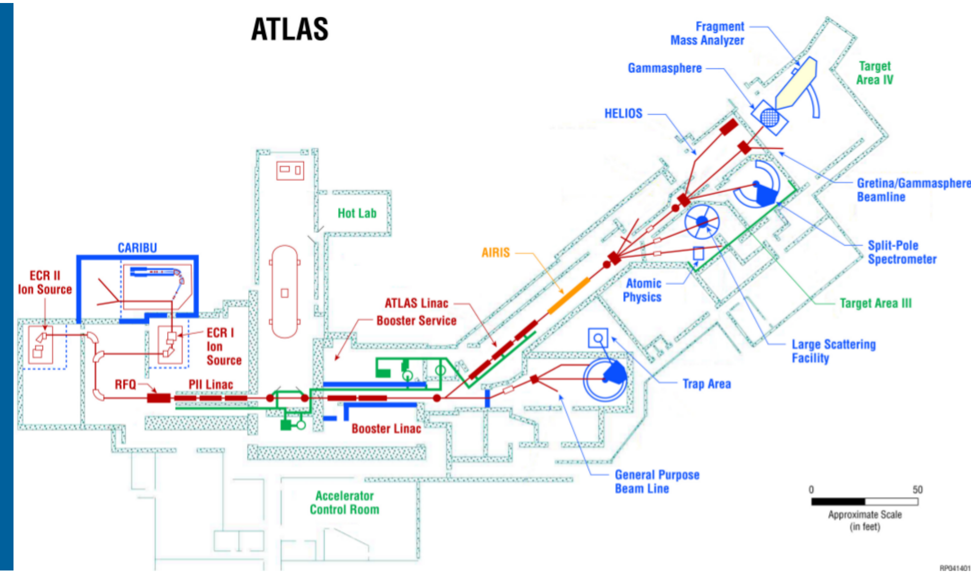
LEE TENG FELLOWSHIP

ATLAS BEAMLINE TUNING AND CHARACTERIZATION



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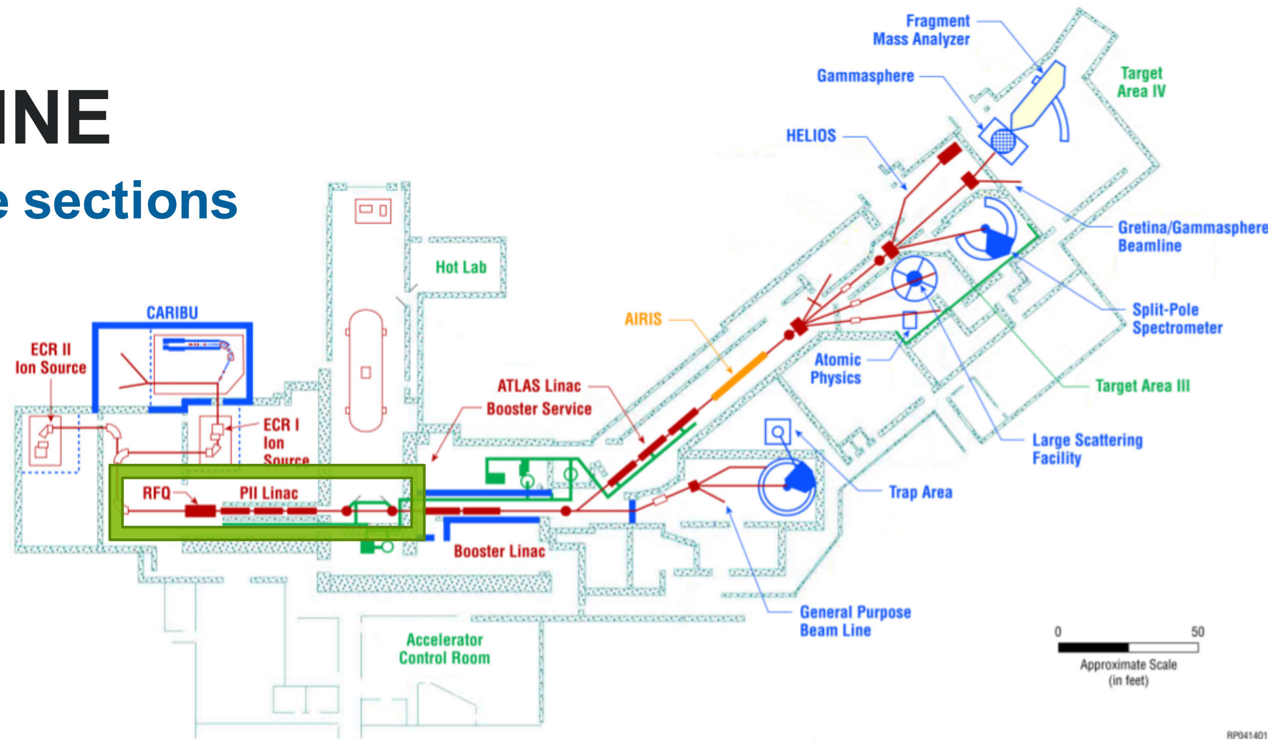
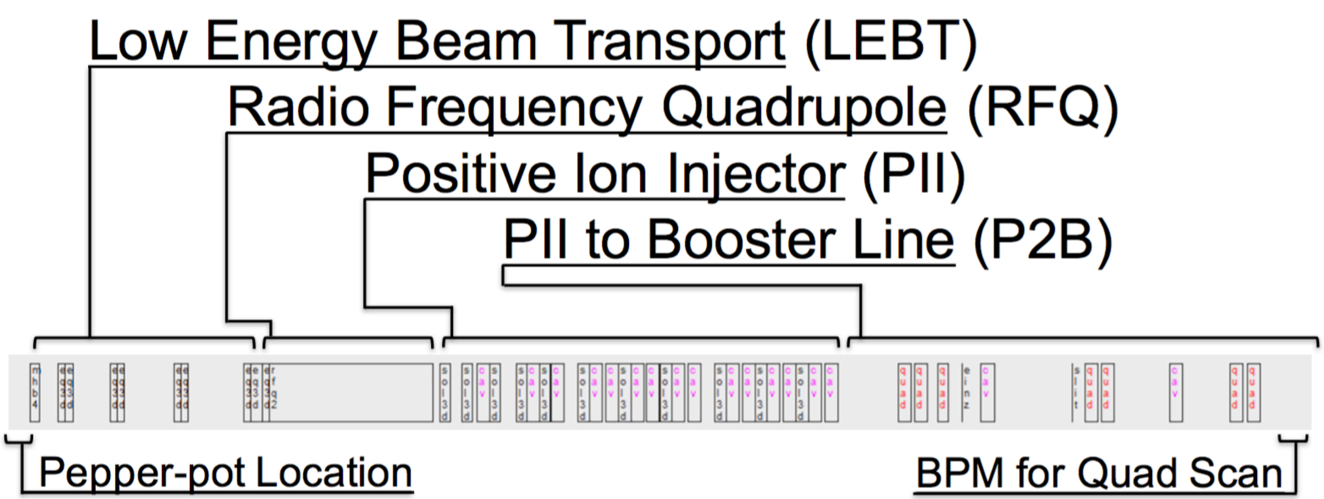
INTRODUCTION AND MOTIVATION

ATLAS BEAMLINE

Overview of beamline sections

- Accelerates ions from H to U
- m/q ratio of up to 6
- 7-17 MeV/u





Argonne NATIONAL LABORATORY

OVERVIEW

March 2016 Runs

Purpose:

- Test how accelerator handles high intensity beams
  - 52nA to 5.2uA beams

Results:

- Found beam transmission was low
  - 90.3% through P2B when 100% should have been easily achievable

Project:

- Find where this beam loss and quality degradation are occurring early on to
  - Prevent quenching of superconducting components
  - Prevent vacuum degradation from outgassing
  - Prevent damage to parts not designed to handle the energy deposited by lost particles
- Calculate emittance at RFQ from quadrupole scan data taken on March 10th

