Beam control, monitoring and measuring techniques

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USPAS 2019

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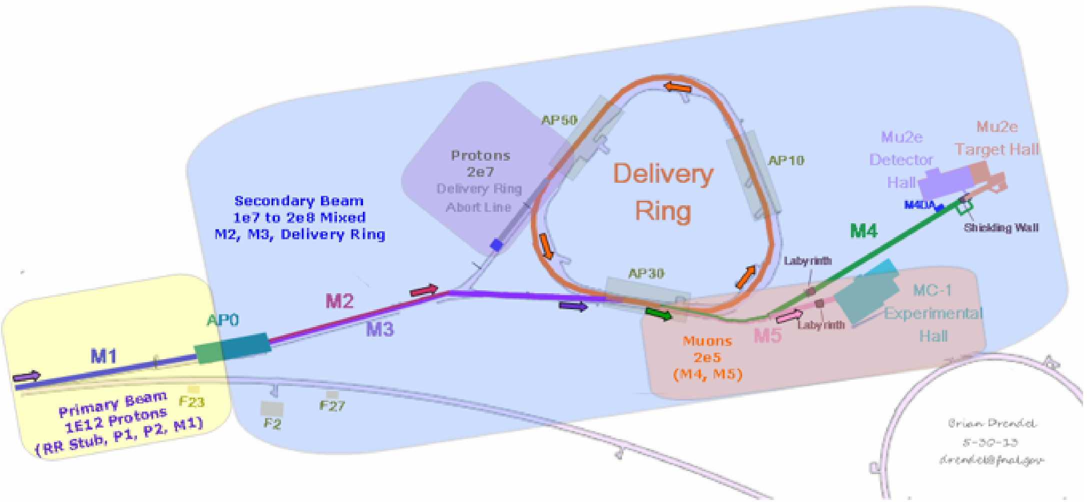
Outline

- 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.

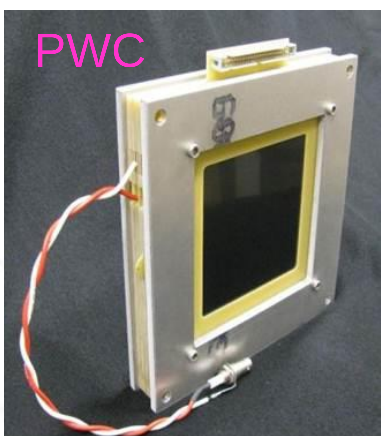
- **Primary Proton Beam**:
  - Intensity: Toroids
  - Position: BPMs, SEMs
  - Losses: BLMs
- **Proton-only**
  - Intensity: Ion Chambers
  - Position: SEMs
  - Losses: BLMs
- **Mixed Secondary Beam**
  - Intensity: Ion Chambers
  - Position: SEMs, PWCs
  - Losses: BLMs
- **Muon-only**
  - Intensity: Ion Chambers
  - Position/Profile: PWCs

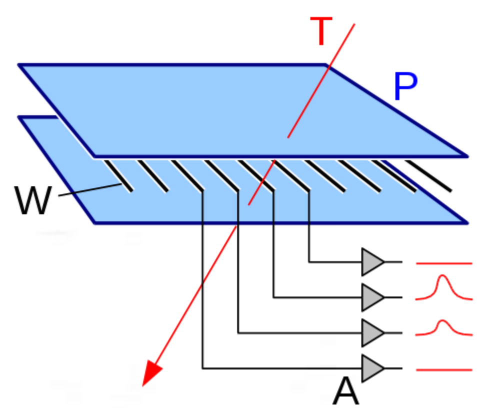
Monitoring example

- 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





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Nuclear Instruments and Methods

Volume 62, Issue 3, 1 July 1968, Pages 262-268

The use of multiwire proportional counters to select and localize charged particles

G. Charpak, R. Bouclier, T. Bressani, J. Favier, Č. Zupančič

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https://doi.org/10.1016/0029-554X(68)90371-6

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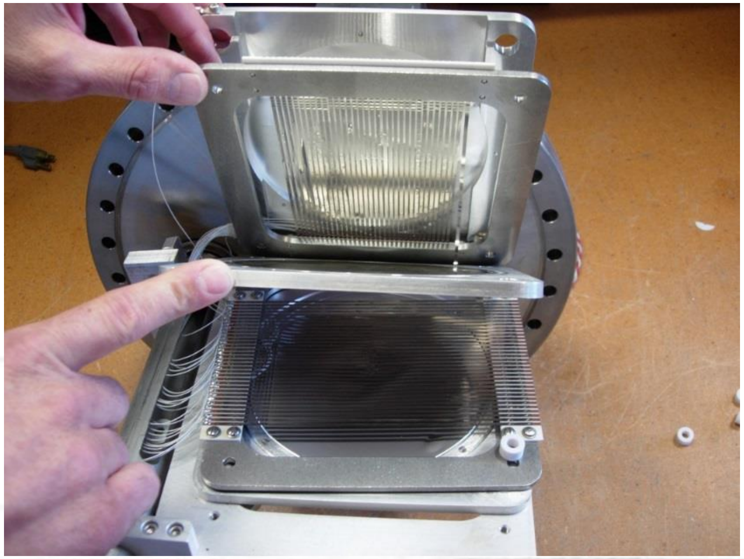
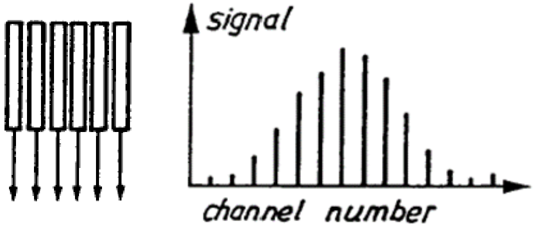
Secondary emission monitors (SEM)

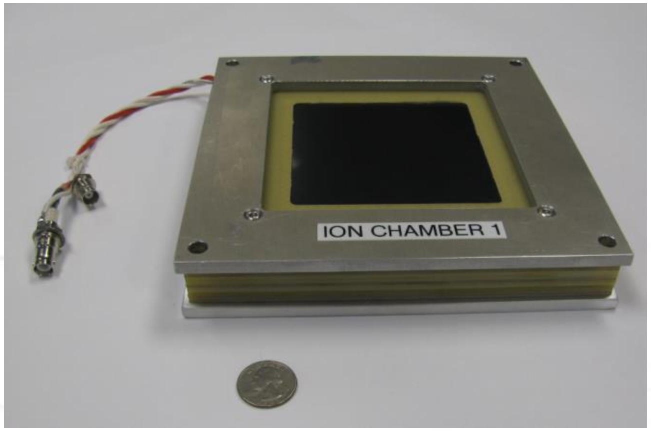
- Measure the beam profile:
  - Under the impact of the beam particles on some solid material, electrons are liberated from the surface and thus are producing a flow of current
- Not so sensitive: Can measure beam intensities down to 10^7 per 12 Hz pulse

