Investigation of Emittance Analysis Methods Using the MuCool Test Area

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Outline

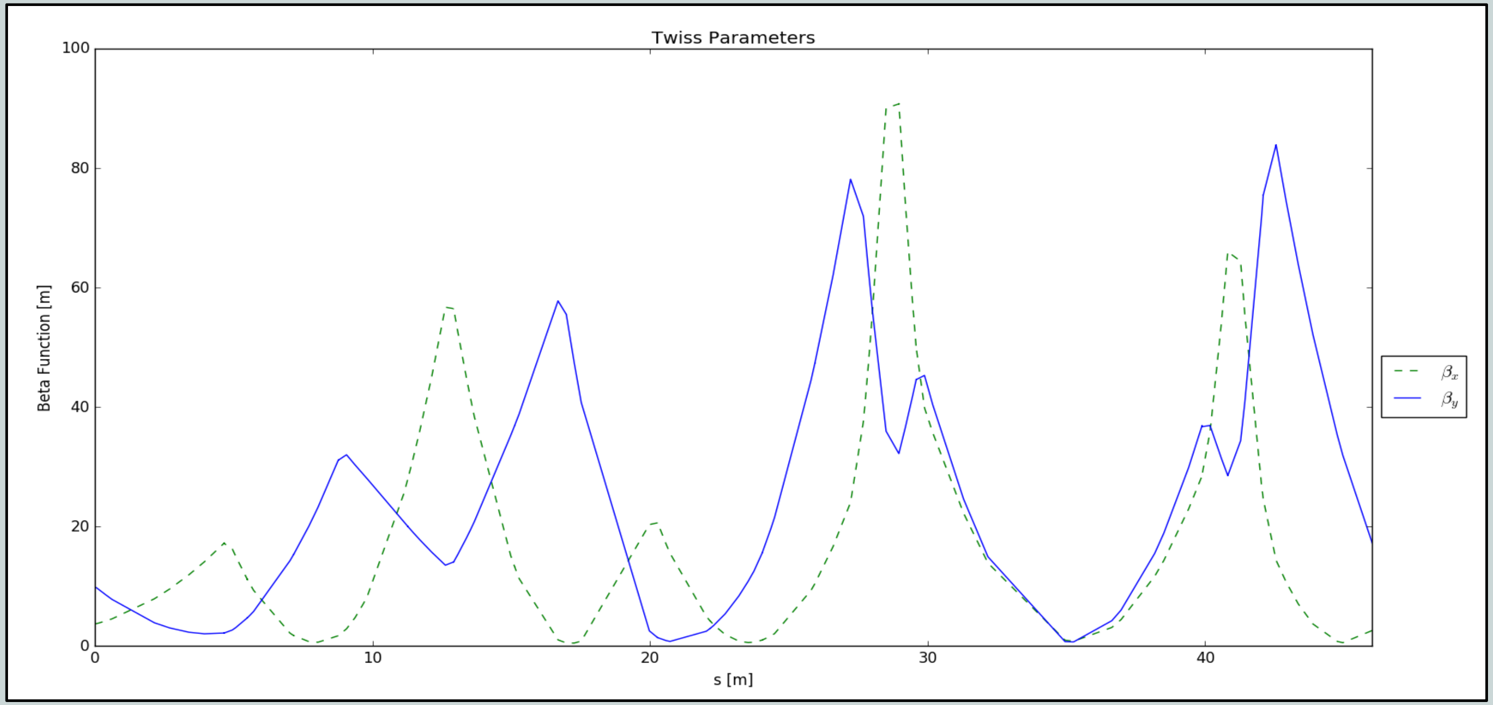
I. Introduction to Beamline Physics
   I. Emittance
II. MTA Beamline
III. Multiwires
   I. Instrumentation
   II. Data Analysis
IV. Emittance Calculation
   I. MAD Simulation
   II. 3-Wire Method
V. Conclusions & Future Directions

Purpose

- Use the MuCool Test Area (MTA) beamline as a diagnostic line to measure a parameter known as emittance coming out of Linac
- Knowledge of the transverse properties of the Linac beam can help improve Booster injection efficiency

Courant-Snyder Parameters

- Model the beam and understand how the envelope propagates
- Utilize transfer matrices derived from magnet optics to calculate beam trajectory and properties



$$x(s) = A\sqrt{\beta_x(s)}\cos(\psi_x(s) + \phi)$$

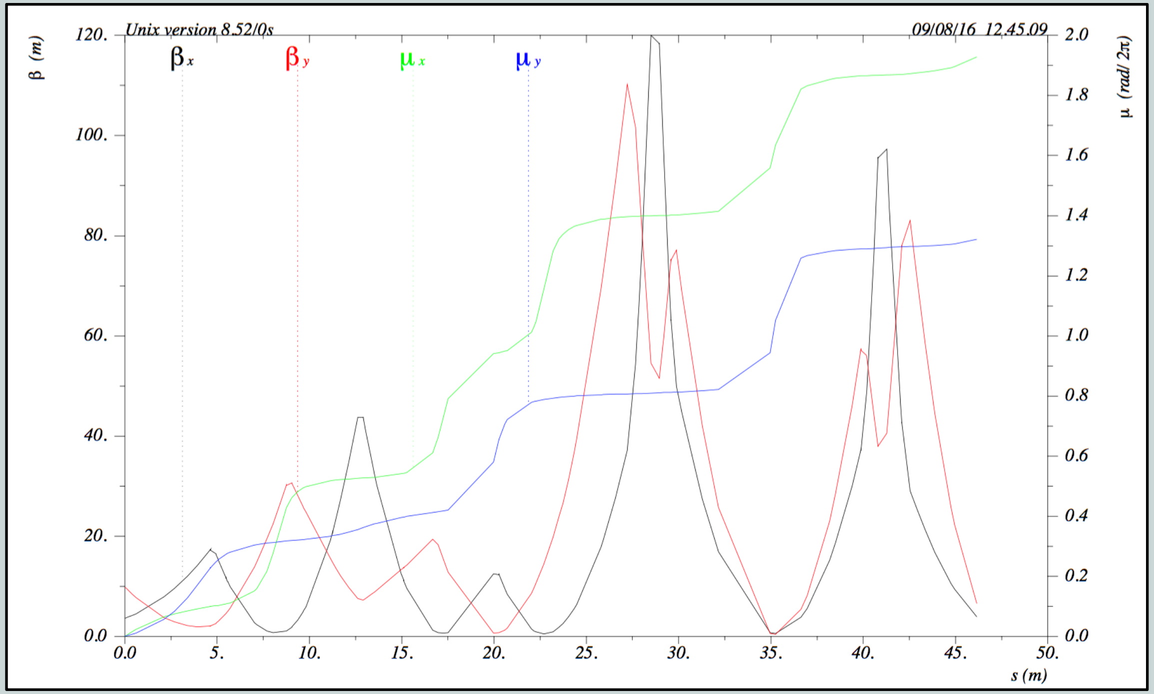
$$\alpha(s) \stackrel{\text{def}}{=} -\frac{1}{2}\frac{d\beta(s)}{ds}$$

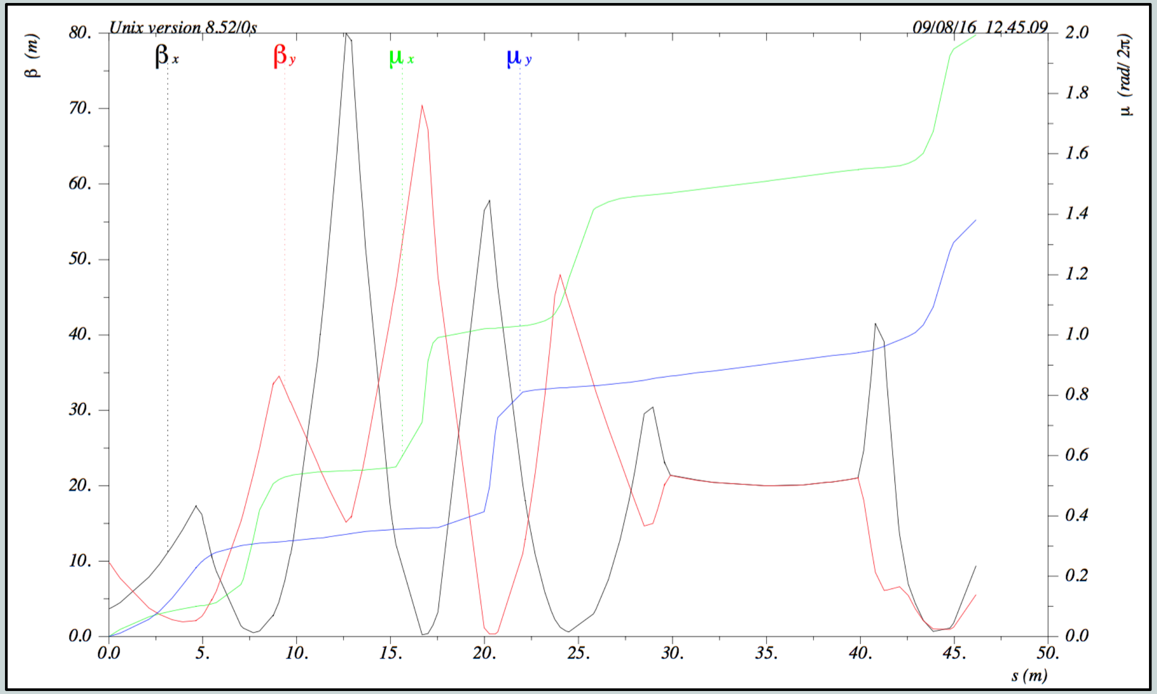
$$\gamma(s) \stackrel{\text{def}}{=} \frac{1 + \alpha(s)^2}{\beta(s)}$$