TRACK BEAMLINE SIMULATIONS

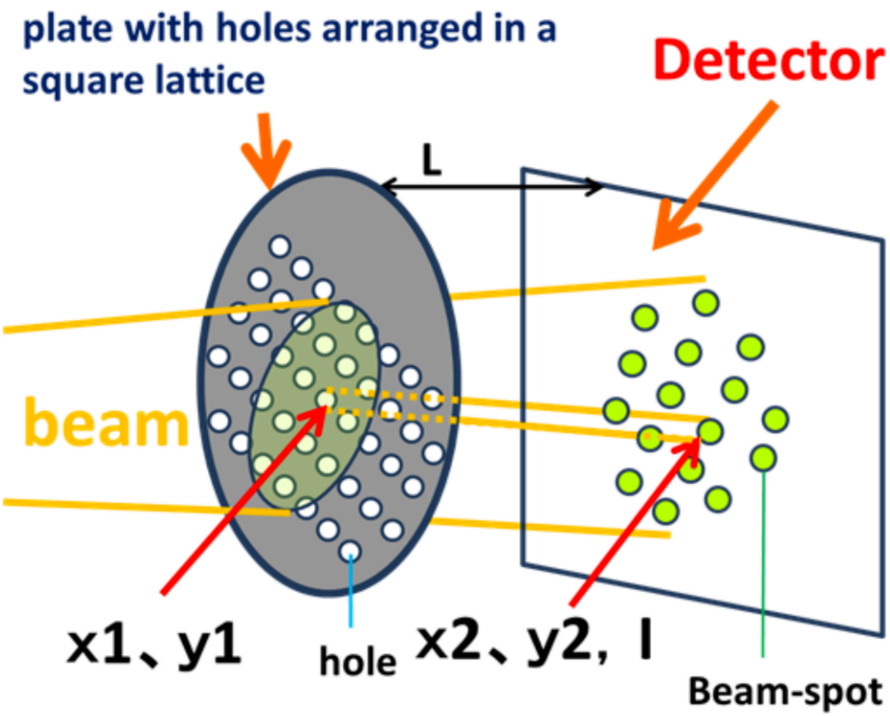
Popular Beam Dynamics Simulation Software

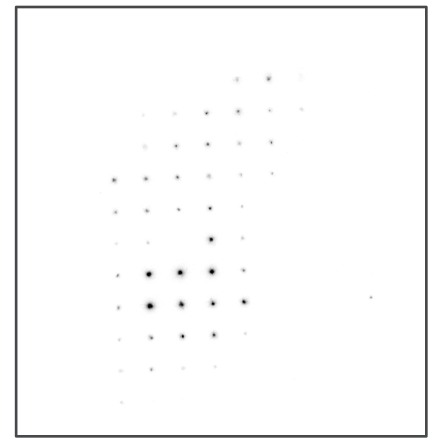
Used for:

- Visualization of the beam envelope along the beamline
- Verification of experimental results

PEPPER-POT DETECTOR

Finding Beam Initial Conditions



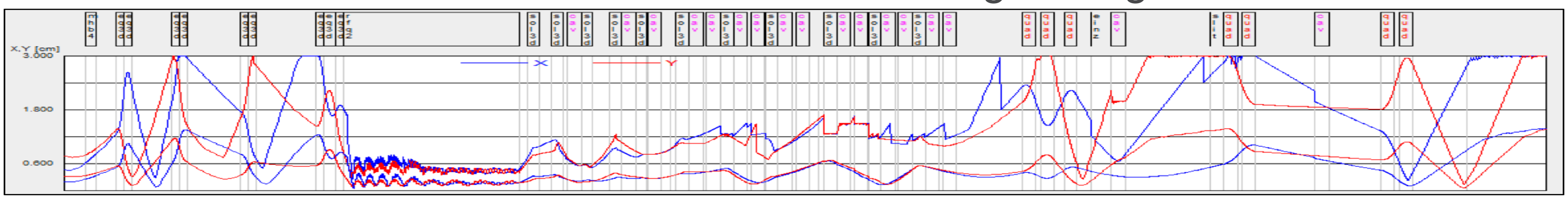


ε_{xn} $[pi\,cm\,mrad]$	0.041 ± 0.004
ε_{yn} $[pi\,cm\,mrad]$	0.069 ± 0.008
α_x	0.23 ± 0.06
α_y	0.30 ± 0.05
β_x $[cm/rad]$	44 ± 6
β_y $[cm/rad]$	72 ± 9

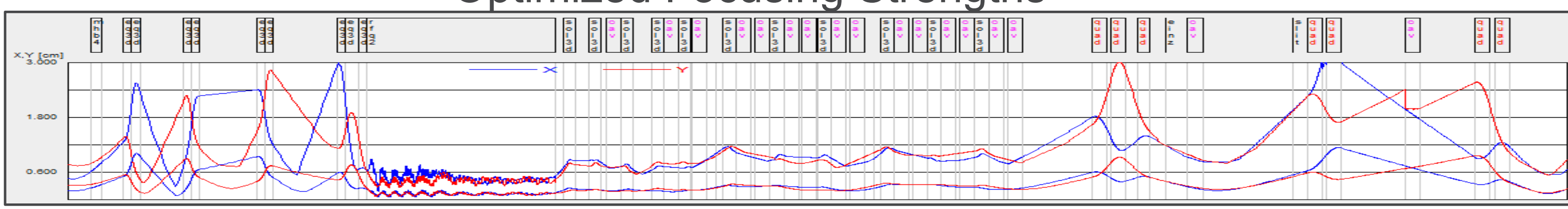
OPTIMIZATION OVERVIEW

Comparison between the recorded focusing element strengths and values optimized for beam transmission in TRACK

