Beam Optics Analysis from the Mu2e External Line Commissioning

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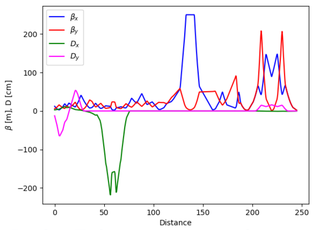
Introduction/Motivations

The first commissioning of the M4 beamline on Fermilab's Muon Campus obtained many beam profiles. The beam profiles cannot directly give us the twist parameters for the beam (essential in optimizing the experiment) so we implore two methods to extract the beam optics

The Twiss parameters describe the phase-space of the beam via the equation

$$A^2 = \gamma x^2 + 2\alpha x x' + \beta x'^2$$



Design Twiss parameters, observe that between 100m and 200m, there is no dispersion

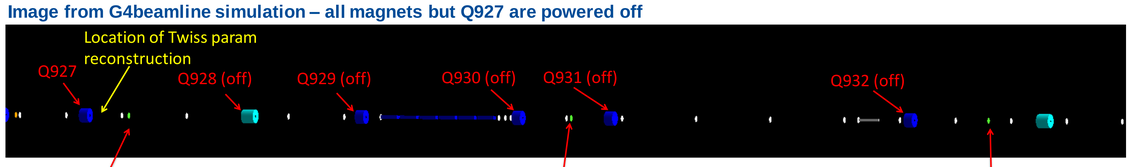
3-Screen Method

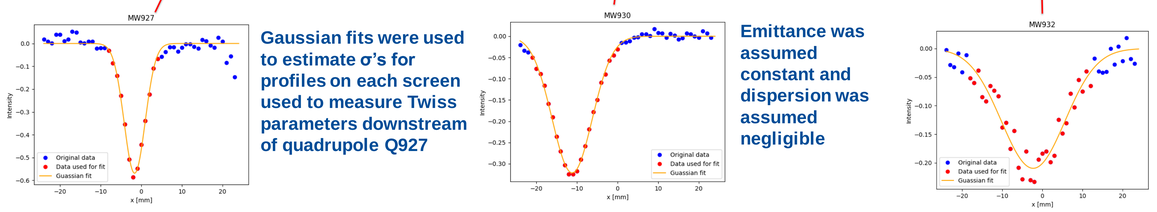
Using three σ's taken from three beam profile monitors downstream of a quadrupole magnet, we can solve the 3-equation nonlinear system given by the equations

$$\sigma^2 = \beta_0\epsilon - 2d\alpha_0\epsilon + d^2\epsilon(1+\alpha_0^2)/\beta_0$$

For β_0, α_0, and ϵ. Here d is the distance of the drift space

Image from G4beamline simulation – all magnets but Q927 are powered off





Gaussian fits were used to estimate σ's for profiles on each screen used to measure Twiss parameters downstream of quadrupole Q927

Emittance was assumed constant and dispersion was assumed negligible

The three-screen method was done for 3 separate locations where data had been taken: downstream of Q927, Q924, and Q926

Parameter	3-screen method	G4beamline
α_x	-0.217 ± 0.077	-1.453
β_x [m]	17.745 ± 0.770	25.513
ϵ_x [μm]	0.354 ± 0.021	0.244
α_y	-0.535 ± 0.120	-1.011
β_y [m]	30.897 ± 2.954	30.908
ϵ_y [μm]	0.435 ± 0.042	0.250

Table 9: Downstream of magnet Q927

Parameter	3-screen method	G4beamline
α_x	0.0264 ± 0.0510	0.197
β_x [m]	8.208 ± 0.195	4.014
ϵ_x [μm]	0.361 ± 0.016	0.244
α_y	0.311 ± 0.023	0.259
β_y [m]	21.860 ± 0.710	20.634
ϵ_y [μm]	0.420 ± 0.017	0.250

Table 1: Downstream of magnet Q924

Parameter	3-screen method	G4beamline
α_x	0.718 ± 0.0475	-0.408
β_x [m]	18.310 ± 0.304	20.216
ϵ_x [μm]	0.3550 ± 0.0043	0.244
α_y	-1.047 ± 0.297	-1.268
β_y [m]	17.834 ± 3.381	16.762
ϵ_y [μm]	0.442 ± 0.039	0.250

Table 8: Downstream of magnet Q926

Quadrupole-Scan Method

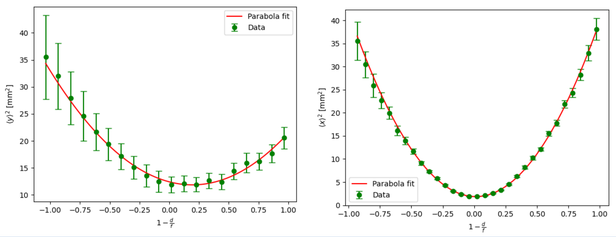
For a quadrupole and drift space, the measured σ's will satisfy the equation

$$\sigma^2 = A\left(1-\frac{d}{f}\right)^2 - 2dB\left(1-\frac{d}{f}\right) + Cd^2$$