Phase Advance

- Amount of oscillation period a particle has gone through in a certain arc – will be used to parameterize data sets

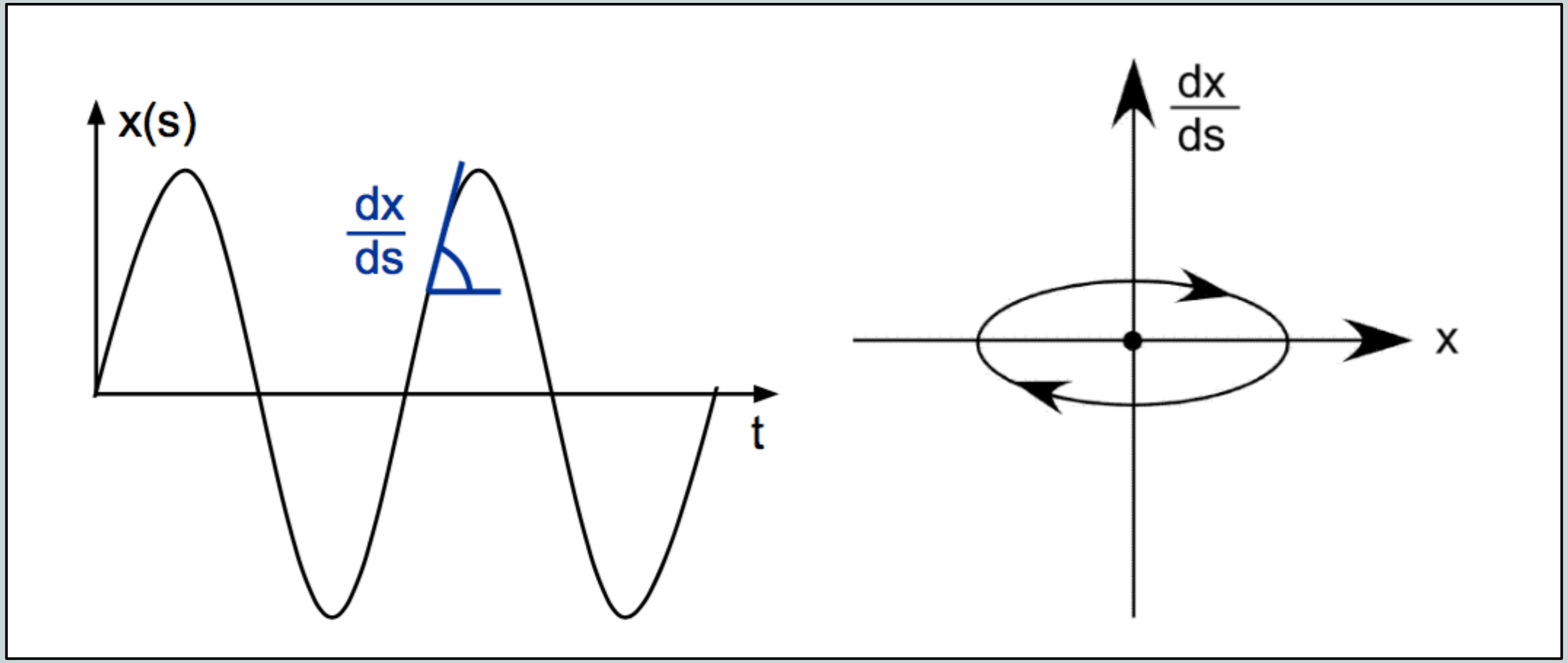
$$\psi_{s_1 s_2} = \int_{s_1}^{s_2} \frac{ds}{\beta(s)}$$





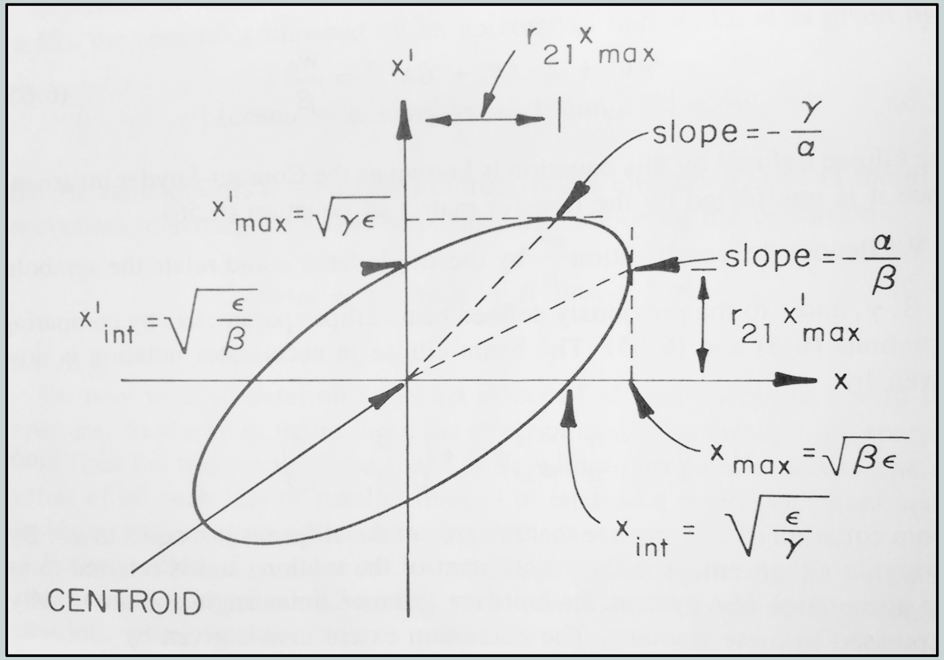
Phase Space

- Betatron oscillation as a function of distance along the beam path
- Parameter space that is used for emittance calculations



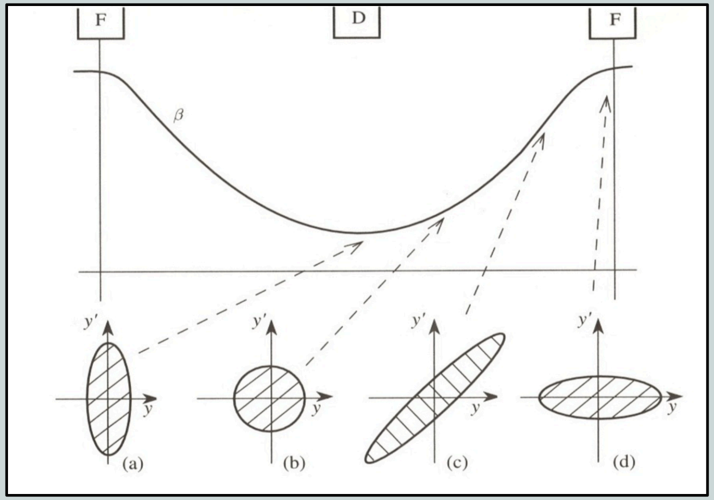
Emittance

- Envelope of particles in phase space is elliptical when beam is exposed to linear forces
- Emittance is equal to the area of this envelope – invariant quantity
- Important metric for understanding beam properties & optics models
- Need to have a method of calculating the emittance from beam position measurements



