Beam control, monitoring and measuring techniques

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Outline

- Instrumentation and diagnostics for the Muon Campus
- Beam measuring techniques
- Phase-space mapping techniques
Muon Campus beam monitoring

Beam requirements can be broken down into the following categories:

- **Primary Proton Beam:**
  - Intensity: Toroids
  - Position: BPMs, SEMs
  - Losses: BLMs

- **Mixed Secondary Beam**
  - Intensity: Ion Chambers
  - Position: SEMs, PWCs
  - Losses: BLMs

- **Proton-only**
  - Intensity: Ion Chambers
  - Position: SEMs
  - Losses: BLMs

- **Muon-only**
  - Intensity: Ion Chambers
  - Position/Profile: PWCs
Monitoring example

• Beam monitoring in the secondary beam lines relies mainly on PWC or SEM (beam profile) and IC (beam intensity)
Proportional wire chambers (PWC)

- Measure the beam profile:
  - Beam ionizes the gas inside the device and the resulting charge is collected by the wires
  - Nobel prize in 1992 to G. Charpak for his invention and development of particle detectors, in particular the multiwire proportional chamber

- Very sensitive: Can measure beam intensities down to $10^3$ per 12 Hz pulse
Secondary emission monitors (SEM)

- Measure the beam profile:
  - Under the impact of the beam particles on some solid material, electrons are liberated from the surface and thus are producing a flow of current

- Not so sensitive: Can measure beam intensities down to $10^7$ per 12 Hz pulse
Ionization chambers (IC)

• Measure the beam intensity
  – Beam ionizes the gas-filled-chamber that is placed between two electrodes that are at voltage potential
  – The charge from the created ion-pairs are a measure of the beam intensity

• Sensitive: Can measure beam intensities down to $10^5$ per 12 Hz pulse
Diagnostics along the Muon Campus

- SEM (2)
- IC (1)
- SEM (6)
- PWC (2)
- IC (1)
- PWC (6)
- IC (2)
- PWC (7)
- IC (1)
Monitoring of the beam as it circulates the DR
Multiple scattering

- Muon will be deflected due to Coulomb scattering from nuclei
- The angle has a roughly Gaussian distribution of width $\theta_0$:

$$\theta_0 = \frac{13.6 \text{ MeV}}{\beta c p} \sqrt{\frac{x}{L_R}} \left[1 + 0.038 \ln \left(\frac{x}{L_R}\right)\right]$$
Emittance growth from scattering

- For an individual particle after scattering: $x' = x'_0 + \Delta \theta$

- Taking second order moments:
  - $\langle x^2 \rangle = \langle x^2_0 \rangle$
  - $\langle x'^2 \rangle = \langle (x'_0 + \Delta \theta)^2 \rangle$
  - $\langle xx' \rangle = \langle x_0 x'_0 \rangle$

- The new emittance after scattering is:
  $$\epsilon = \langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2 \quad \text{or}$$
  $$\epsilon = \epsilon_0 \sqrt{1 + \frac{\langle x^2_0 \rangle \theta_{rms}^2}{\epsilon_0}}$$

- Emittance growth depends on size and material

M. Syphers, GM2-doc-2343
PWCs scattering effect in the DR

![Graph showing scattering effect]

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**INSTRUMENTATION AND ITS INTERACTION WITH THE SECONDARY BEAM FOR THE FERMILAB MUON CAMPUS **

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Momentum scrapers in dispersive areas can be used for:
- Cutting unwanted momentum particles
- Selecting particles at certain momenta and therefore allowing measurement of the dispersion downstream

![Image of momentum scrapers](image_url)
Measuring the beam phase-space

- Recall that $\sigma = \sqrt{\beta \varepsilon}$; with PWCs we measure only $\sigma$. Not enough!
Importance of Twiss parameters

• Every simulation requires this input

```cpp
beam gauss nEvents=${nparticles} particle=pi+ meanP=3094.0
beamX=0.0 beamY=0.0 beamZ=0.0 sigmaX=0.0024 sigmaY=0.0024
sigmaXp=0.000001 sigmaYp=0.000001 sigmaP=0.0
```

• Muon Campus has several diagnostic stations to measure the beam sizes $x$ and $y$

• But we don’t measure momentum $x'$ and $y'$

• Assuming wrong initial conditions gives wrong results:

```
In = Out
```

• KNOWLEDGE of the beam phase-space is important
Recall the final focus...