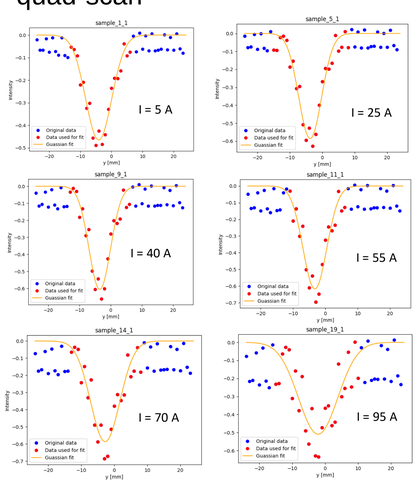
Where d is the distance of the drift space, f is the quadrupole focal length and

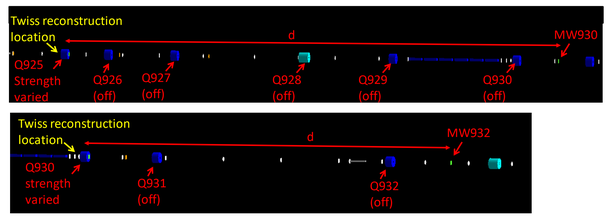
$$A = \beta_0\epsilon, B = \alpha_0\epsilon, C = \gamma_0\epsilon$$

Quad-scan parabola fit for Q925 in y-plane (left) and Q930 in x-plane (right)



Although profiles for the x-plane at Q925 and y-plane at Q930 were collected, these cases do not pass through a waist (the σ^2 would not pass through a minimum) so they were not used for a quad-scan





Parameter	Quad-scan method	G4beamline
α_y	0.218 ± 0.013	0.010
β_y [m]	37.316 ± 1.500	19.339
ϵ_y [μm]	0.396 ± 0.008	0.250

Table 7: Upstream of magnet Q925

Parameter	Quad-scan method	G4beamline
α_x	0.0596 ± 0.0073	-0.102
β_x [m]	115.073 ± 1.251	255.480
ϵ_x [μm]	0.339 ± 0.002	0.244

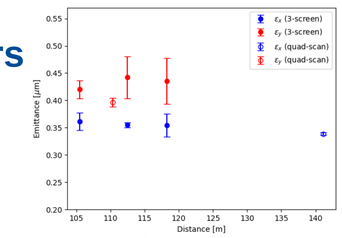
Table 10: Upstream of magnet Q930

(left) 6 of 26 gaussian fits done for the quad-scan data collected at MW930, varying the current in Q925 (labeled in figure)

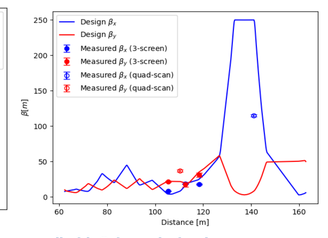
Comparison to Design Parameters

Phase-space ellipses were generated by the Twiss parameters found via the analysis, Twiss parameters given by G4beamline (specified design emittance) and Twiss parameters given by G4beamline specifying the measured emittance (average among data points)

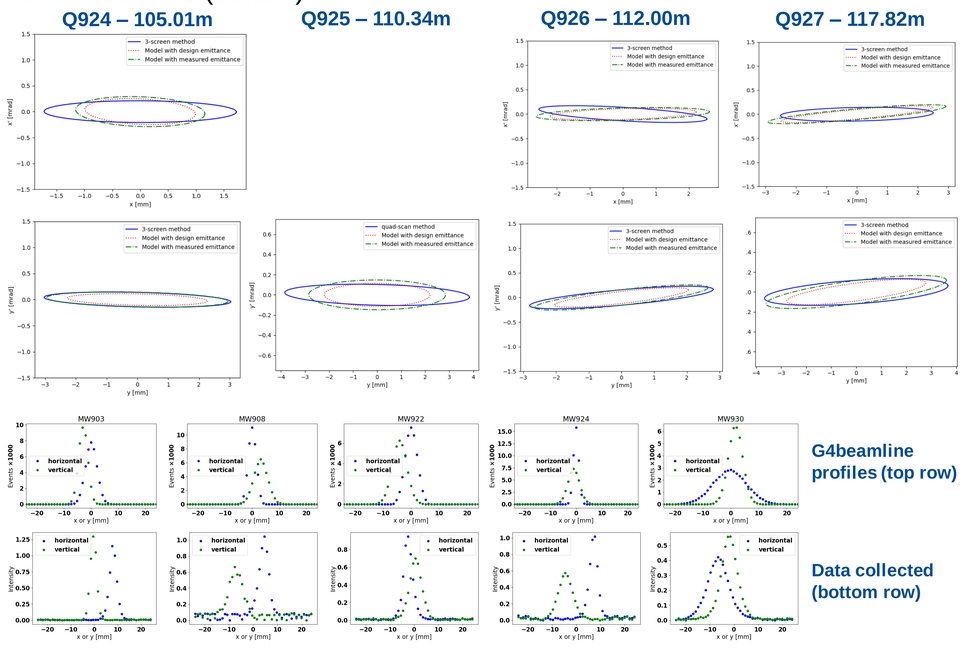
Beam profiles were directly compared with that of G4beamline (bottom)



Measured emittance between Q924 and MW930; theory predicts constant emittance in absence of nonlinear beam interactions



(left) β found via data analysis overlaid on M4 beamline design parameters



G4beamline profiles (top row)

Data collected (bottom row)

- Greatest deviation from model in x-plane, and in α's
- Model assumes resonant extraction of beam where data saw no resonant extraction
- Data shows large increase in β near Q930 as design predicts
- Emittance differs from model in both planes but is relatively constant throughout data

Fermilab mentor: Diktys Stratakis

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