Beam energy optimization for Mu2e @ PIP-II

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Introduction

- An improved proton source will be required for a next generation Mu2e
- Necessary to understand:
  - Expected muon yield and muon stopping rates as a function of proton energy
  - Potential performance constraints as a function of proton beam energy
- MARS15 is used because the energy-deposition-related quantities are well modeled as well as DPA damage (displacement-per-atom)
- PIP-II: Mu2e upgrade potential (@800 MeV) > 100 kW (linac), 120 kW (@8 GeV) (Booster), energies within the range were also considered
- The energy range studied: 0.5 GeV – 8 GeV.
Baseline Mu2e and MARS15 simulations

- 8 GeV 8 kW proton beam
- W target L=16 cm D=0.6 cm (beam \(\sigma=0.1\) cm)
- Bronze HRS (tungsten considered for upgrade), CDR design is used for the study
- PS, TS, DS (17-foil Al stopping target (STT))

In MARS15 simulations: LAQGSM, thresholds: 1E-12 GeV for neutrons, 100 keV for charged h., muons, photons

DPA and power density vs beam energy vs HRS material
Muon yield/stopping rate vs beam energy
Figure of merit (stopping rate per DPA)
DPA limit and model

HRS: Bronze, Tungsten
DPA model: NRT (below 20 (150) MeV ENDFB-VII/NJOY based cross section library FermiDPA 1.0) is used. NbTi coils
DPA limits incorporate KUR measured data 4-6E-5 DPA
Power density (PD) and other limits

Power density limit:
- depends on the cooling scheme
- involves many other assumptions

Dynamic heat load limit:
- scales with the number of cooling stations

Absorbed dose limit: usually high

<table>
<thead>
<tr>
<th>Quantity</th>
<th>DPA, $10^{-5}$</th>
<th>Power density, $\mu$W/g</th>
<th>Absorbed dose, MGY/yr</th>
<th>Dynamic heat load, W</th>
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</thead>
<tbody>
<tr>
<td>Specs</td>
<td>4-6</td>
<td>30</td>
<td>0.35</td>
<td>100</td>
</tr>
</tbody>
</table>
DPA as a function of beam energy

DPA damage and peak power density are:
Largest at ~3 GeV and drops with energy below that energy
Larger for bronze than for tungsten by a factor of ~3-4
DPA and power density @ 100 kW

- DPA: Current coil design can likely tolerate 100 kW at proton energies < 1 GeV (if HRS thickness is increased).
- Power density: current coil design/cooling scheme can tolerate 100 kW at $E_p = 0.8$ GeV and lower. For higher energies another cooling scheme may be required.
- Above 1 GeV (DPA) or 2 GeV almost flat with energy.
Mu- spectra and yields at TS

Constant beam intensity (not power) = $6 \cdot 10^{12}$ p/s
Steepest rise in $\mu^-$ yields is between 0.5 and 2 GeV.
Effective flux-based approach was used for counting muons
Acceptance

At 0.8 GeV
Calculated using G4beamline, used with MARS15 calculated muon spectra at TS

Average 1-8 GeV

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Mu- stopping rates and Figure of Merit

3 years = 4.7E21 protons on target @ 8 GeV (4.7E22 @ 0.8 GeV)
If only stopped muons are considered: 2-3 GeV
If DPA is also considered: 1-3 GeV
The FOM for 0.8 GeV is about the same as it is for 8 GeV
Single-event sensitivity and limiting beam power

- The single-event-sensitivity (SES) corresponds to the rate of \( \mu \)-to-\( e \) conversion at which the experiment would observe 1 event

\[ \text{Current Mu2e } R_{ses} = 3 \cdot 10^{-17} \]

- Estimated SES as a function of proton beam energy

**Estimate is made assuming**
- 3y run at 100 kW (same timing structure, but increased duty factor)
- Aluminum stopping target (ie. unchanged)
- Total number of stopped muons as on page 10
- Detectors can be made to handle increased rates so that acceptance and resolution comparable to current estimates

**Could achieve >x10 improvement for Tp in 0.8 – 5 GeV range**
Future plans

Inner bore radius = 20 cm
No yield drop for R > 17 cm

Investigate the DPA and Power density deposition for a tungsten HRS with a reduced inner bore
Conclusions

• Energy dependence of DPA damage, power density, muon yield and muon stopping rate is studied.

• A Figure of Merit is proposed: the ratio of stopped muon rate to DPA
  – FOM is largest in the 1-3 GeV range
  – FOM for 0.8 GeV is comparable to 8 GeV

• Assuming detectors can be made to handle increased rates, can plausibly achieve x10 improvement in sensitivity for 100 kW at \( T_p = 0.8-5 \) GeV

• Additional work required to understand whether current coil + tungsten HRS design can likely tolerate 100 kW
# Mu-entering TS

<table>
<thead>
<tr>
<th>Ep, GeV</th>
<th>Mu-/proton</th>
<th>Stat. uncertainty</th>
<th>Stat. uncertainty, %</th>
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<tbody>
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<td>0.5</td>
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<td>5.17E-06</td>
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<td>0.6</td>
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<td>0.7</td>
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<td>0.8</td>
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<td>8</td>
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</table>
### Mu2e@PIP-II upgrade plans

- Early next decade
- 250 meter linac (20 Hz)?
- 800 MeV proton beam (2 mA)
- -> Booster -> 8 GeV (120 kW)
- -> Main Injector/Recycler
- ->120 GeV (1.2 MW)

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>PIP</th>
<th>PIP-II</th>
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<tbody>
<tr>
<td>Linac Beam Energy</td>
<td>400</td>
<td>800 MeV</td>
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<tr>
<td>Linac Beam Current</td>
<td>25 mA</td>
<td>2 mA</td>
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<tr>
<td>Linac Beam Pulse Length</td>
<td>0.03</td>
<td>0.5 msec</td>
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<tr>
<td>Linac Pulse Repetition Rate</td>
<td>15 Hz</td>
<td>15 Hz</td>
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<tr>
<td>Linac Beam Power to Booster</td>
<td>4 kW</td>
<td>13 kW</td>
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<tr>
<td>Linac Beam Power Capability (@&gt;10% Duty Factor)</td>
<td>4</td>
<td>~200 kW</td>
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<tr>
<td>Mu2e Upgrade Potential (800 MeV)</td>
<td>NA</td>
<td>&gt;100 kW</td>
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<tr>
<td>Booster Protons per Pulse</td>
<td>$4.2 \times 10^{12}$</td>
<td>$6.4 \times 10^{12}$</td>
</tr>
<tr>
<td>Booster Pulse Repetition Rate</td>
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<tr>
<td>Booster Beam Power @ 8 GeV</td>
<td>80 kW</td>
<td>120 kW</td>
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<td>Beam Power to 8 GeV Program (max)</td>
<td>32 kW</td>
<td>40 kW</td>
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<tr>
<td>Main Injector Cycle Time @ 120 GeV</td>
<td>1.33 sec</td>
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<td>LBNF Beam Power @ 120 GeV*</td>
<td>0.7 MW</td>
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<tr>
<td>LBNF Upgrade Potential @ 60-120 GeV</td>
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<td>&gt;2 MW</td>
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Table from S.Holmes, Neutrino Summit, 2014