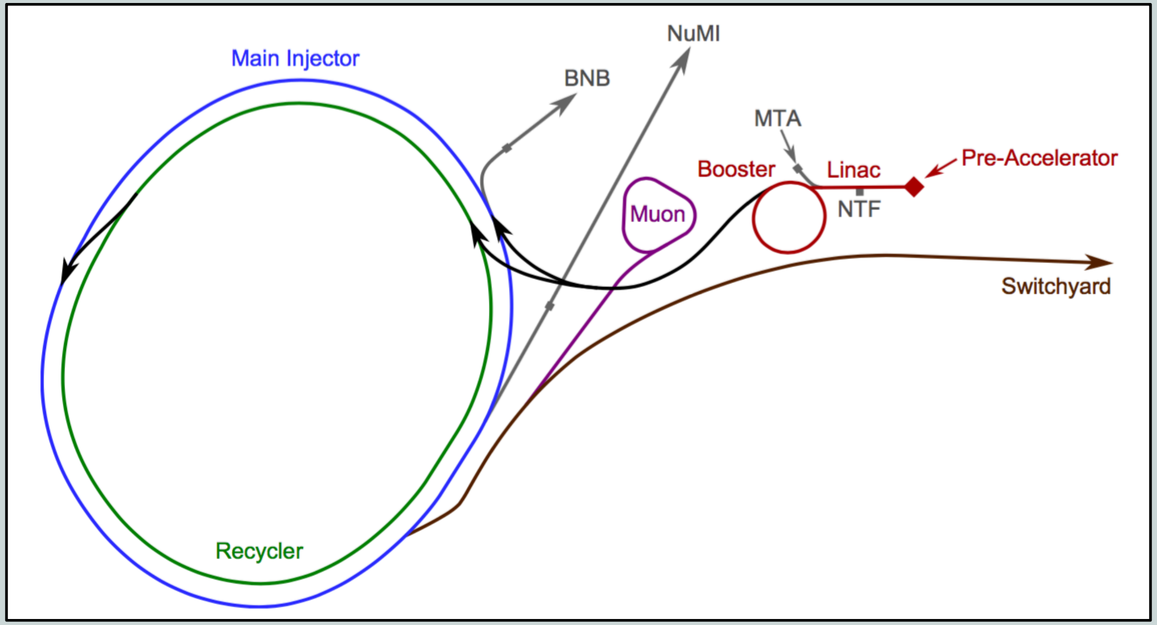
$$\frac{\epsilon}{\pi} = \gamma x^2 + 2\alpha x x' + \beta x'^2$$

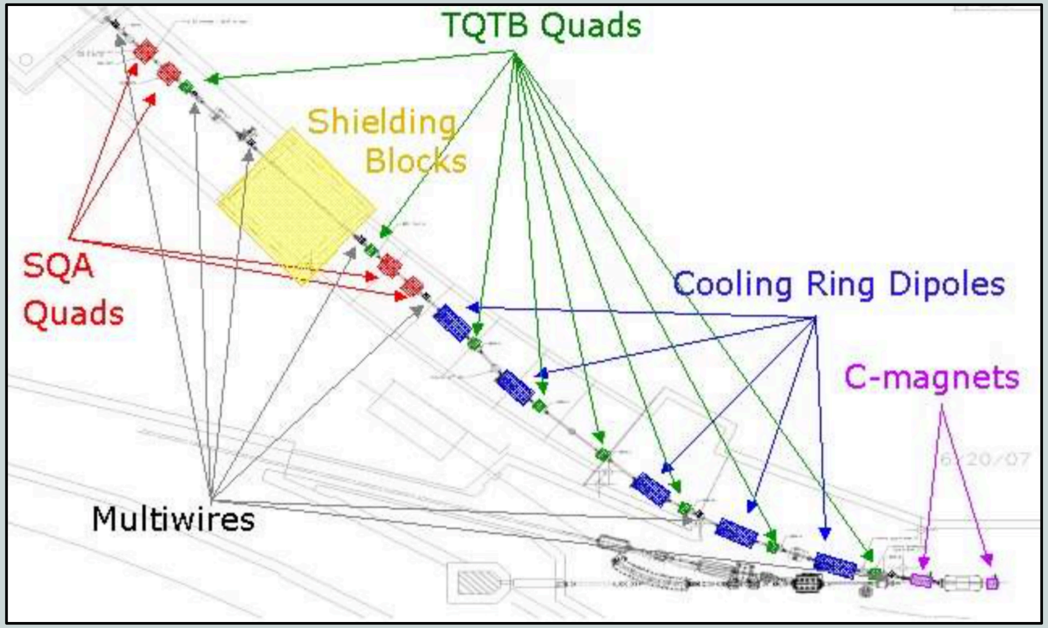
$$\epsilon = \frac{\sigma^2}{\beta}$$



Muon Test Area (MTA)

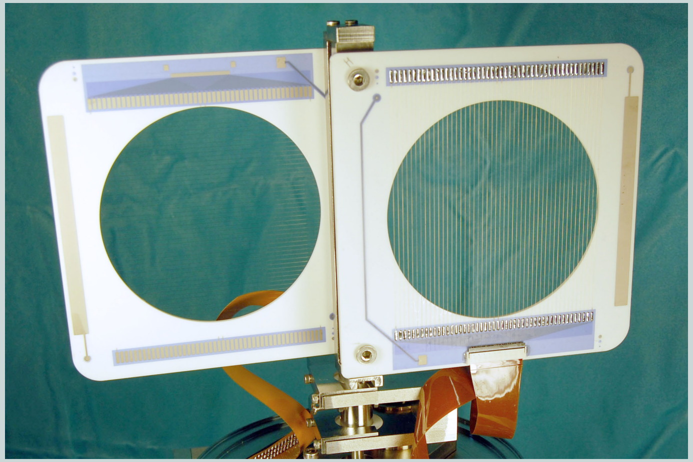
- 400 MeV line off of Fermi's linear accelerator
- Useful for beam diagnostics and testing
- Data used for beam profile reconstruction





Secondary Emission Multiwires

- 48 evenly spaced parallel wires in both planes
- Protons strike the wires and liberate electrons, producing a net charge proportional to the beam intensity
- 0.5, 1, or 2mm spacing
- Profile monitor can be rotated in and out of beam to minimize losses



Analyzing Multiwire Data

- Gaussian Curve Fit
  - *Non-linear least squares method done using Python to determine function parameters*
  - χ^2 *goodness of fit test*

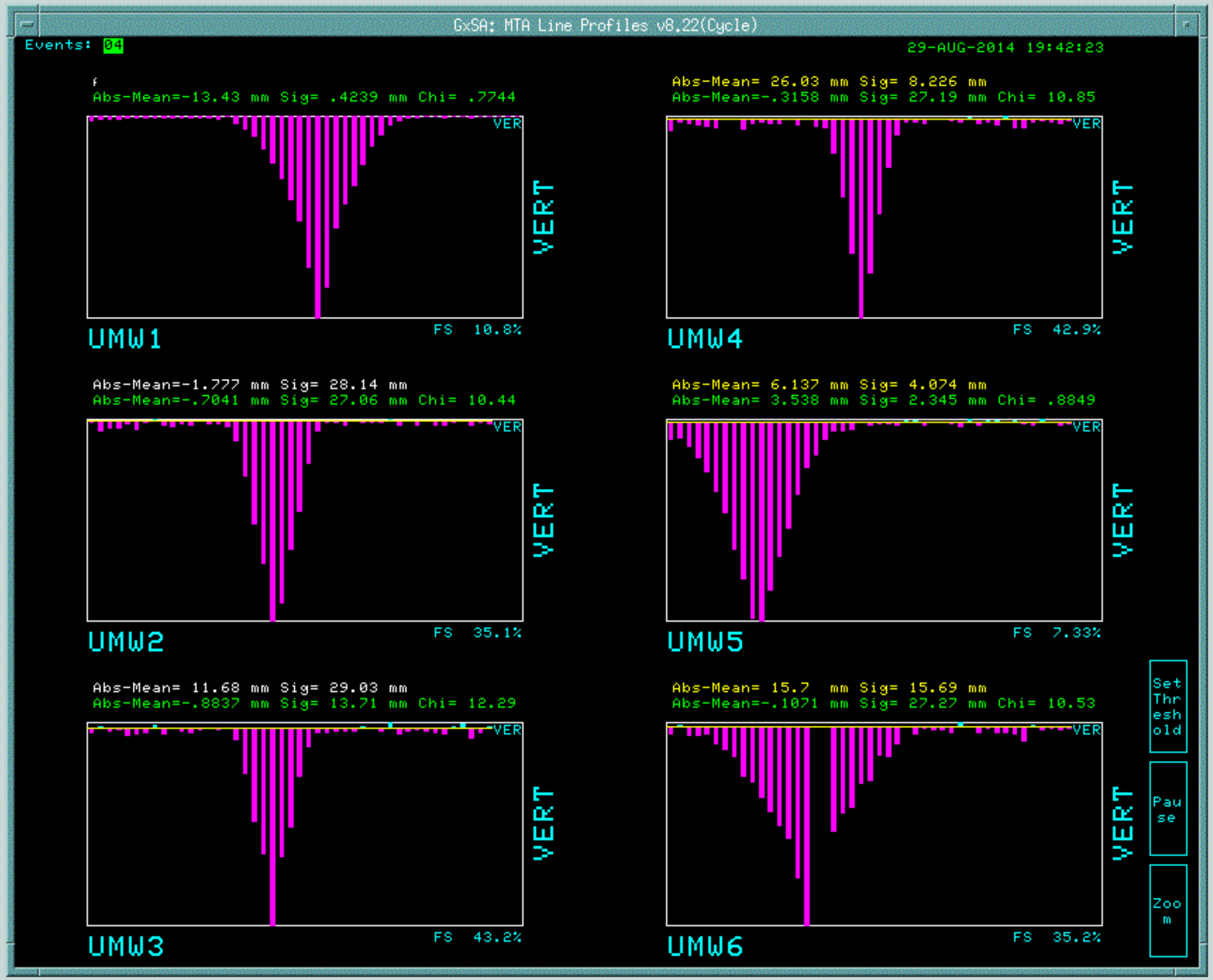
$$g(x) = \frac{A}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