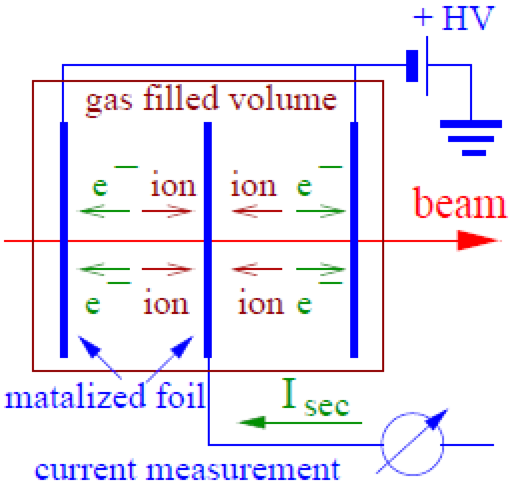




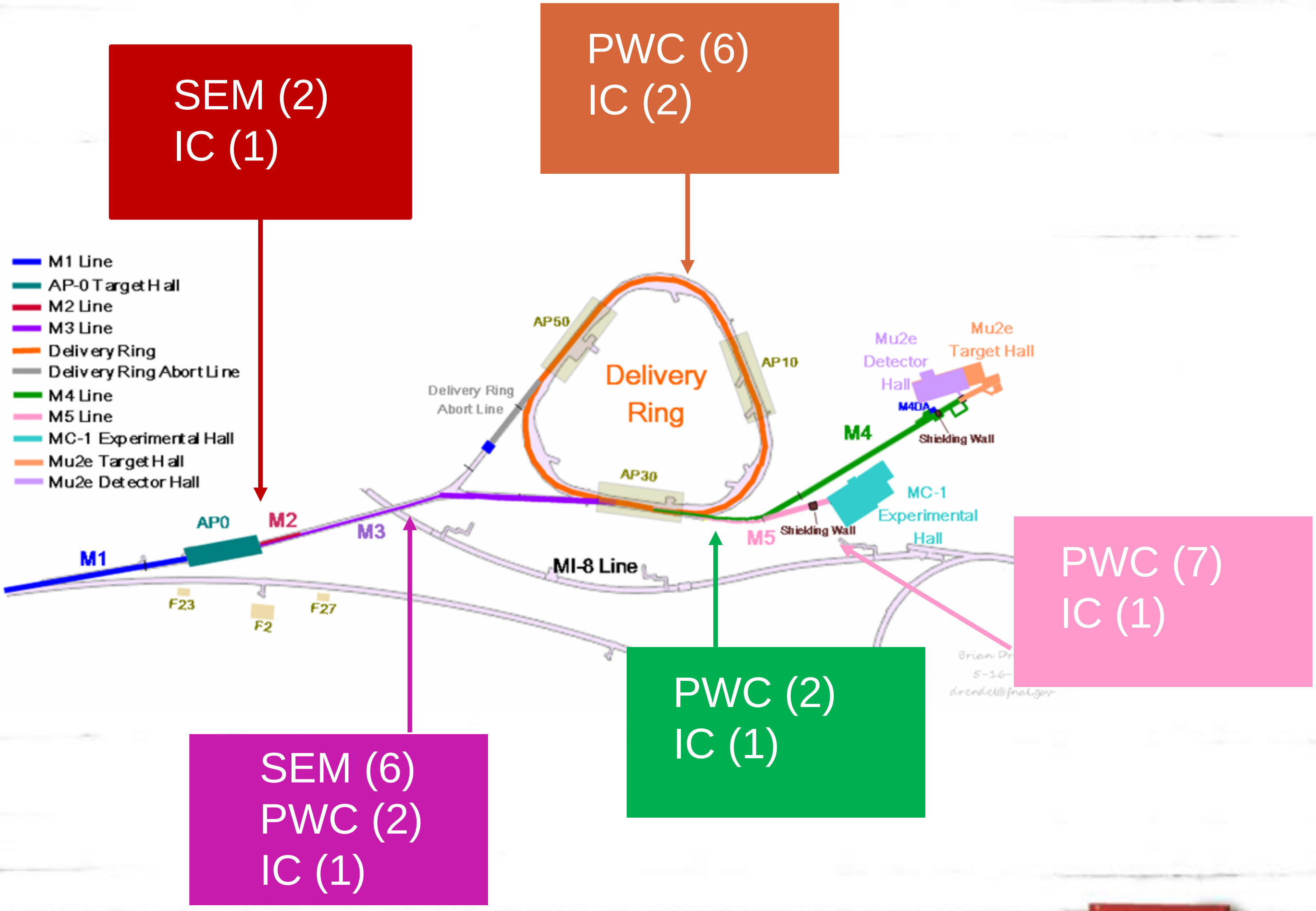
Ionization chambers (IC)

