Surface muon beam at PSI and Project X

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Argonne National Laboratory
Outline

• General introduction to surface / cloud muons

• Muon beam facilities overview

• General considerations for muon beam
  • Experimental requirements
  • Proton target
  • Beam channel
  • Muon stopping target

• What could the future bring (PSI, Project X, ...)?
Surface muons \((p_\mu = 29.8 \text{ MeV/c})\)

Figure 6: Surface muon production schematic. Pions decay in the green region.

- Surface muons:
  - Pions stop and decay close to the surface of the production target.
  - Source is well defined, allowing precise beam optics.
  - Polarization is near 100%.
  - \(\mu^+\) only, since \(\pi^-\) interact with nuclei before decay.
  - Beams are contaminated with positrons if no separation system is used.
  - Thin windows and vacuum beam transport necessary.
  - Stopping density very high due to short range \((R_\mu \sim 0.14 \text{ g/cm}^{-2}\) in carbon\)

\[
R_\mu \propto p^{3.5} \Rightarrow \frac{\Delta R_\mu}{R_\mu} \sim \sqrt{(3.5 \frac{\Delta p}{p})^2 + (\Delta R_{str})^2}
\]

See A.E. Pifer et al., Nucl. Instr. and Meth. 135, 39.
Cloud muons \( (p_\mu > 30 \text{ MeV/c}) \)

**Muon production: cloud muons**

Figure 3: Cloud muon production schematic. Pions decay in the *green* region.

- **Cloud muons:**
  - From pion decay in flight, close to the production target.
  - Wide range of momentum available.
  - Source is larger than the production target.
  - Contaminated by \( \pi^\pm \) and \( e^\pm \).
  - Polarization is low, depending on momentum and geometry.
Muon beams

πE5 beamline PSI

\[ N_{\mu} \text{[mA}^{-1}\text{s}^{-1}] \]

\[ p_\mu \text{[MeV/c]} \]

http://aea.web.psi.ch/beam2lines/
Facilities overview
### Muon beams

<table>
<thead>
<tr>
<th>Laboratory/Beam line</th>
<th>Energy/Power</th>
<th>Present Surface $\mu^+$ rate (Hz)</th>
<th>Future estimated $\mu^+/\mu^-$ rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PSI (CH)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEMS</td>
<td>(590 MeV, 1.3 MW, DC)</td>
<td>$4 \cdot 10^8$</td>
<td></td>
</tr>
<tr>
<td>$\pi E5$</td>
<td></td>
<td>$1.6 \cdot 10^8$</td>
<td></td>
</tr>
<tr>
<td>HiMB</td>
<td>(590 MeV, 1 MW, DC)</td>
<td></td>
<td>$4 \cdot 10^{10} (\mu^+)$</td>
</tr>
<tr>
<td><strong>J-PARC (JP)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MUSE D-line</td>
<td>(3 GeV, 1 MW, Pulsed)</td>
<td>$3 \cdot 10^7$</td>
<td></td>
</tr>
<tr>
<td>MUSE U-line</td>
<td></td>
<td></td>
<td>$2 \cdot 10^8 (\mu^+)$ (2012)</td>
</tr>
<tr>
<td>COMET</td>
<td>(8 GeV, 56 kW, Pulsed)</td>
<td></td>
<td>$10^{11} (\mu^-)$ (2019/20)</td>
</tr>
<tr>
<td>PRIME/PRISM</td>
<td>(8 GeV, 300 kW, Pulsed)</td>
<td></td>
<td>$10^{11-12} (\mu^-)$ (&gt; 2020)</td>
</tr>
<tr>
<td><strong>FNAL (USA)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mu2e</td>
<td>(8 GeV, 25 kW, Pulsed)</td>
<td></td>
<td>$5 \cdot 10^{10} (\mu^-)$ (2019/20)</td>
</tr>
<tr>
<td>Project X Mu2e</td>
<td>(3 GeV, 750 kW, Pulsed)</td>
<td></td>
<td>$2 \cdot 10^{12} (\mu^-)$ (&gt; 2022)</td>
</tr>
<tr>
<td><strong>TRIUMF (CA)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M20</td>
<td>(500 MeV, 75 kW, DC)</td>
<td>$2 \cdot 10^8$</td>
<td></td>
</tr>
<tr>
<td><strong>KEK (JP)</strong></td>
<td></td>
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</tr>
<tr>
<td>Dai Omega</td>
<td>(500 MeV, 2.5 kW, Pulsed)</td>
<td>$4 \cdot 10^5$</td>
<td></td>
</tr>
<tr>
<td><strong>RAL -ISIS (UK)</strong></td>
<td></td>
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<tr>
<td>RIKEN-RAL</td>
<td>(800 MeV, 160 kW, Pulsed)</td>
<td>$1.5 \cdot 10^6$</td>
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<tr>
<td><strong>RCNP Osaka Univ. (JP)</strong></td>
<td></td>
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<tr>
<td>MUSIC</td>
<td>(400 MeV, 400 W, Pulsed)</td>
<td></td>
<td>$10^8 (\mu^+)$ (2012) means $&gt; 10^{11}$ per MW</td>
</tr>
<tr>
<td></td>
<td>currently max 4W</td>
<td></td>
<td></td>
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<tr>
<td><strong>DUBNA (RU)</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Phasatron Ch:II-III</td>
<td>(660 MeV, 1.65 kW, Pulsed)</td>
<td>$3 \cdot 10^4$</td>
<td></td>
</tr>
</tbody>
</table>
Muon beams at PSI