- Root Mean Square (RMS) Method
  - *Highly sensitive to tails*
  - *Where x represents the wire position and P(n) is the signal at that wire*

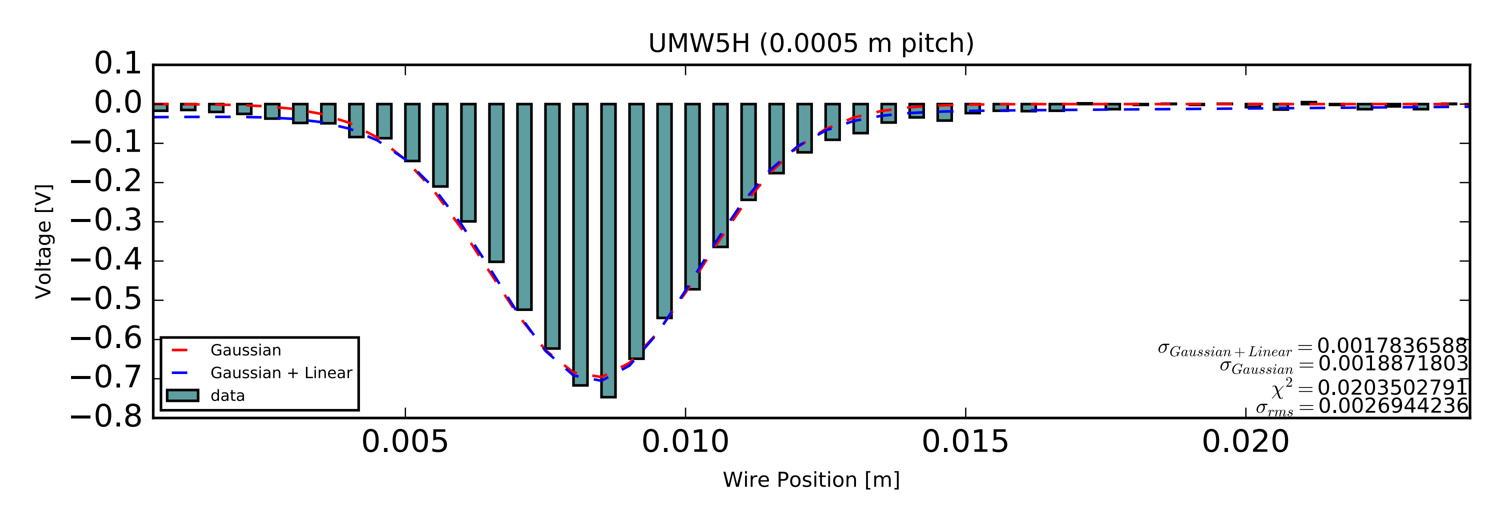
$$\mu = \frac{\sum_n n|P(n)|}{\sum_n |P(n)|} \qquad \sigma_{rms}^2 = \frac{\sum_n (x-\mu)^2 |P(n)|}{\sum_n |P(n)|}$$

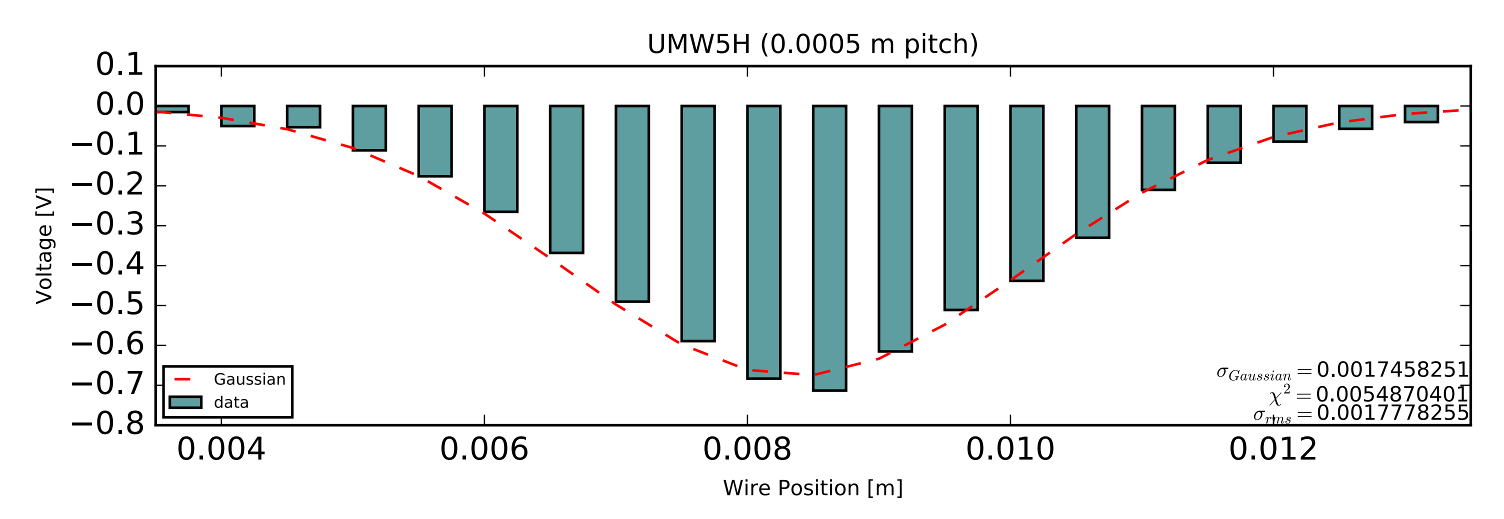
Secondary Emission Multiwires

- Assume Gaussian distribution, compute beam radius in both planes & compare to RMS
- Specifically looking at 10 m drift in MTA (wires 4, 5, & 6 with 2mm, 0.5mm, & 1mm pitches respectively)
- August 2014: 5 data sets taken at each multiwire for all of the 5 phase advances, also referred to as the tune