- 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



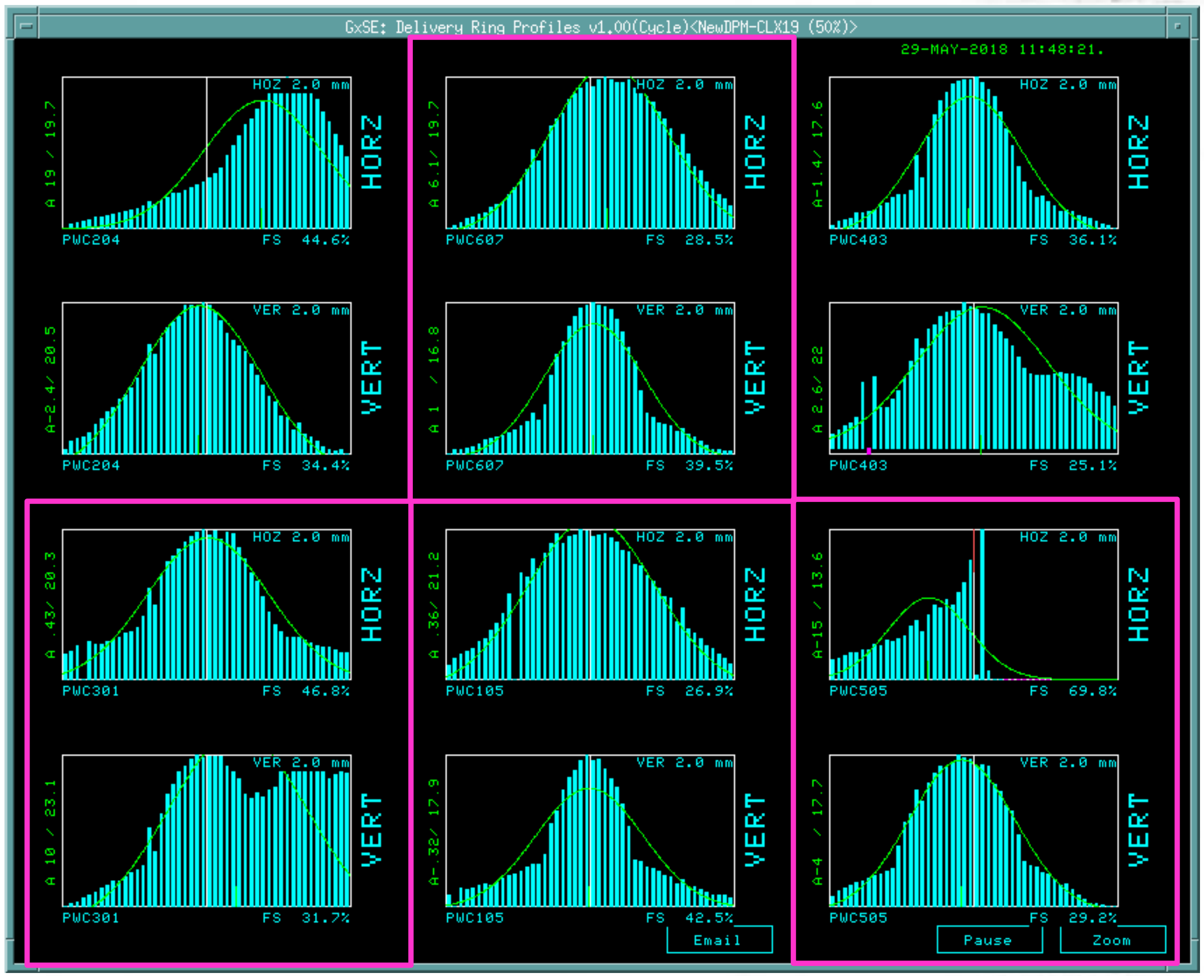


Diagnostics along the Muon Campus

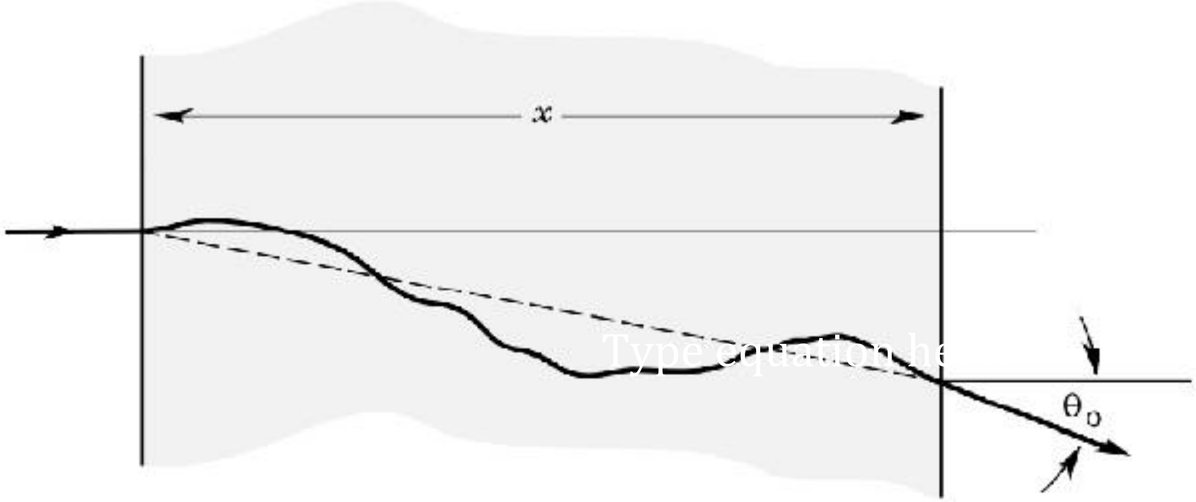


PWC monitoring example

Monitoring of the beam as it circulates the DR



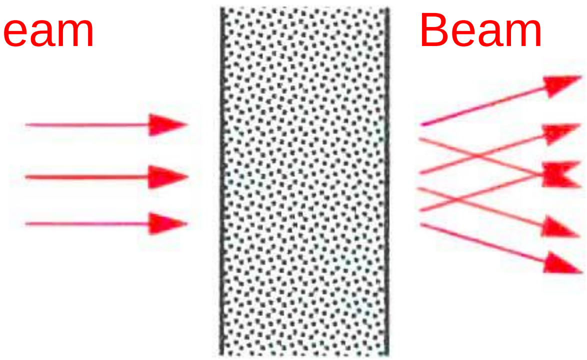
Multiple scattering



- Muon will be deflected due to Coulomb scattering from nuclei
- The angle has a roughly Gaussian distribution of width θ_0:

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

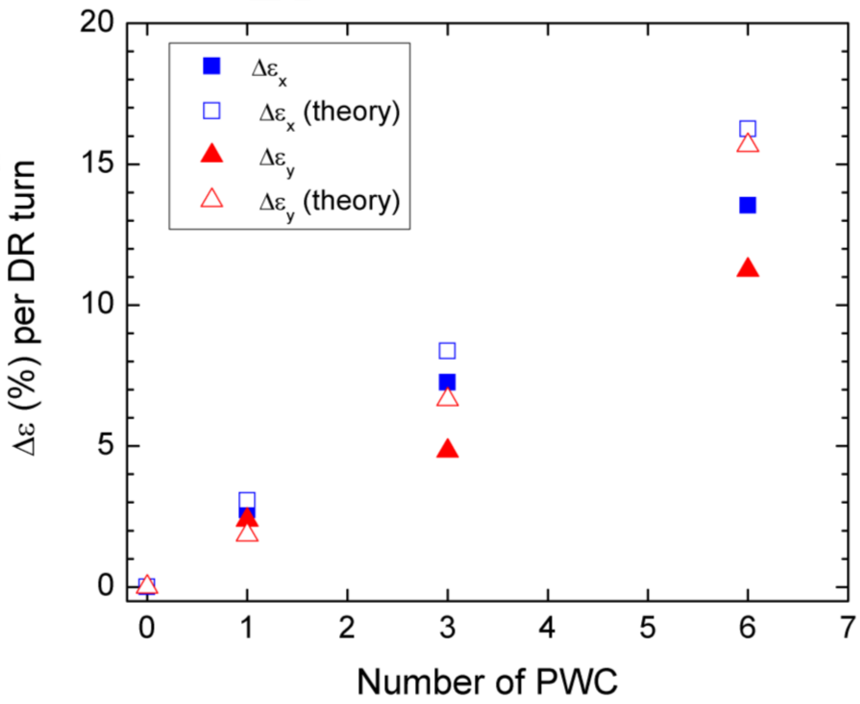
Emittance growth from scattering



M. Syphers, GM2-doc-2343

- For an individual particle after scattering: $x' = x_0' + \Delta\theta$
- Taking second order moments:
  - $\langle x^2 \rangle = \langle x_0^2 \rangle$
  - $\langle x'^2 \rangle = \langle (x_0' + \Delta\theta)^2 \rangle$
  - $\langle x x' \rangle = \langle x_0 x_0' \rangle$
- The new emittance after scattering is: $\epsilon = \langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2$ or $\epsilon = \epsilon_0 \sqrt{1 + \frac{\langle x_0^2 \rangle \theta_{rms}^2}{\epsilon_0}}$
- Emittance growth depends on size and material

PWCs scattering effect in the DR



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

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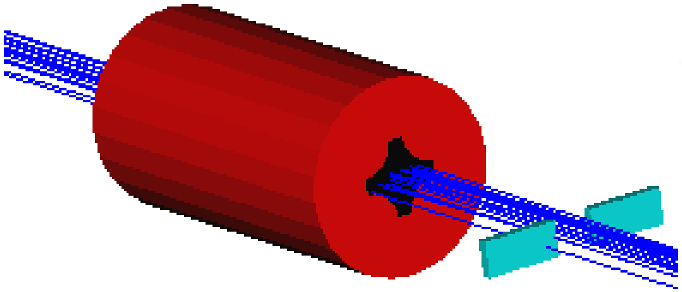
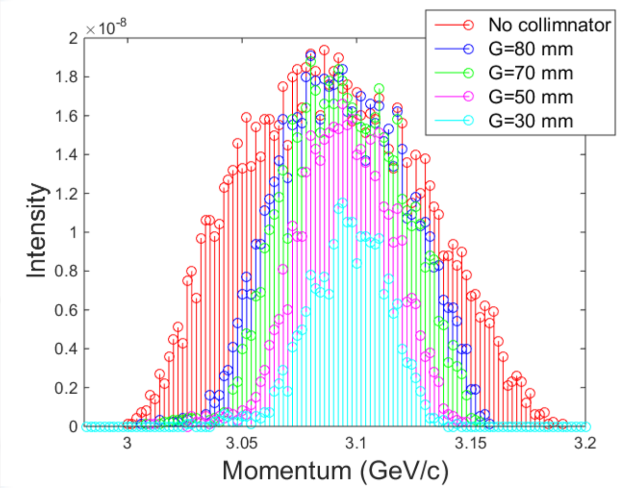
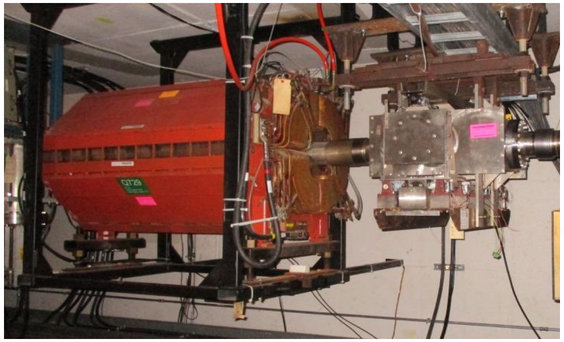
Momentum scrapers