http://aea.web.psi.ch/beam2lines/
- $175^\circ$ relative to proton beam
- dipole and focussing quadrupole channel
- Solid angle: 150 mSr
- $\Delta p / p = 10\%$ (acceptance)
- Spot size: 15mm, 20mm
- $2 \times 10^8$ muons/s @ 2.4mA (590 MeV)
Muon beams: J-PARC

S-Line
Surface $\mu^+(30\text{ MeV}/c)$
For material sciences

H-Line
Surface $\mu^+$ For HF, g-2 exp.
e$^-$ up to 120 MeV/c For DeeMe
$\mu^-$ up to 120 MeV/c For $\mu$CF

U-Line
Ultra Slow $\mu^+(0.05-30\text{keV})$
For multi-layered thin foils, nano-materials, catalysis, etc

D-Line
Surface $\mu^+(30\text{ MeV}/c)$
 Decay $\mu^+$/ $\mu^-(\text{up to 120 MeV/c})$
Users’ RUN, in Operation

MUSE
Some muon experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Beam</th>
<th>Momentum</th>
<th>Rates</th>
<th>Beamline</th>
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<tr>
<td>MEG</td>
<td>$\mu^+$</td>
<td>29.8 MeV/c</td>
<td>$3 \times 10^7$/s</td>
<td>$\pi E5 \ @ \ PSI$</td>
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<tr>
<td>MuLan</td>
<td>$\mu^+$</td>
<td>29.8 MeV/c</td>
<td>$8 \times 10^6$/s</td>
<td>$\pi E3 \ @ \ PSI$</td>
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<tr>
<td>TWIST</td>
<td>$\mu^+$</td>
<td>29.8 MeV/c</td>
<td>$&lt;5 \times 10^3$/s</td>
<td>TRIUMF</td>
</tr>
<tr>
<td>MuCap / MuSun</td>
<td>$\mu^-$</td>
<td>34 MeV/c</td>
<td>$1 \times 10^5$/s</td>
<td>$\pi E3 \ @ \ PSI$</td>
</tr>
<tr>
<td>SINDRUM II</td>
<td>$\mu^-$</td>
<td>88 MeV/c</td>
<td>$1.2 \times 10^7$/s</td>
<td>$\mu E1 \ @ \ PSI$</td>
</tr>
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Material science community (muSR) using surface muons as well!
Some muon experiments