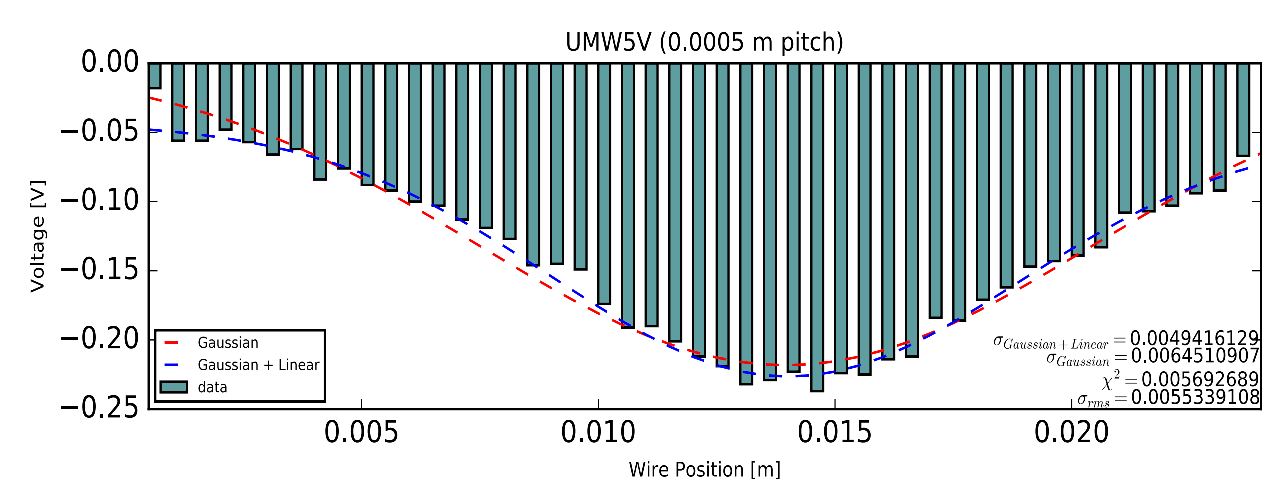
Cleaning up Data

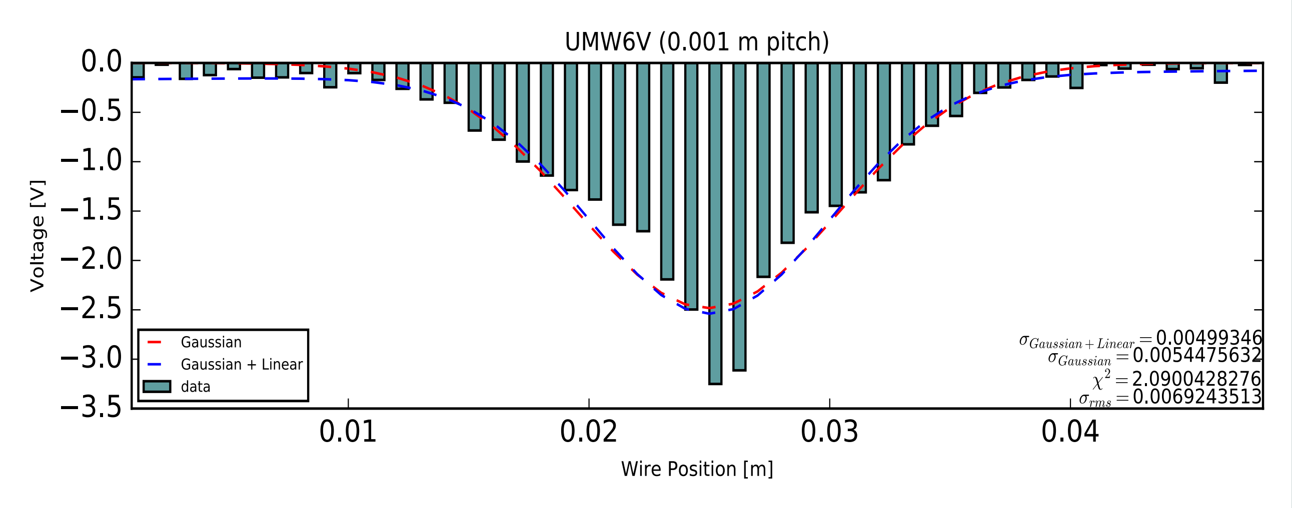




- Gaussian distribution + linear background component fit
- Linear intercept subtracted as background
- Gaussian tails outside 3σ/4σ from peak cut for more accurate RMS calculations

Issues with Gaussian Fit and RMS Calculation

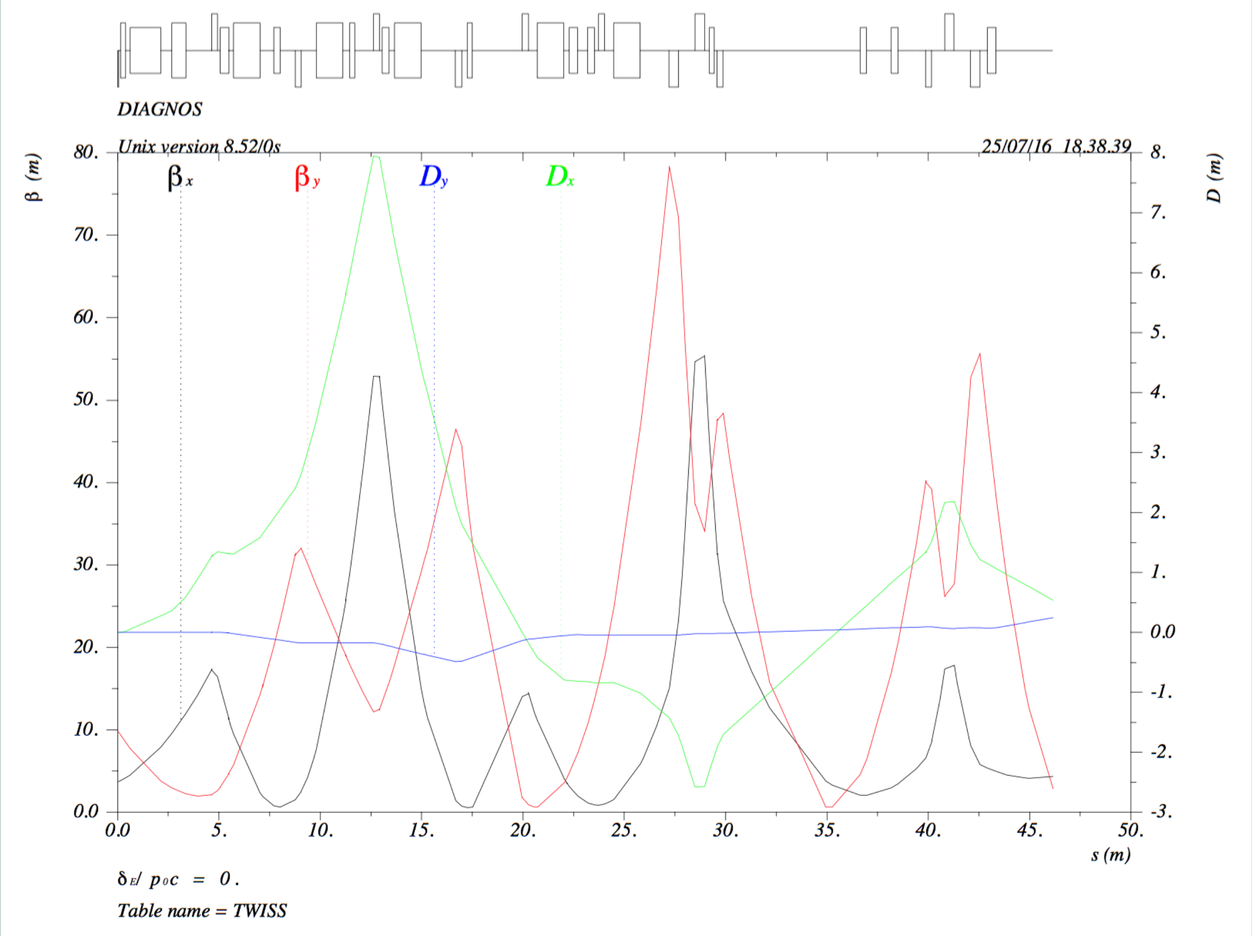




- Beam scraping leads to fractured beam profiles
- Distribution is not always well defined with a Gaussian function
- RMS method highly sensitive to cutoff point because of tails

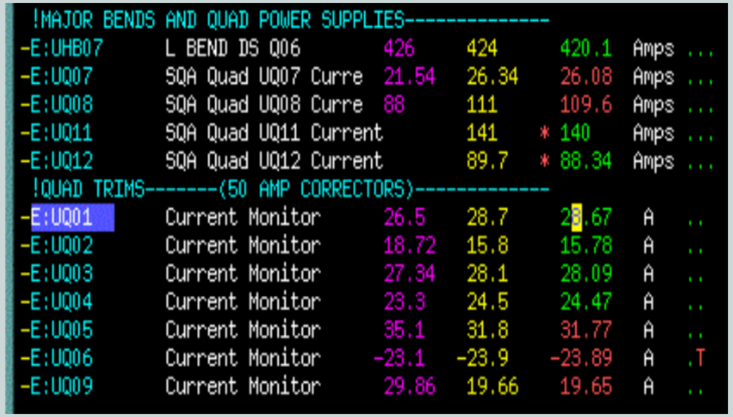
Methodical Accelerator Design (MAD)

- Simulation program developed at CERN
- Models the beam using Courant-Snyder parameters
- Input lattice of all magnets & respective strengths at each tune



Current Conversion & Simulations

- Use currents from operator log to determine quadrupole k-values
- Run simulation with different lattices based on calculations



!MAJOR BENDS AND QUAD POWER SUPPLIES-------------

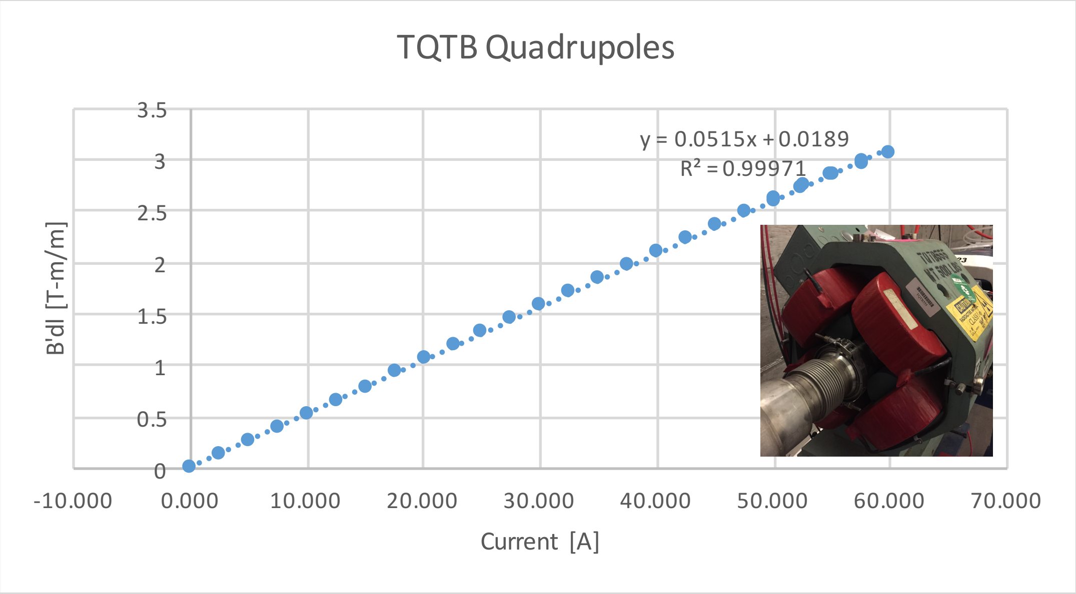
-E:UHB07	L BEND DS Q06	426	424	420.1	Amps	...
-E:UQ07	SQA Quad UQ07 Curre	21.54	26.34	26.08	Amps	...
-E:UQ08	SQA Quad UQ08 Curre	88	111	109.6	Amps	...
-E:UQ11	SQA Quad UQ11 Current		141	* 140	Amps	...
-E:UQ12	SQA Quad UQ12 Current		89.7	* 88.34	Amps	...