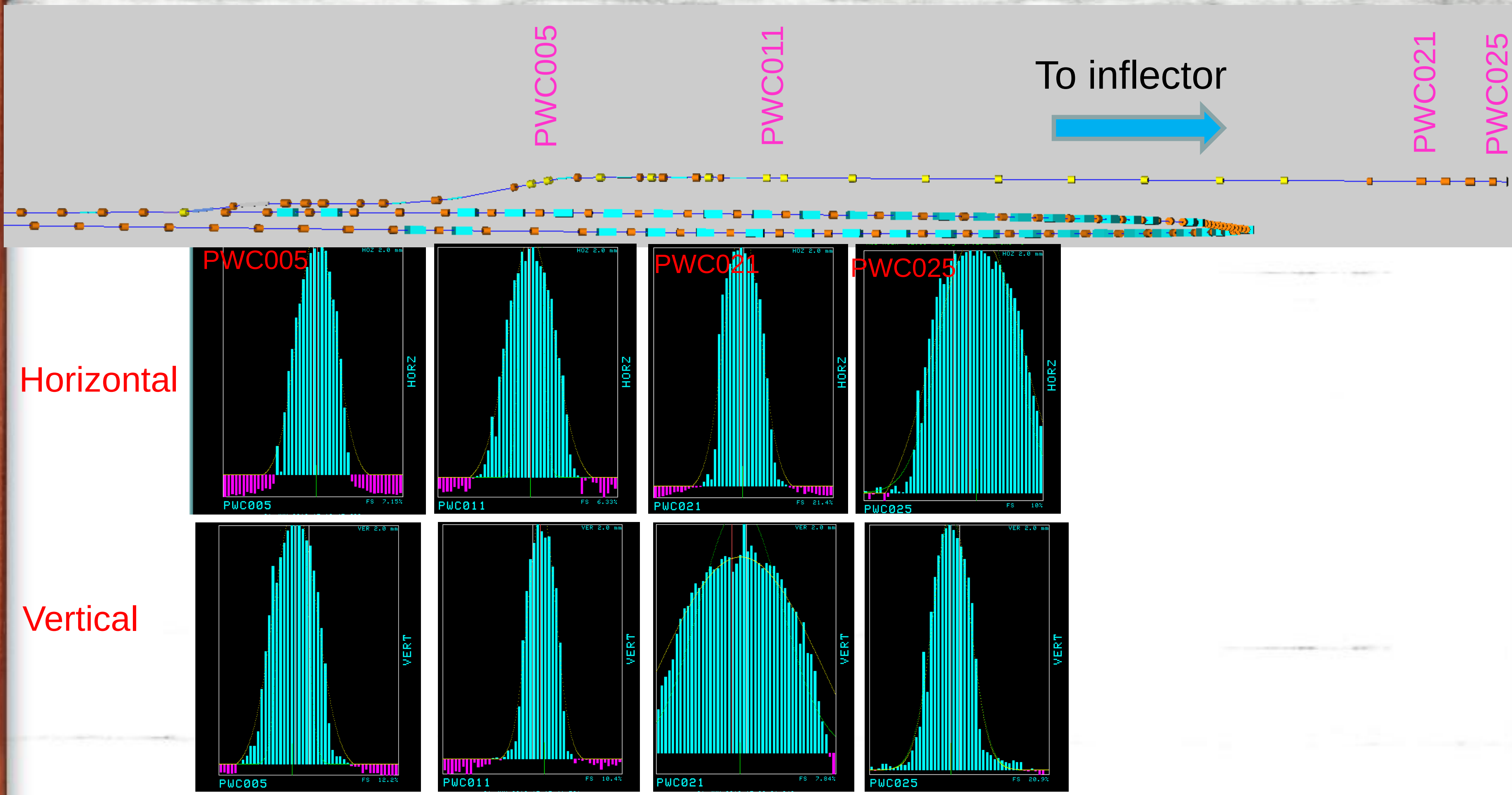
- Momentum scrapers in dispersive areas can be used for:
  - Cutting unwanted momentum particles
  - Selecting particles at certain momenta and therefore allowing measurement of the dispersion downstream







Measuring the beam phase-space



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

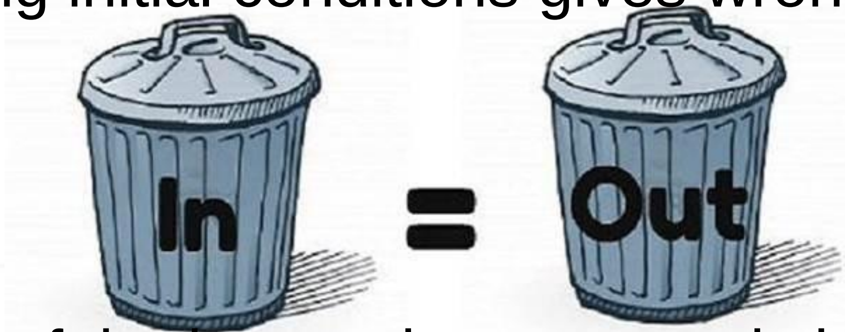
Importance of Twiss parameters

- Every simulation requires this input

G4Beamline Example

```
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
```

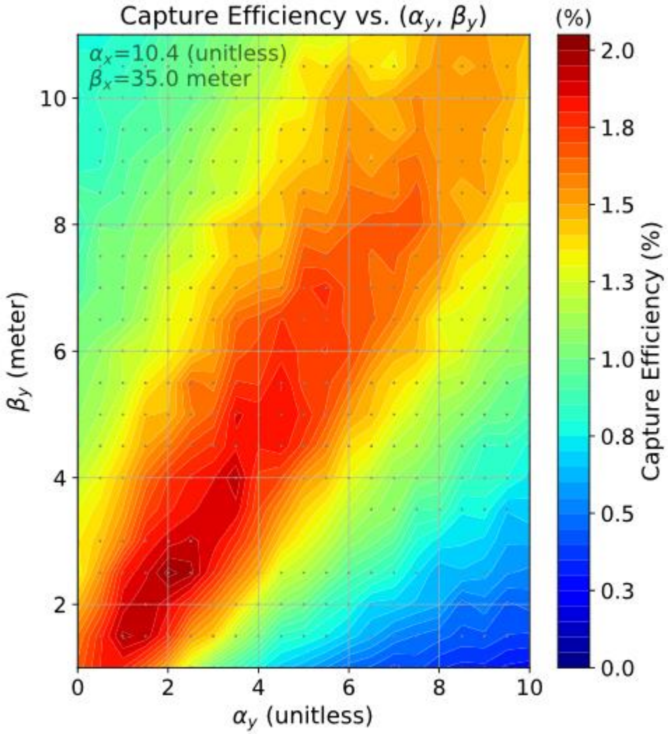
- Muon Campus has several diagnostic stations to measure the beam sizes x and y
- But we don't measure momentum x' and y'
- Assuming wrong initial conditions gives wrong results:



- KNOWLEDGE of the beam phase-space is important

Recall the final focus…

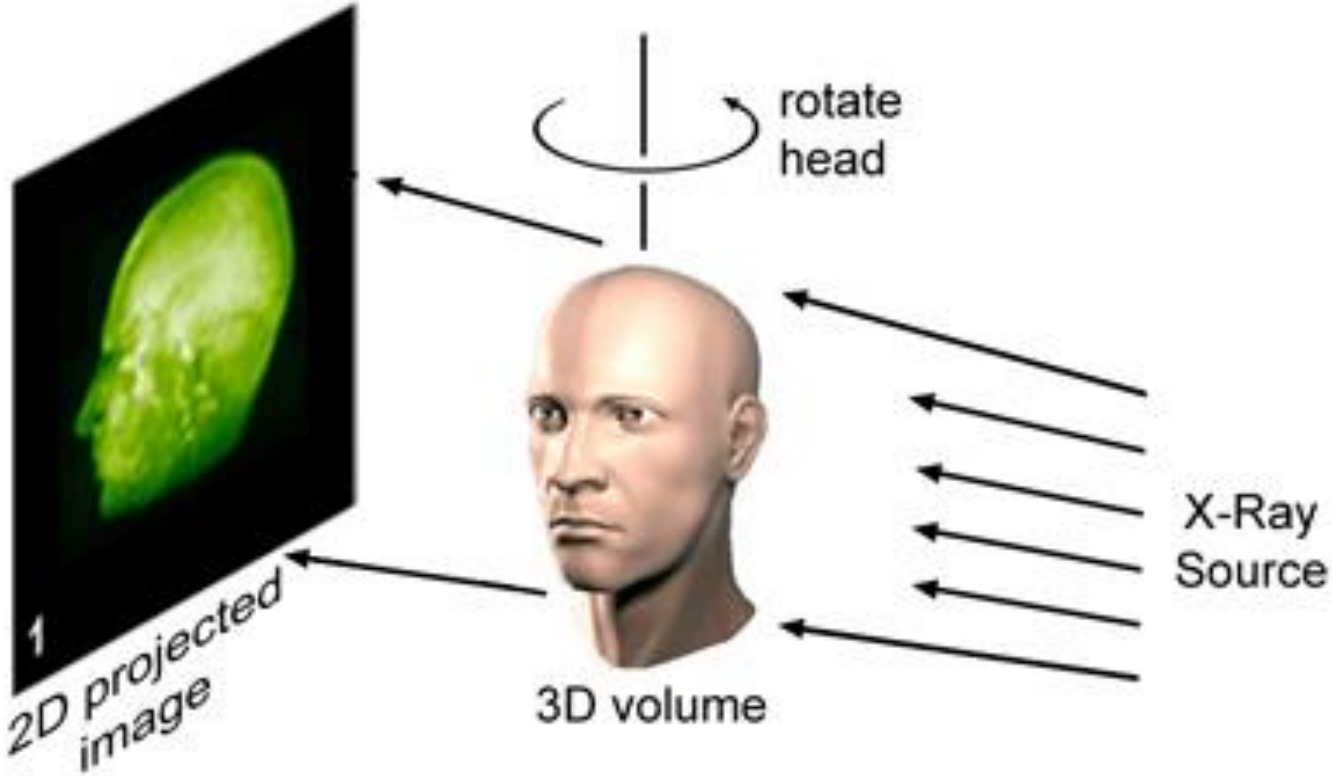
- Last five magnets can be adjusted to a wide range of focusing strengths in order to maximize performance



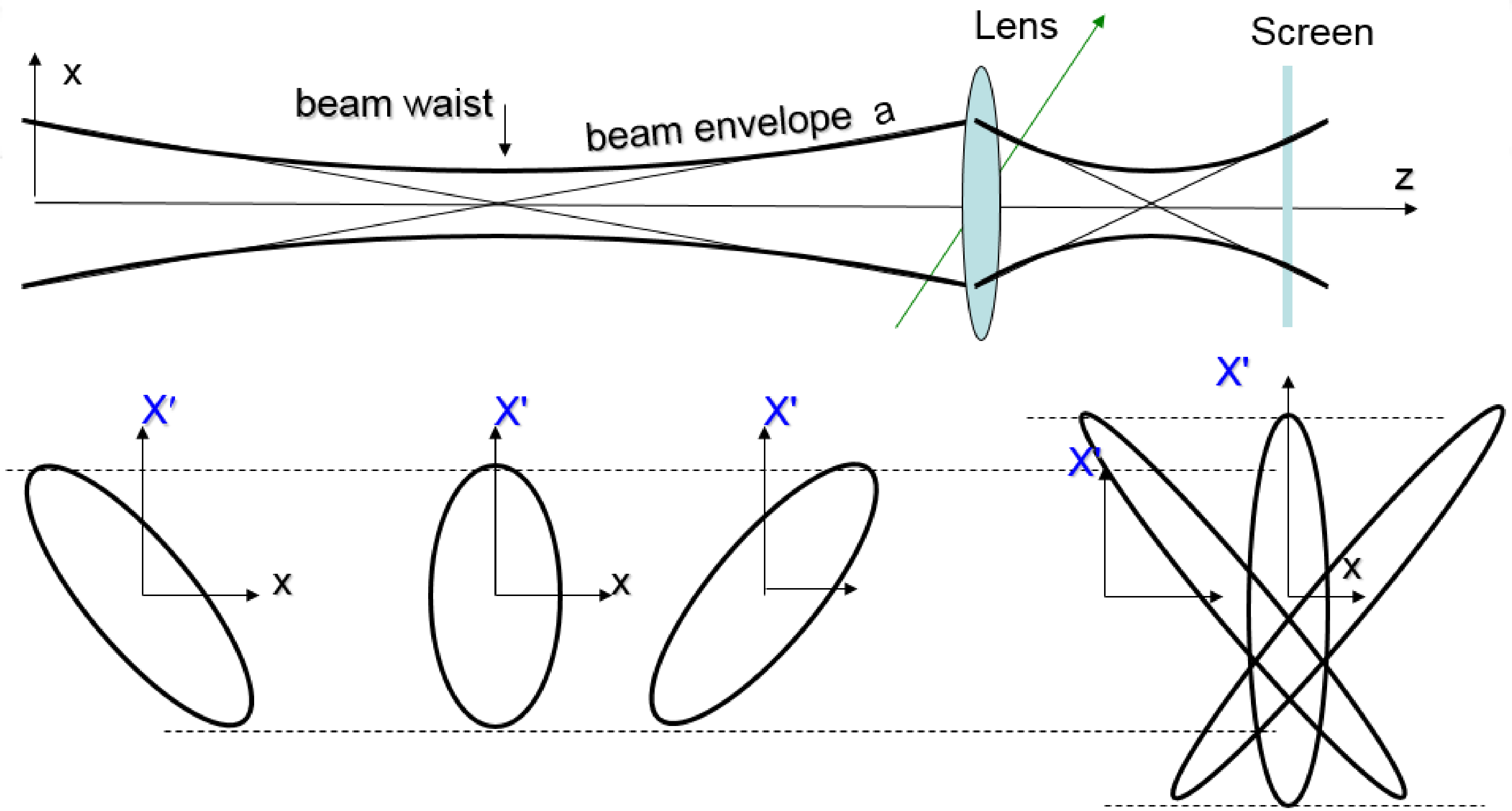
Froemming, gm2-docdb-6938

Phase-space Tomography

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



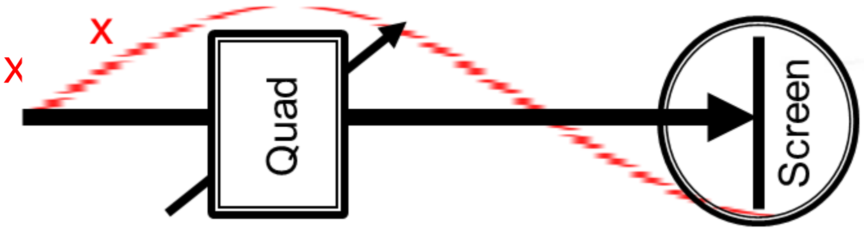
Tomography with muon beams



- 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: $x'' = -\kappa x + F_{SC}$