- Last five magnets can be adjusted to a wide range of focusing strengths in order to maximize performance.

Froemming, gm2-docdb-6938
Phase-space Tomography

- An object in n-dimensional space can be recovered from a sufficient number of projections onto (n-1)-dimensional space.
Tomography with muon beams

- No additional hardware needed: Only a profile monitor and quadrupole. Very simple!!!
Phase space rotation by a magnet

- Simple example: Assume one quadrupole

- Particle motion: \( x'' = -\kappa x + F_{SC} \) \( \kappa \rightarrow \text{Lens focusing strength} \)

- No space-charge: \( x'' = -\kappa x \)

- Phase space:

\[
\begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} \cos \sqrt{\kappa z} & \frac{1}{\sqrt{\kappa}} \sin \sqrt{\kappa z} \\ -\sqrt{\kappa} \sin \sqrt{\kappa z} & \cos \sqrt{\kappa z} \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \end{pmatrix} \propto \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \end{pmatrix}
\]

\( \theta \rightarrow \text{Function of } (\kappa) \)
Phase-Space projections

\[ c_\theta(x) = \iiint f(x, x', y, y') \, dx' \, dy \, dy' = \mu_\theta(x) \]
Profiles collected

Beam Profile
Real Space Projection
Phase Space Projection

Beam Profile

Beam Profile

Beam Profile

Scaled Profile

Scaled Profile Scaled Profile

Scaled Profile Scaled Profile

s=1.83
θ=163.2°

s=0.24
θ=46.3°

s=6.28
θ=-13.3°
Reconstruction process
Proof-of-principle: End of M5

Final focus M5

Vary Q024 strength

Profile monitor

Direct

Tomography
Quadrupole scan technique

- We can estimate the rms emittance by measuring the beam spot size as a function of the focal length of the quad.

\[
\begin{pmatrix}
\beta_0 \\
\alpha_0 \\
\gamma_0
\end{pmatrix}
\begin{pmatrix}
\beta \\
\alpha \\
\gamma
\end{pmatrix} =
\begin{pmatrix}
(1 - \frac{d}{f})^2 & -2d \left(1 - \frac{d}{f}\right) & d^2 \\
\left(1 - \frac{d}{f}\right) & 1 - 2\frac{d}{f} & -d \\
\frac{1}{f^2} & -2\frac{1}{f} & 1
\end{pmatrix}
\begin{pmatrix}
\beta_0 \\
\alpha_0 \\
\gamma_0
\end{pmatrix}
\]

\[
\sigma_x^2 = \beta \varepsilon = a \left(1 - \frac{d}{f}\right)^2 2 - b \left(1 - \frac{d}{f}\right) d + cd^2
\]

where \(a = \beta_0 \varepsilon\), \(b = \alpha_0 \varepsilon\), and \(c = \gamma_0 \varepsilon\).
Profiles collected at PWC021

- $f = 6.6$ m
- $f = 5.9$ m
- $f = 5.3$ m
- $f = 4.8$ m
- $f = 4.6$ m
- $f = 4.0$ m
- $f = 3.7$ m
- $f = 3.4$ m
- $f = 3.3$ m
Measuring beam optics at the end of M5
First measurement of traverse beam optics for the Fermilab Muon Campus using a magnet scanning technique

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ABSTRACT

In the following years the Fermilab Muon Campus will deliver highly polarized muon beams to the storage ring of the Muon g-2 Experiment. The transmission fraction of the storage ring has been shown to depend strongly on the transverse optics of the injected beam. Unfortunately, the current diagnostics in the Muon Campus allow only measurement of the beam configuration space which limits how well propagation can be predicted. This paper demonstrates an experimental technique based on a conventional magnet scan to obtain the Twiss parameters at a point, using only beam profiles such that installation of new equipment is not required. A proof-of-principle experiment is presented which shows that this new method is applicable to the Muon Campus, offering a viable approach to optimization of injection in the Muon g-2 Experiment.