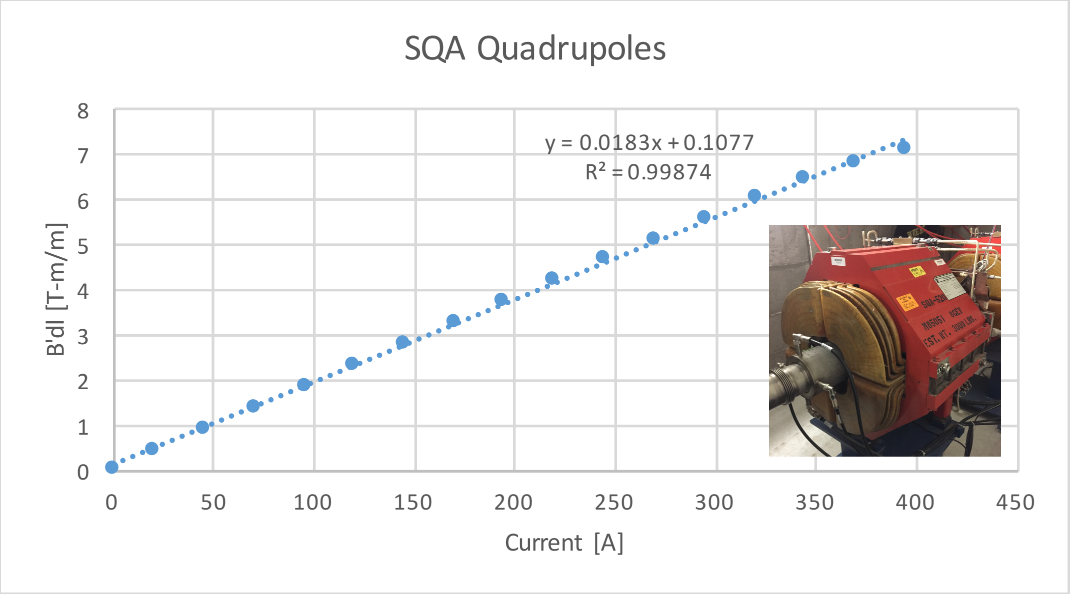
!QUAD TRIMS-------(50 AMP CORRECTORS)------------

-E:UQ01	Current Monitor	26.5	28.7	28.67	A	..
-E:UQ02	Current Monitor	18.72	15.8	15.78	A	..
-E:UQ03	Current Monitor	27.34	28.1	28.09	A	..
-E:UQ04	Current Monitor	23.3	24.5	24.47	A	..
-E:UQ05	Current Monitor	35.1	31.8	31.77	A	..
-E:UQ06	Current Monitor	-23.1	-23.9	-23.89	A	.T
-E:UQ09	Current Monitor	29.86	19.66	19.65	A	..

$$k = \frac{B'}{Bp}$$

Bp=3.1823 GeV/c





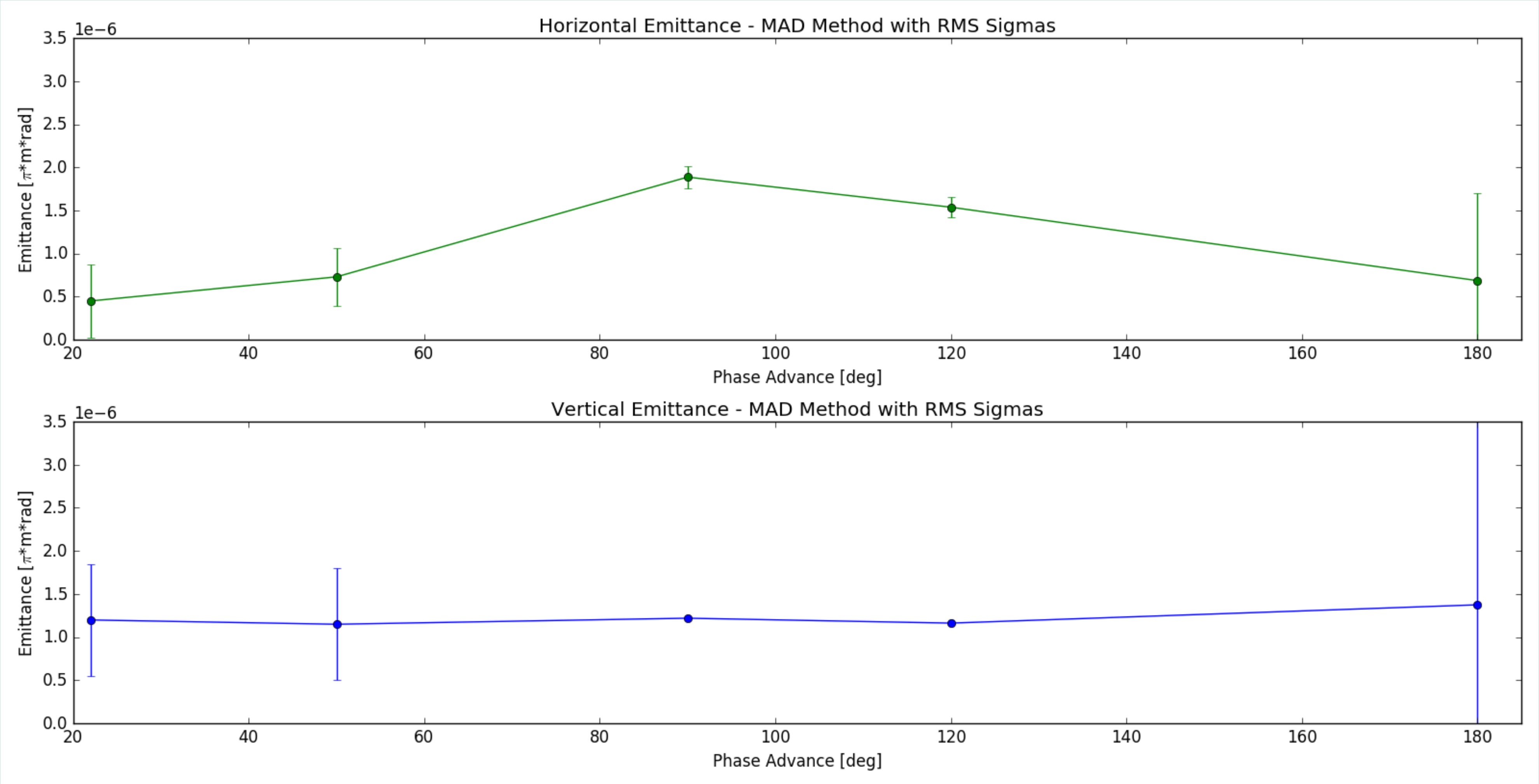
MAD Method

- Use calculated quadrupole settings to recreate conditions when beam profiles were recorded
- 'Match' method used to fit emittance values
  - *Introduce constraint using computed beam width values at each wire*

$$\epsilon = \frac{\sigma^2}{\beta}$$

- MAD returns emittance values with penalty function

MAD Method: Results



* Error bars denote penalty function (scaled by 10e-9)

Issues with MAD Method

- This method relies on initial conditions coming out of Linac
  - *The measurements we have were taken before recent upgrades*
- Have minimal control over convergence of MAD's matching algorithm
  - *Our system is underconstrained and the algorithm will not always iterate enough times to find a solution with high confidence values*
- Heavily reliant on a lattice that requires correct component spacing data, magnet current values, & consistent fields and strengths from magnet to magnet