$\kappa \rightarrow$ Lens focusing strength

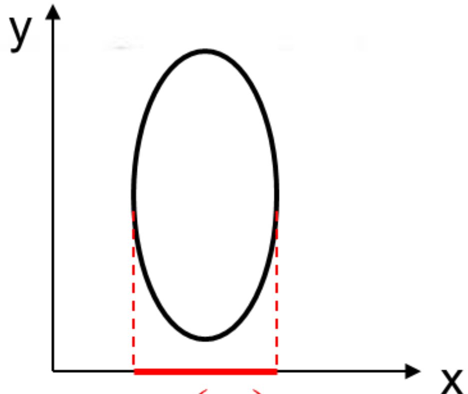
- No space-charge: $x'' = -\kappa x$
- Phase space:

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

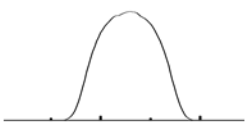
$\theta \rightarrow$ Function of (κ)

Phase-Space projections

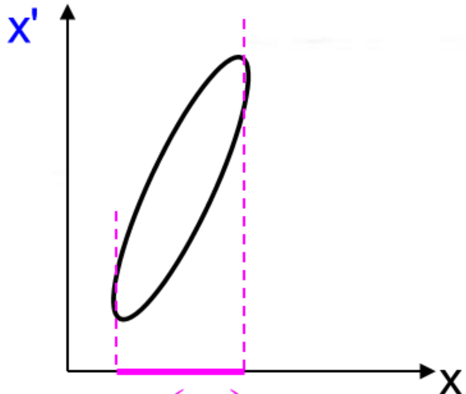
Screen Image



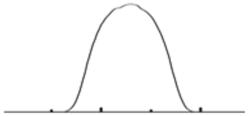
$c(x)$



Phase Space (at screen)

