, heavy-ion and low-energy neutron transport in accelerator, detector, spacecraft and shielding components in the energy range from a fraction of an electronvolt up to 100 TeV.
- **MARS15 (2010)** code version was used
- Thresholds: neutrons (from thermal energies), other particles from 0.2 MeV
- Linux cluster, up to 24 processors were used
- Were simulated: DPA, power densities, neutron fluxes, dynamic head loads
Optimization parameters

- Absorber (heat and radiation shield) is intended to prevent radiation damage to the magnet coil material and ensure quench protection and acceptable heat loads for the lifetime of the experiment
  - Total dynamic heat load on the coils
  - Peak power density in the coils
  - Peak radiation dose to the insulation and epoxy
  - DPA to describe how radiation affects the electrical conductivity of metals in the superconducting cable

Materials:
- 8.35% NbTi
- 8.35% Cu
- 17.33% G10
- 65.97% Al
Optimization parameters. Peak power density

Power density (peak) = 11 μW/g
ΔT = 4.827K - 4.2K = 0.627K
Tcr = 4.6 K
T0 should be ~4.0K
Absorbed dose 300kGy/yr (0.015 mW/g)
Optimization parameters. DPA-1

- DPA (displacement per atom). Radiation damage in metals, displacement of atoms from their equilibrium positions in a crystalline lattice due to radiation with formation of interstitial atoms and vacancies in the lattice.
  - A (PKA) primary knock-on atom is formed in elastic particle-nucleus collisions, generates a cascade of atomic displacements (damage function, $v(T)$).
  - A PKA displaces neighboring atoms, this results in an atomic displacement cascade. Point defects are formed as well as defect clusters of vacancies and interstitial atoms (time scale=ps).

- DPA model in MARS15 includes all products of elastic and inelastic nuclear interactions and Coulomb elastic scattering of transported charged particles (hadrons, electrons, muons and heavy ions) from 1 keV to 10 TeV.
Optimization parameters. DPA -2

- Irradiation-induced changes of material properties are measured as a function of DPA (the radiation damage cannot be fully characterized by a single parameter)
- Radiation-induced microstructural changes in materials:
  - Dimensional instability
  - Radiation hardening and embrittlement
  - Irradiation creep
  - Reduction in fatigue performance
  - Degradation of physical properties
    Residual Resistivity Ratio degradation (RRR, ratio of the electric resistance of a conductor at room temperature to that at the liquid He one), the loss of superconducting properties due to change of conditions of electron transport in metals.

- DPA limit for SC coils = 2.5E-5 /yr
Optimization parameters. DPA -3

T. Ogitsu’s (COMET, Japan) talk at FNAL:

- Resistivity will degrade by Frenkel Pairs induced by neutron
- Number of Frenkel Pairs = DPA

DPA: 2E-5 per 1E21 protons
MARS15 model of the Mu2e hall

(not to scale)
Absorber versions (first optimization)

- Tungsten, WC, U-238
- W, 5cm
- Fe (Cu, WC), 20cm
- BCH2, 12 cm
- Fe (Cu, Cd), 3cm
- Tungsten/copper

Cases #1-#10

multilayer
Dynamic Heat Load (first design, role of the end caps and neutrons)

- Al no end cap En>100 keV
- Coil no end cap En>100 keV
- Al w/end cap En>100 keV
- Coil w/end cap En>100 keV
- Al w/end cap En>1E-12 GeV
- Coil w/end cap En>1E-12 GeV

Total Dynamic Heat Load, W

Distance in the absorber coordinate system, cm

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Neutron flux >100 keV and power density

Absorbed dose (Gy/s) = Power density (mW/g), i.e., peak in the coils ~ 40 kGy/yr
Neutron flux ratio for W/WC absorbers

![Graph showing neutron flux ratio for W/WC absorbers with labels for NbTi/Al, Al coils, w/yoke, and full model.](image)

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DPA ratios for W/WC absorbers
Neutron lethargies at 1-st coil

Lethargy = $\frac{d\text{Flux}}{d(\ln E)} = E \cdot \frac{d\text{Flux}}{dE}$

“Simple” model includes only the absorber and the coils

“Full” model includes also cryostat, end cap, yoke, beam shield and 1-st TS coil
Mu2e vs MECO DPA comparison

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Absorbed dose (Gy/s) = Power density (mW/g)

0.025 mW/g = 500kGy/yr (300kGy/yr (0.015 mW/g) requirement)
Amount of tungsten: optimization-1

Blue – tungsten, yellow - copper

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Amount of tungsten: optimization-2

Pink – HEVIMET (90% W, 6% Ni, 4% Cu),
yellow – copper,
brown – high silicon bronze (97% Cu, 3% Si)
M (W) = 20.3 tons
M (Cu) = 37.5 tons

V. Pronskikh, Mu2e Capture Solenoid
Power density, mW/g

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<tr>
<th></th>
<th>1 coil</th>
<th>2 coil</th>
<th>3 coil</th>
<th>TS-1</th>
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DPA, yr^-1

limit

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Capital cost vs operational cost are trade off

Dynamic Heat Load, W

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<th>TS-1</th>
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Towards Engineering Design

Gray – HEVIMET, brown – bronze

by L.Bartoszek based on MARS15 model
Conclusions

• Compact (Mu2e) shielding has advantages (DPA etc.) compared to the MECO one
• As a result of optimization, a combination of tungsten-based and copper-based alloys was selected as the materials for the absorber
• Analysis of WC+H₂O for the absorber showed that its advantages are not so big in the case when the influence of other Production Solenoid surrounding structures is considered. While the neutrons below 1 MeV are better suppressed by the WC+H₂O absorber, tungsten performs better at high energies (100s MeV) which dominate DPA and power density.
Conclusions-2

• While tungsten carbide with water better slows down neutrons compared to pure tungsten (with neutron flux after WC absorber being significantly lower), WC as having smaller than W its effective Z, stops charged particles worse. As a result, more abundant in the WC absorber charged particles make the effect of decrease in DPA not so evident, while give more rise to the peak power density than neutrons.

• Proposed optimized absorber satisfies the DPA, power density and absorbed dose requirements (although close to the limits), whereas the simple W/Cu version seems to be more safe, especially from the point of view of thermal analysis.