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</tr>
<tr>
<td>SINDRUM II</td>
<td>$\mu^-$</td>
<td>88 MeV/c</td>
<td>$\sim 10^7$/s</td>
<td>$\mu E1 \ @ \ PSI$</td>
</tr>
<tr>
<td>Mu2e</td>
<td>$\mu^-$</td>
<td>$\sim 40$ MeV/c</td>
<td>$5 \times 10^{10}$/s</td>
<td>FNAL</td>
</tr>
<tr>
<td>MEG upgrade</td>
<td>$\mu^+$</td>
<td>29.8 MeV/c</td>
<td>$7 \times 10^7$/s</td>
<td>$\pi E5 \ @ \ PSI$</td>
</tr>
<tr>
<td>$\mu^+ \rightarrow e^+e^-e^+$ (Ph. I)</td>
<td>$\mu^+$</td>
<td>29.8 MeV/c</td>
<td>$&lt;1 \times 10^8$/s</td>
<td>$\pi E5 \ @ \ PSI$</td>
</tr>
<tr>
<td>$\mu^+ \rightarrow e^+e^-e^+$ (Ph. II)</td>
<td>$\mu^+$</td>
<td>29.8 MeV/c</td>
<td>$2 \times 10^9$/s</td>
<td>HIMB @ PSI</td>
</tr>
</tbody>
</table>

MEG, $\mu 3e$:
- **DC $\mu^+$ beam**: Accidental background $\sim R_\mu^2$ (see pulsed mode comments at end of slides)

Mu2e:
- **Pulsed $\mu^-$ beam**: Wait until beam background gone ($\pi$, e, ...) are gone
1. Proton beam: momentum, power and beam structure
No gain is achieved in going to higher energies for this particular target geometry and material.

(a) Variation of muon yield with proton energy at higher energies.

(b) Normalisation of the muon yield to the proton energy.
New Geant4 generator vs HARP data: INCL 4.2 already in Geant4, INCL HE coming soon?

Sergei Striganov Fermilab
Project X Muon Spin Rotation Forum October 18, 2012
Conclusion – surface muon beam

- ISIS study claims that intensity/watt of surface muon beam at Project X energies is about 3-7 times lower than at 500 MeV.
- This result is based on GEANT4 model which underestimates measured cross section of positive pion production about few times at 2–8 GeV.
- Our crude estimate predicts nearly same surface beam intensity/watt for 2 GeV and 590 MeV protons.
- Direct simulation of surface muons based on developed approximation of low energy pion yield is need to make more solid conclusion.
- Optimization study of target geometry and material should be performed in new energy range.
Muon beams: General considerations

1. Proton beam: momentum, power and beam structure
2. Target: Material, cooling, size
1. Proton beam: momentum, power and beam structure
2. Target: Material, cooling, size
3. Proton transmission: Neutron facility or last in chain
Proton target

- Target material and shape for high yields of pions (muons)
- Cooling: Low heat production and high dissipation
- Minimize secondary particles (e, $\pi$, $\gamma$, n)
- Target size influences channel acceptance and beam spot
- Low activation
- Long lifetime (mechanical stress, fatigue)
PSI target E

- 6 cm long rotating graphite ring, radiation cooled
- ~70 kW power deposited at 2.4mA (590 MeV protons)

TABLE 1. Some Parameters For The Targets

<table>
<thead>
<tr>
<th>Meson Production Target</th>
<th>M</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Diameter (mm)</td>
<td>320</td>
<td>450</td>
</tr>
<tr>
<td>Target Length (mm)</td>
<td>5.2</td>
<td>60</td>
</tr>
<tr>
<td>Target Width (mm)</td>
<td>20</td>
<td>6</td>
</tr>
<tr>
<td>Graphite Density (g/cm³)</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>Proton Beam Losses (%)</td>
<td>1.6</td>
<td>18</td>
</tr>
<tr>
<td>Power Deposition (KW/mA)</td>
<td>2.4</td>
<td>30</td>
</tr>
<tr>
<td>Irradiation Damage Rate (dpa/Ah)</td>
<td>0.11</td>
<td>0.1</td>
</tr>
<tr>
<td>Operating Temperature (K)</td>
<td>1100</td>
<td>1700</td>
</tr>
<tr>
<td>Rotational Speed (Turns/s)</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
1. Proton beam: momentum, power and beam structure
2. Target: Material, cooling, size
3. Proton transmission: Neutron facility or last in chain
4. Muon beam: Momentum, rates, polarization
1. Proton beam: momentum, power and beam structure
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4. Muon beam: Momentum, rates, polarization
5. Beam channel: Acceptance, transmission, momentum bite $\Delta p/p$, contamination ($\pi$, e)
Muon beams: General considerations