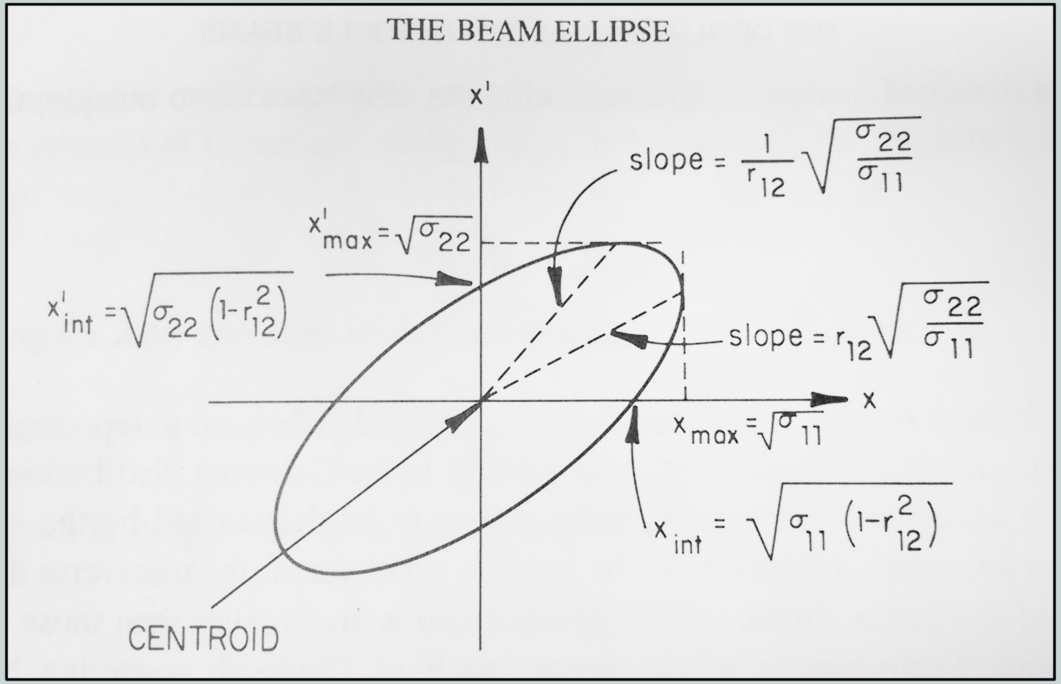
3-Wire Method

- Beam width calculated at 3 multiwires in a drift
  - *Solve linear system derived from linear optics transfer matrices*

$$R_2^2 = R_1^2 + 2L_1\sigma_{12} + L_1^2\sigma_{22}$$

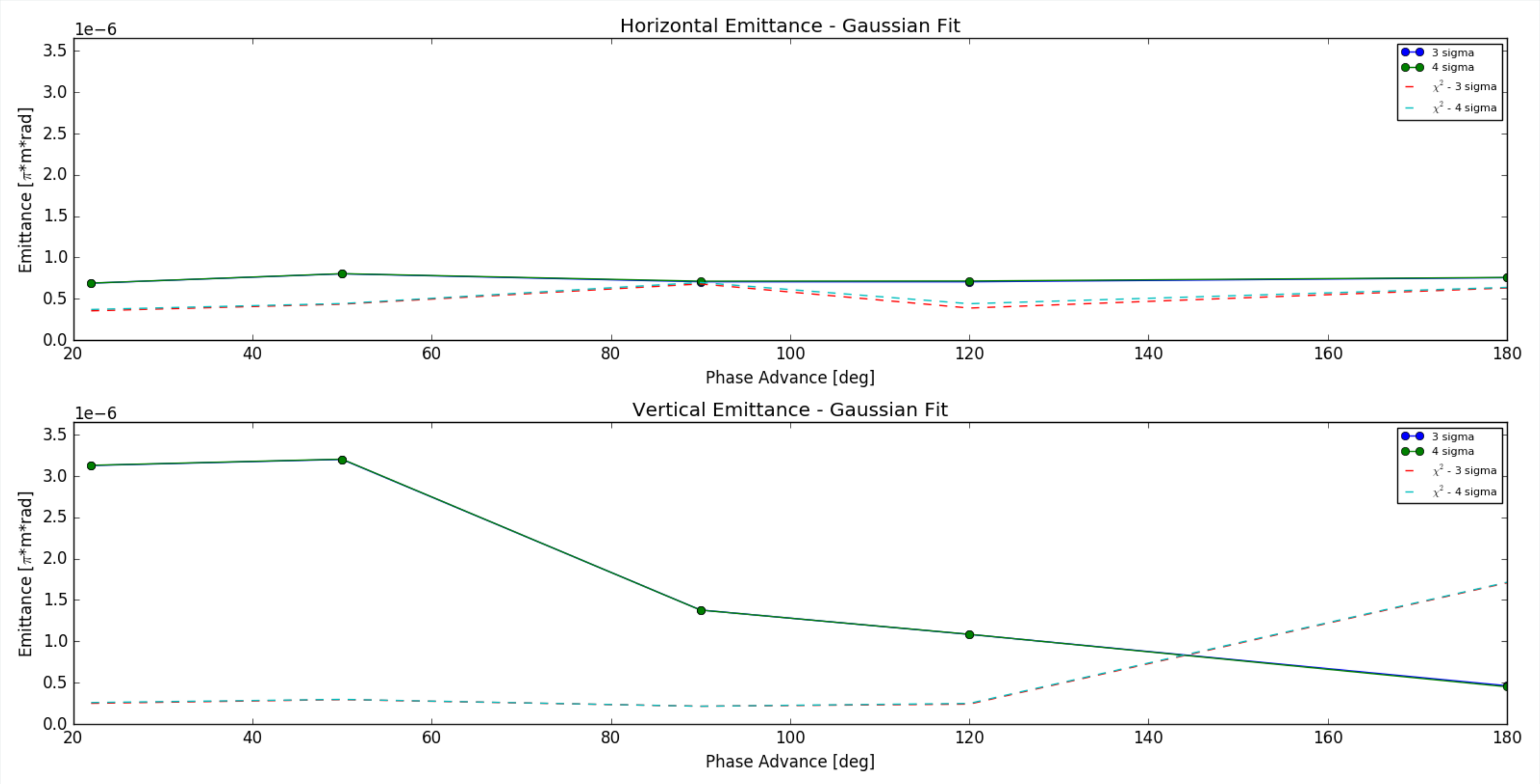
$$R_3^2 = R_1^2 + 2(L_1+L_2)\sigma_{12} + (L_1 + L_2)^2\sigma_{22}$$

where L_1 & L_2 are distances along nominal trajectory and σ values are beam radii ($\sigma = R^2$)

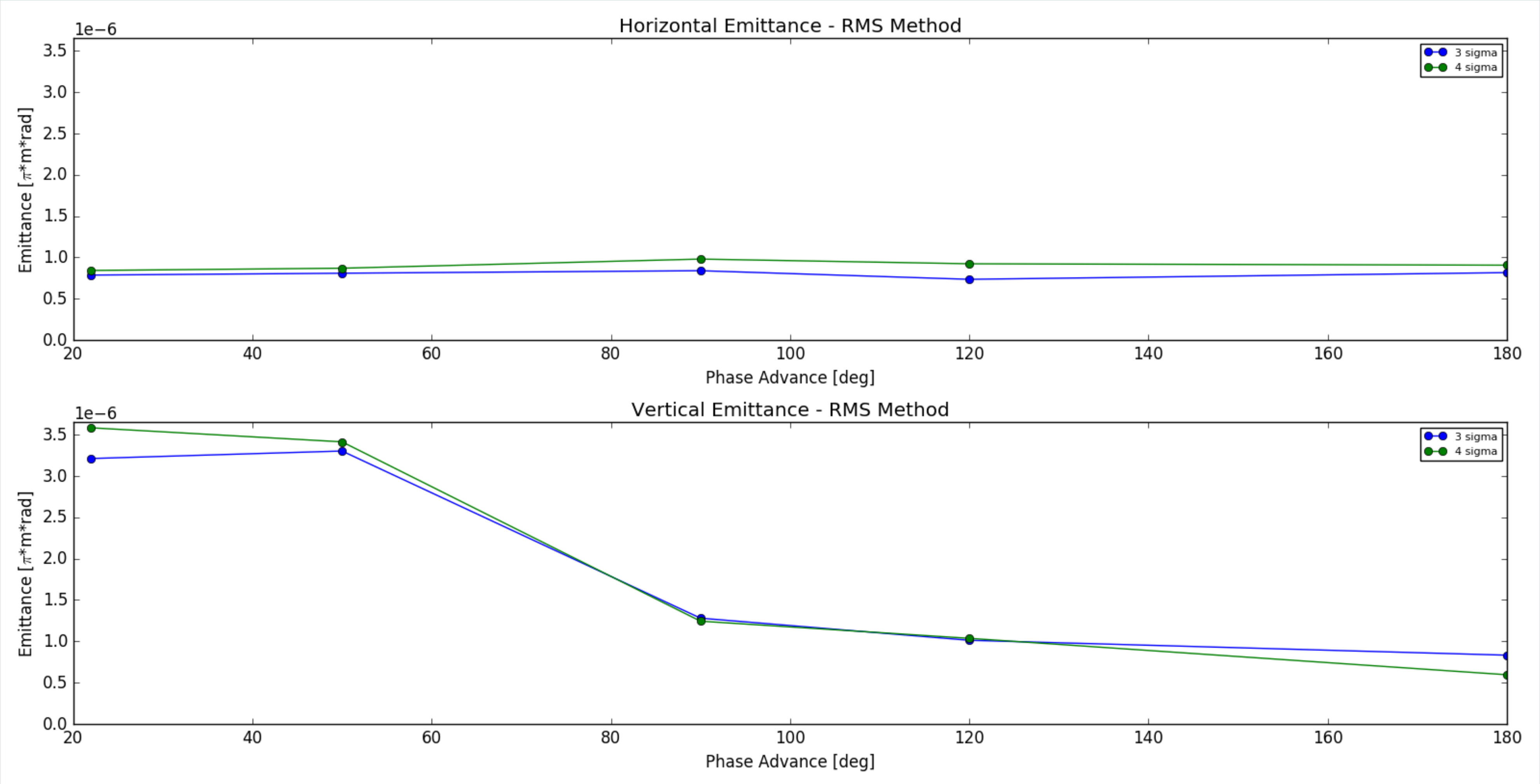


$$\epsilon_{rms} = \sqrt{\sigma_{11}\sigma_{22} - \sigma_{12}^2}$$

3-Wire Method Using Gaussian σ



3-Wire Method Using RMS σ



Conclusions & Future Directions

- We appear to see violation of emmitance conservation in the vertical but not in the horizontal
- Most likely source of this violation is non-elliptical beam
- Using tomographic techniques to reconstruct the beam profile and test this assertion
  - *Move away from reliance on Courant-Snyder parameters which assume elliptical properties*
- Once beam is running again, we can take more data for tomographic reconstruction
- Investigation into causes of non-elliptical envelope
- Better understanding of beam in transverse phase space will help beam losses into Booster