Simulation with Recorded Focusing Strengths



Optimized Focusing Strengths

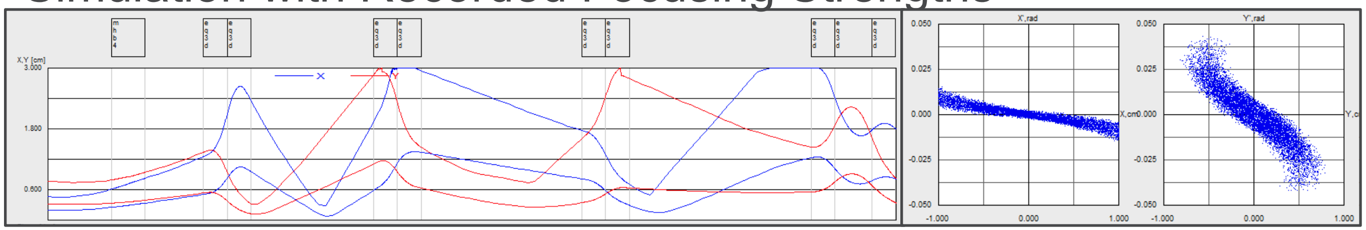


	TRACK Simulated Results		From Measured Data
	Recorded Values % Transmission	Optimized Values % Transmisson	Measured % Transmission
LEBT	91.5%	100.0%	100.0%
RFQ	31.5%	82.4%	(no measuring device)
PII	92.5%	100.0%	88.1%
P2B	87.97%	99.4%	90.3%
Total	23.5%	81.9%	79.6%

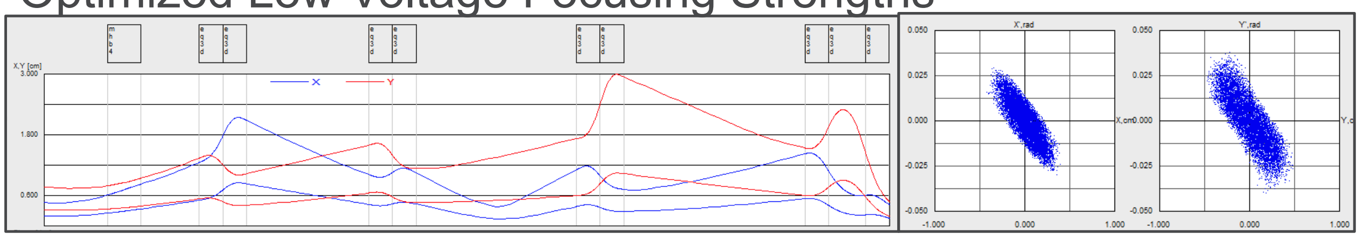
ACCELERATOR BEAMLINE

Low Energy Beam Transport Line (LEBT)

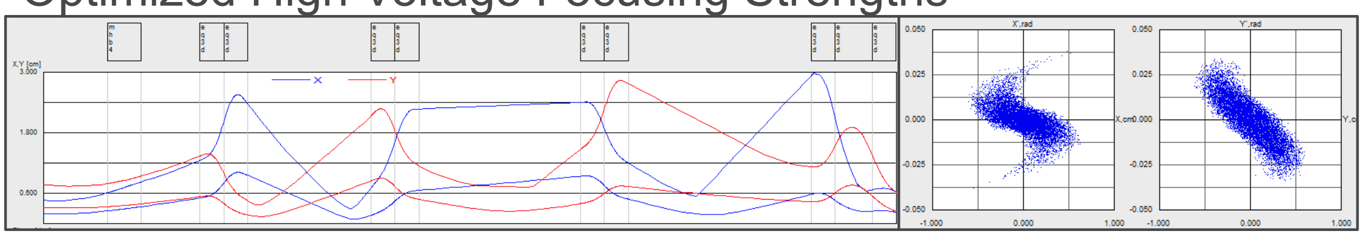
Simulation with Recorded Focusing Strengths