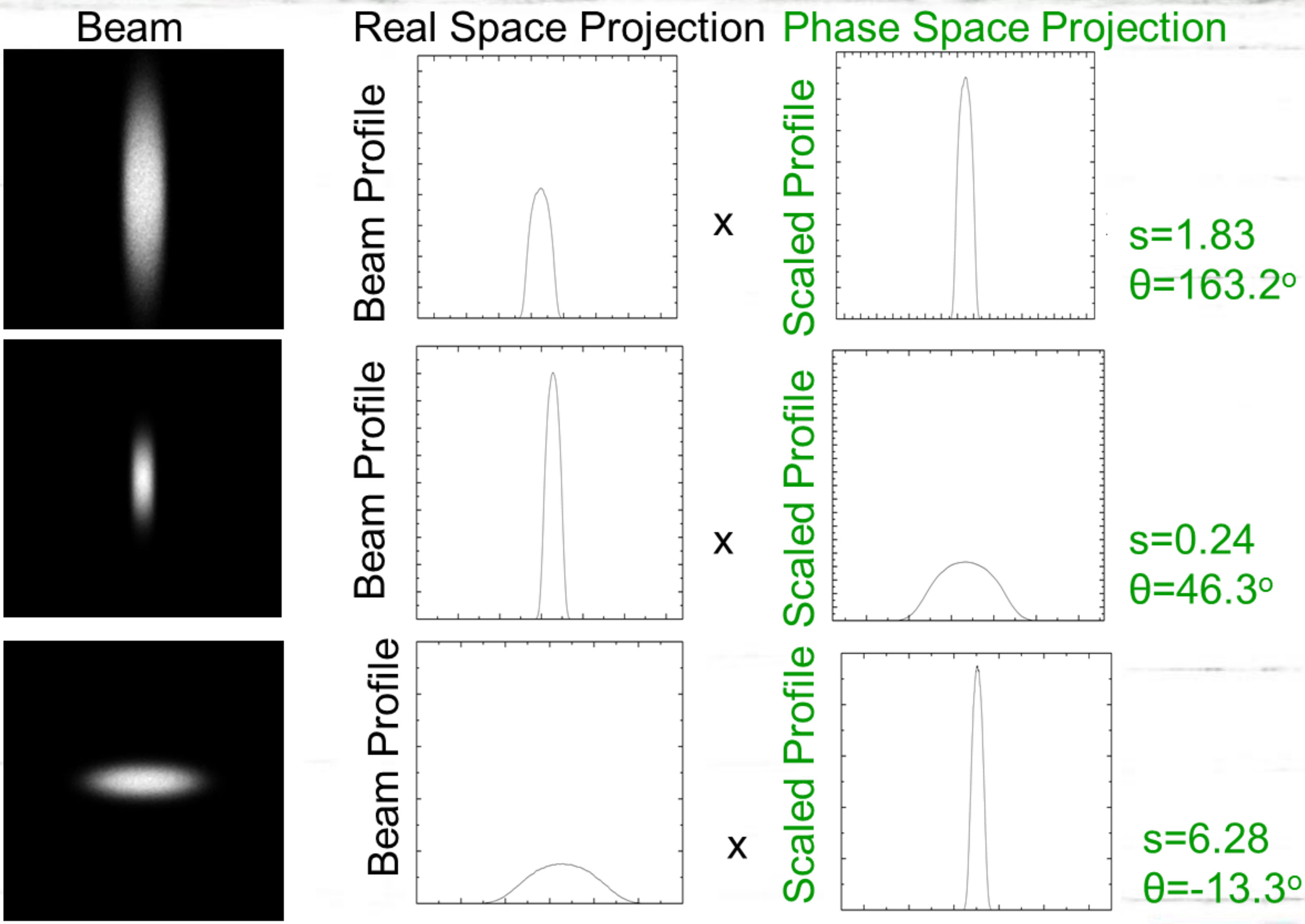


$\mu(x)$

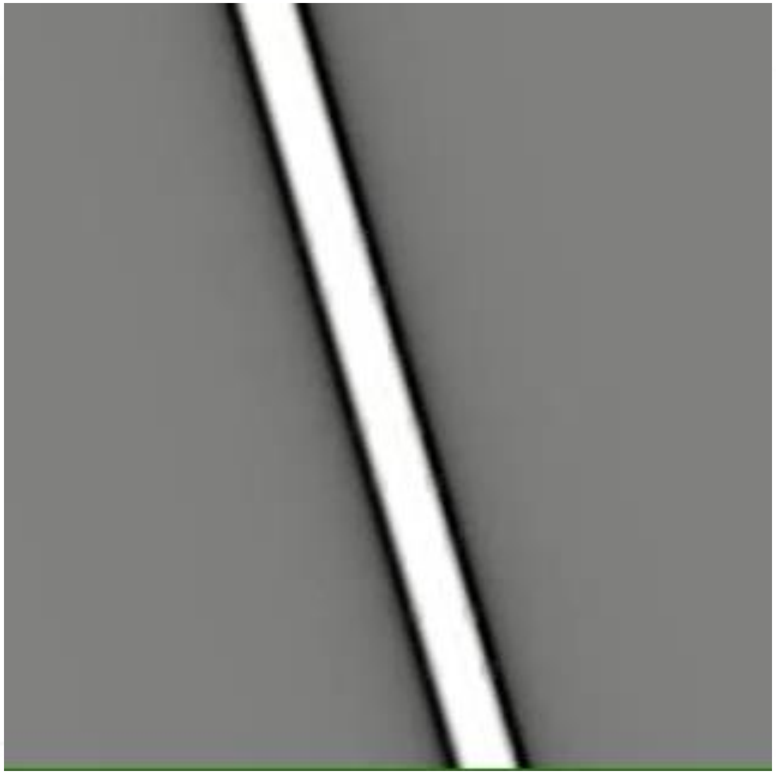


$$c_\theta(x) = \iiint f(x, x', y, y')\,dx'\,dy\,dy' = \mu_\theta(x)$$

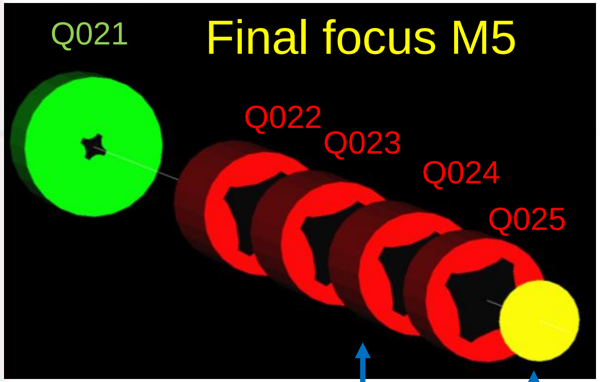
Profiles collected



Reconstruction process

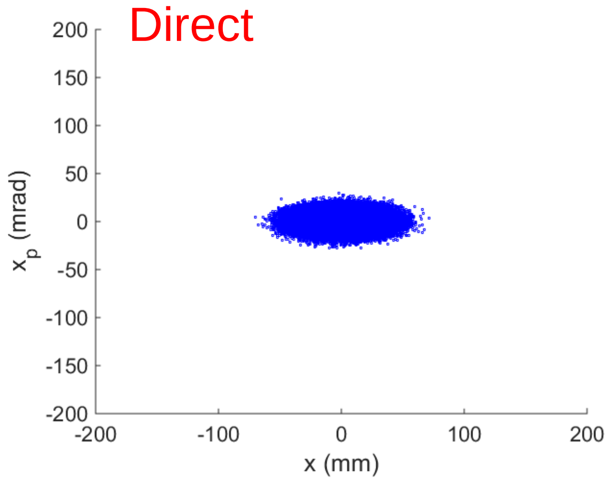


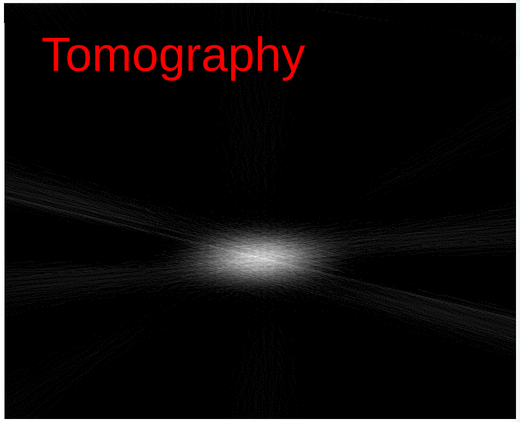
Proof-of-principle: End of M5

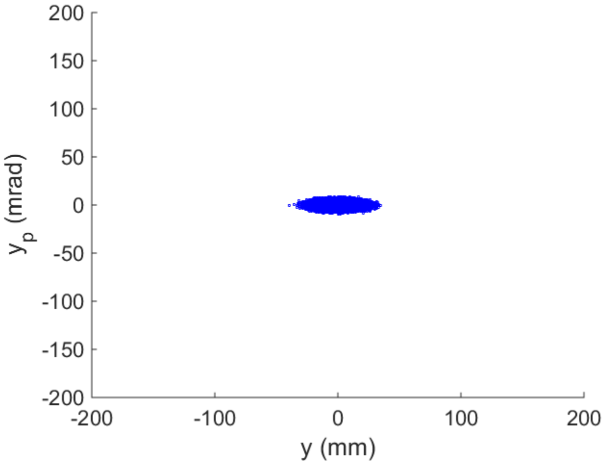


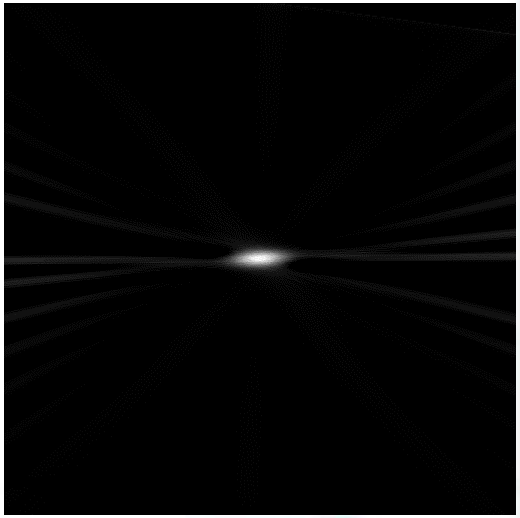
Vary Q024 strength

Profile monitor



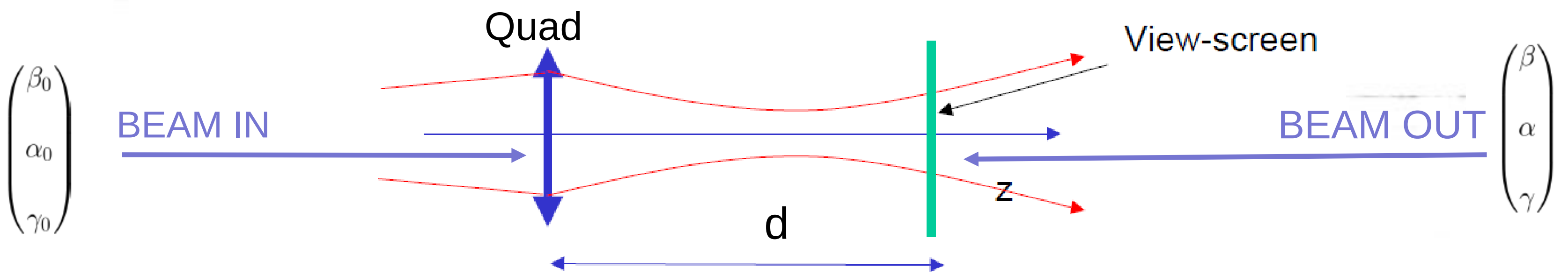






Quadrupole scan technique

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

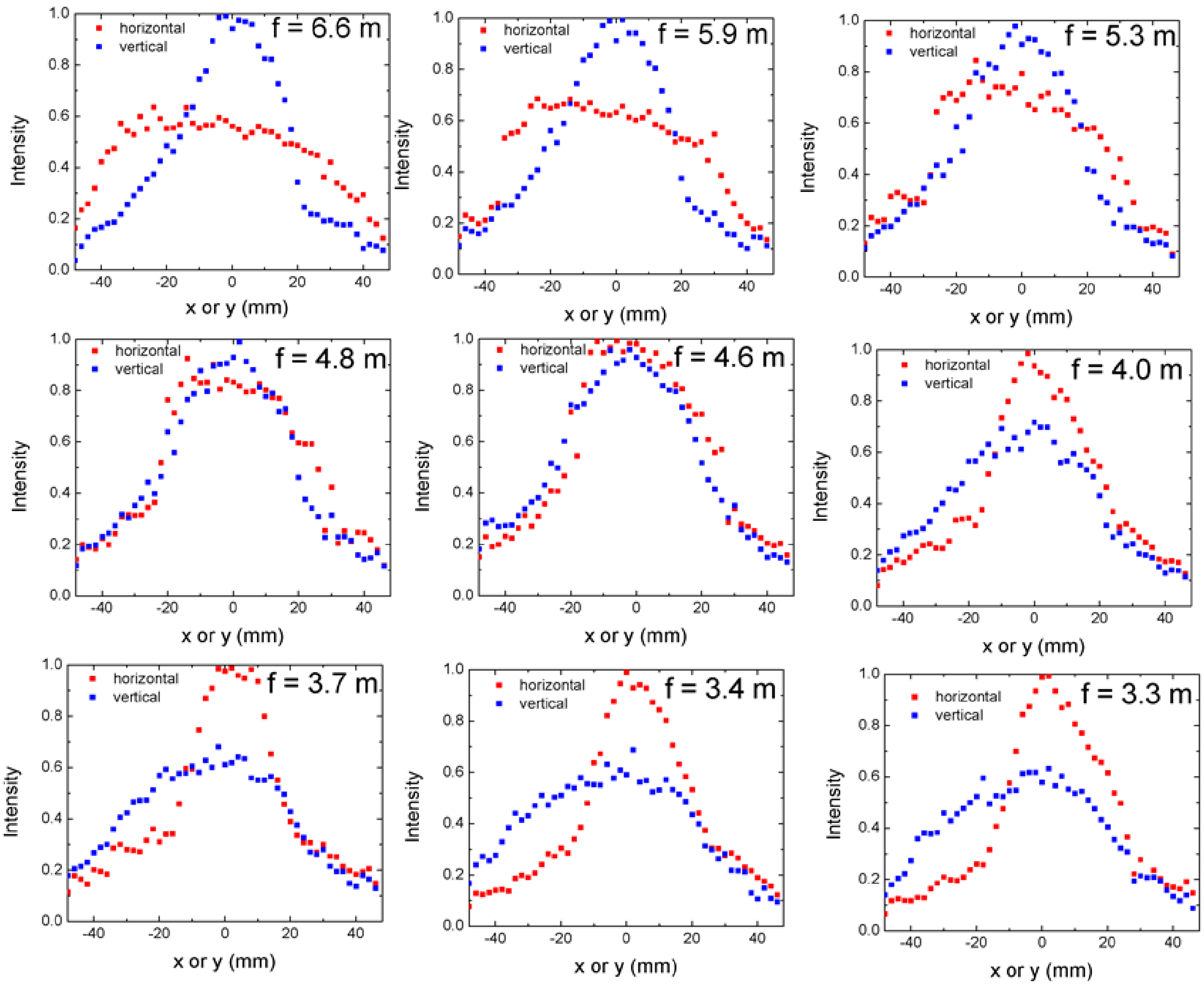


$$\begin{pmatrix} \beta \\ \alpha \\ \gamma \end{pmatrix} = \begin{pmatrix} \left(1-\frac{d}{f}\right)^2 & -2d\left(1-\frac{d}{f}\right) & d^2 \\ \left(1-\frac{d}{f}\right)\frac{1}{f} & 1-2\frac{d}{f} & -d \\ \frac{1}{f^2} & -2\frac{1}{f} & 1 \end{pmatrix} \begin{pmatrix} \beta_0 \\ \alpha_0 \\ \gamma_0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