Closing Remarks

I would like to extend my deepest gratitude to my supervisors and mentors, Dr. Carol Johnstone and Adam Watts. I would also like to thank Michael Backfish and Dr. John Johnstone for their assistance and insight throughout the duration of this project.

Finally, I would like to thank to the SIST committee, Fermilab, and North Central College for this opportunity.

References

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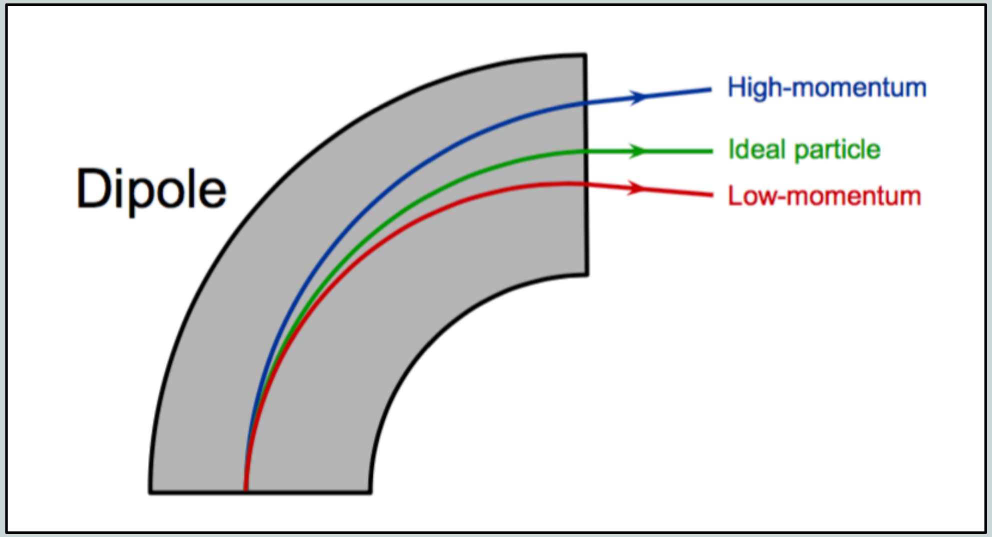
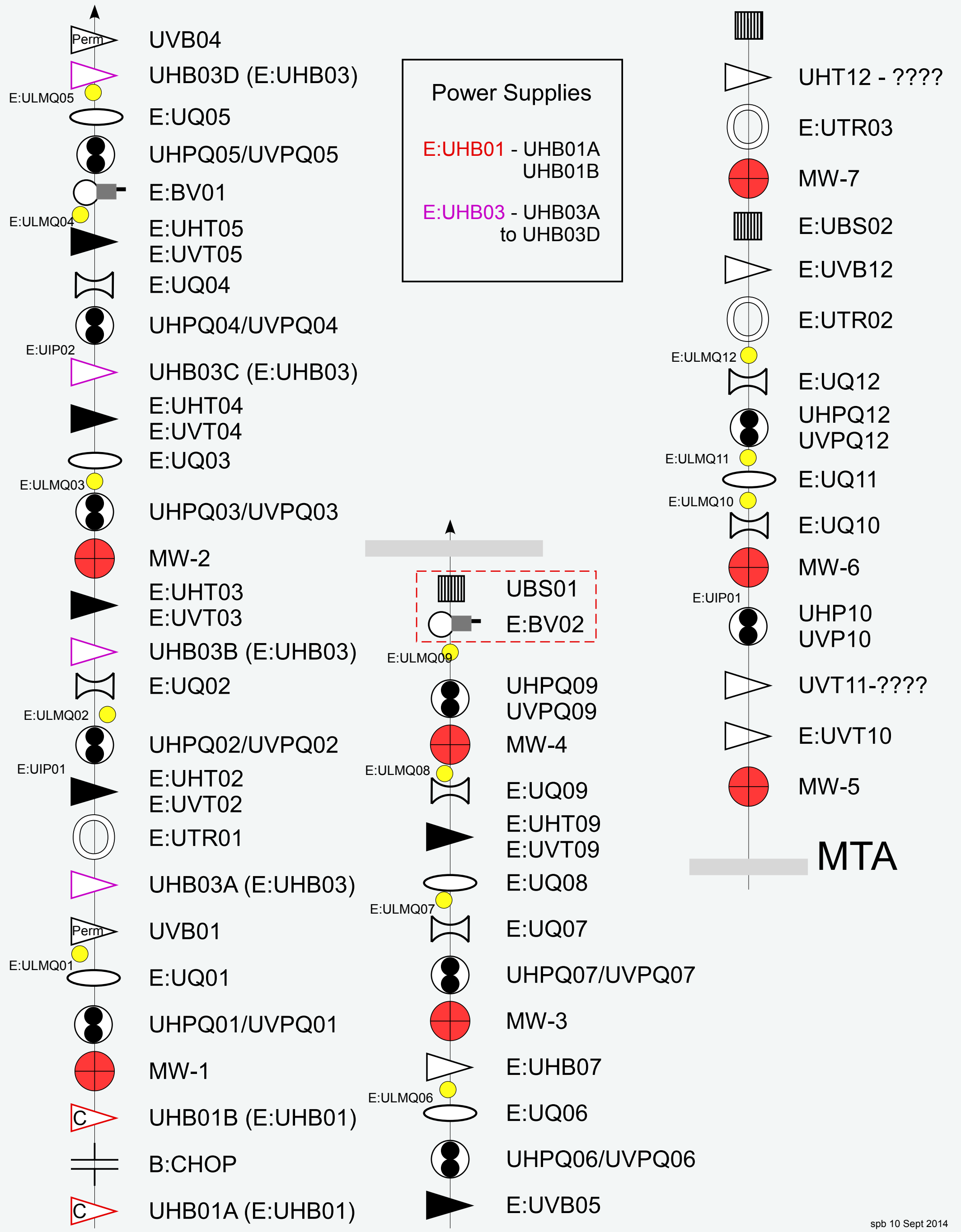
Dispersion

- Force on particles is velocity dependent, so particle trajectories are dependent on momentum
- Analogous to a prism effect in optics
- Needs to be compensated for in measured beam widths, but we do not have a confident measure of $\frac{\sigma p}{p}$ at this time



$$\sigma_{measured} = \sqrt{\beta\epsilon - \left(D\frac{\sigma p}{p}\right)^2}$$


Perm
UVB04
UHB03D (E:UHB03)
E:ULMQ05
E:UQ05
UHPQ05/UVPQ05
E:BV01
E:ULMQ04
E:UHT05
E:UVT05
E:UQ04
UHPQ04/UVPQ04
E:UIP02
UHB03C (E:UHB03)
E:UHT04
E:UVT04
E:UQ03
E:ULMQ03
UHPQ03/UVPQ03
MW-2
E:UHT03
E:UVT03
UHB03B (E:UHB03)
E:UQ02
E:ULMQ02
UHPQ02/UVPQ02
E:UIP01
E:UHT02
E:UVT02
E:UTR01
UHB03A (E:UHB03)
Perm
UVB01
E:ULMQ01
E:UQ01
UHPQ01/UVPQ01
MW-1
C
UHB01B (E:UHB01)
B:CHOP
C
UHB01A (E:UHB01)
Power Supplies
E:UHB01 - UHB01A
UHB01B
E:UHB03 - UHB03A
to UHB03D
UBS01
E:BV02
E:ULMQ09
UHPQ09
UVPQ09
MW-4
E:ULMQ08
E:UQ09
E:UHT09
E:UVT09
E:UQ08
E:ULMQ07
E:UQ07
UHPQ07/UVPQ07
MW-3
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E:UQ06
UHPQ06/UVPQ06
E:UVB05
UHT12 - ????
E:UTR03
MW-7
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UHPQ12
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E:ULMQ11
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MW-6
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UHP10
UVP10
UVT11-????
E:UVT10
MW-5
MTA
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