1. Proton beam: momentum, power and beam structure
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5. Beam channel: Acceptance, transmission, momentum bite $\Delta p/p$, contamination ($\pi$, e)
6. Muon stopping target: Shape, beam spot
Current MEG target

requirements:

* depolarizing material (isotropic e⁺)
* low-Z (γ-background, AlF)
* min. material traversed by decay e⁺ and γ → slanted target
* 2-d flatness <±100 μm

realisation:

* 205 μm thick polyethylene / polyester foil density ρ = 0.895 g/cm³
* freely suspended in Rohacell frame
* ellipse shape: major-axis 200.5 mm minor-axis 79.8 mm
* target angle: (20.5±0.3)°
* holes: 10 mm diameter
* pneumatic drive for „parking position“
Current MEG target

requirements:
• depolarizing material (isotropic e⁺)
• low-Z (γ-background, AlF)
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• 2-d flatness ≤±100 μm

realisation:
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• target angle: (20.5±0.3)°
• holes: 10 mm diameter
• pneumatic drive for „pa

New target in MEG upgrade has two options:
• 160mm surface muons at 15°
• 140mm sub-surface muons at 15°
Double cone shaped to spread out vertices for suppression of accidental background

Figure 9.1: Dimensions of the baseline design target. Note that the material thickness is not to scale.

Figure 9.2: Vertex distribution along the beam direction.

Figure 9.3: Vertex distribution transverse to the beam direction.
Surface muons in the future

- HIMB at PSI
- Mu2e beam channel with surface muons
- Muons in the Project X era
High intensity muon beam

Use spallation neutron source target
### High intensity muon beam

<table>
<thead>
<tr>
<th>$P_0$</th>
<th>$\Delta P/P$</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>MeV/c</td>
<td>% FWHM</td>
<td>Hz</td>
</tr>
<tr>
<td>28</td>
<td>Full</td>
<td>$(7 \pm 1) \cdot 10^{10}$</td>
</tr>
<tr>
<td>28</td>
<td>10</td>
<td>$(3 \pm 1) \cdot 10^{10}$</td>
</tr>
<tr>
<td>26</td>
<td>10</td>
<td>$(3 \pm 1) \cdot 10^{10}$</td>
</tr>
</tbody>
</table>

Table 7.2: Estimated surface and sub-surface muon rates based on a proton current of 2.4 mA on Target E and full transmission efficiency.
Project X
Reference Design

1 MW @ 1 GeV
3 MW @ 3 GeV
200 kW @ 8 GeV
2 MW @ 120 GeV
An example: Bunch structure

Area 1: 700 kW at 1MHz and 80 MHz substructure
Area 2: 1540 kW at 20 MHz
Area 3: 770 kW at 10 MHz
Mu2e with pulsed surface muons

Jim Miller’s quick simulation:

- Start with surface muon point source at Mu2e production target
- Plot point of closest approach along z-axis of detector solenoid

- Study stopping efficiency in thin cylindrical target in more realistic setup
- Need separator for beam background or pulsed mode
- But what about the pulsed mode for accidental background (~ rate²)?
DC versus pulsed: Electron pileup

- DC beam with rate $R$
DC versus pulsed: Electron pileup

- DC beam with rate R
- Pulsed beam with averaged rate R
DC versus pulsed: Electron pileup

- DC beam with rate $R$
- Pulsed beam with averaged rate $R$
- Electrons from DC beam
DC versus pulsed: Electron pileup

- DC beam with rate R
- Pulsed beam with averaged rate R
- Electrons from DC beam
- Electrons from pulsed beam
DC versus pulsed: Electron pileup

- DC beam with rate $R$
- Pulsed beam with averaged rate $R$
- Electrons from DC beam
- Electrons from pulsed beam

Histogram $\Delta t$ between every electron and all others

$\Delta t$'s for one electron
DC versus pulsed: Electron pileup

Ratio at $D_t = 0$ is only 1.06, i.e. accidental rate would increase by $\sim 13\%$
Summary


- Optimization of muon beamline has many knobs
- Should look more into existing studies and continue from there
- Study Mu2e beamline in more details for $\mu^+$ surface beam
- Future experimental requirements play important role in finding best strategy (cost, resources, physics, time, ...)
- It’s hard to get the “Egg-laying-wool-milk-sow” but one should study which compromises might be feasible (multi-purpose or many beamlines)