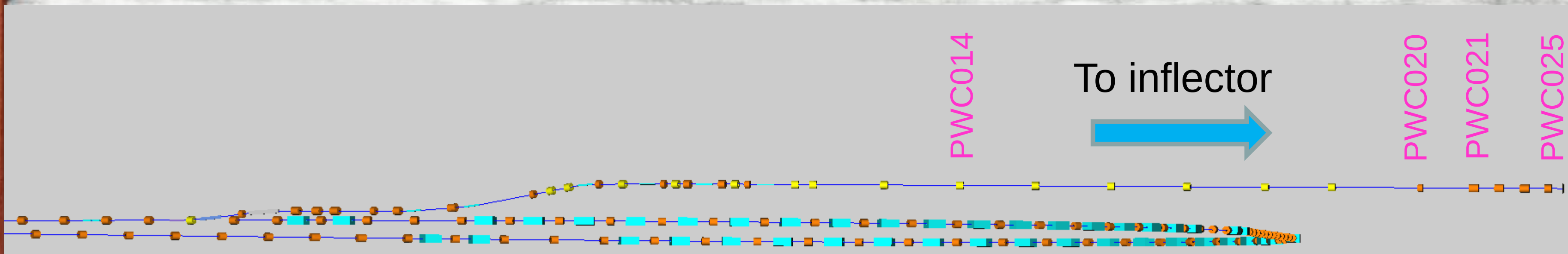
$$\sigma_x^2 = \beta\varepsilon = a\left(1-\frac{d}{f}\right)^2 2 - b\left(1-\frac{d}{f}\right)d + cd^2$$

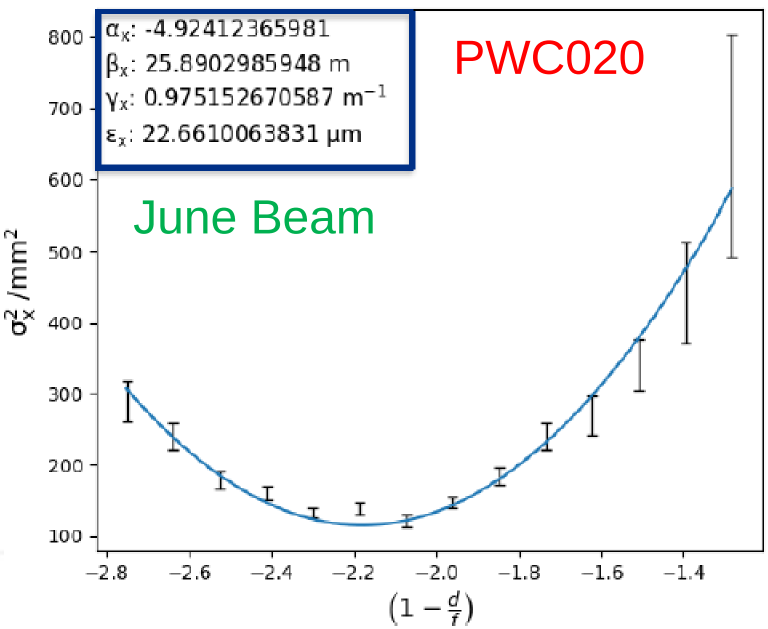
$$where \quad a = \beta_0\varepsilon \qquad b = \alpha_0\varepsilon \qquad c = \gamma_0\varepsilon$$

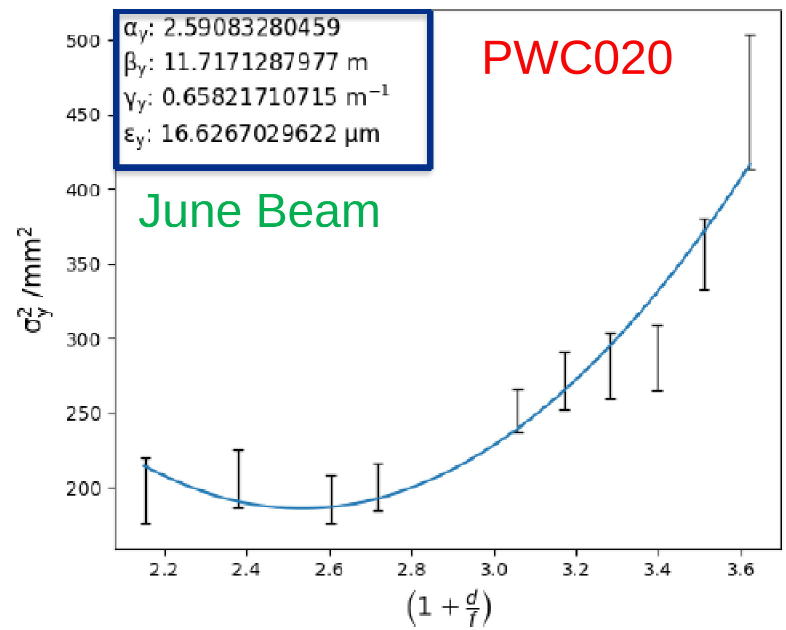
Profiles collected at PWC021



Measuring beam optics at the end of M5







First demonstration reference

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First measurement of traverse beam optics for the Fermilab Muon Campus using a magnet scanning technique

Check for updates

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A R T I C L E I N F O

Keywords:
Muon beams
Beam diagnostics
Emittance measurement

A B S T R A C T

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.