Optimized Low Voltage Focusing Strengths



Optimized High Voltage Focusing Strengths

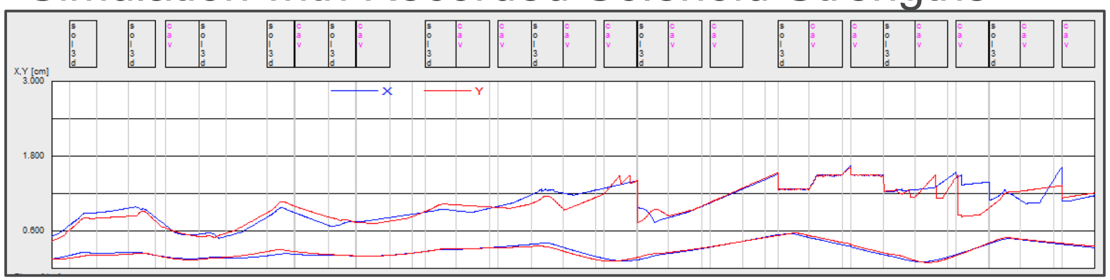


- RFQ Acceptance Matched
- Solns. find 100% Transmission
- LV Quads 42.4% avg. diff.
- HV Quads 17.0% avg. diff.
- **HVε 31.8% larger than LVε**

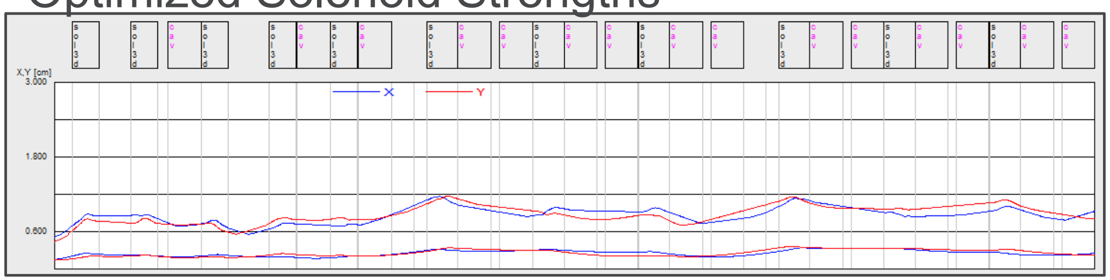
ACCELERATOR BEAMLINE

Positive Ion Injector (PII)

Simulation with Recorded Solenoid Strengths



Optimized Solenoid Strengths



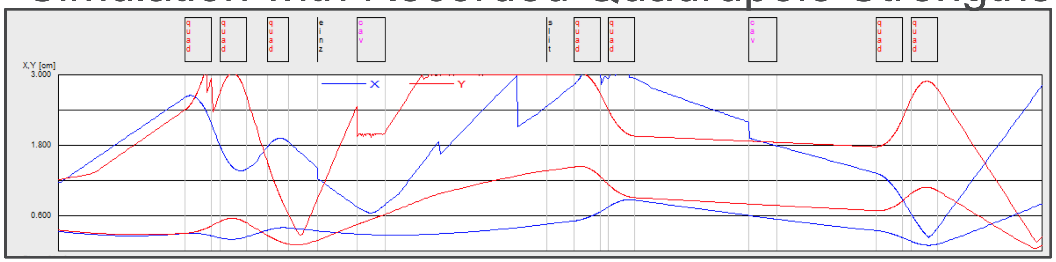
	Recorded [Gs]	Optimized [Gs]	% Diff
sol3d 1	37128.00	39928.00	7.5%
sol3d 2	38188.80	31188.80	-18.3%
sol3d 3	37145.10	33145.10	-10.8%
sol3d 4	36650.64	30650.64	-16.4%
sol3d 5	21958.56	25958.56	18.3%
sol3d 6	20637.00	23637.00	14.5%
sol3d 7	30267.60	20267.60	-33.0%
sol3d 8	27516.00	24516.00	-10.9%
sol3d 9	25796.25	22796.25	-11.6%
sol3d 10	30382.25	16382.25	-46.1%
sol3d 11	30095.63	20095.63	-33.2%

- 20.1% avg. difference between recorded and optimized solenoid strengths
- 100% Transmission

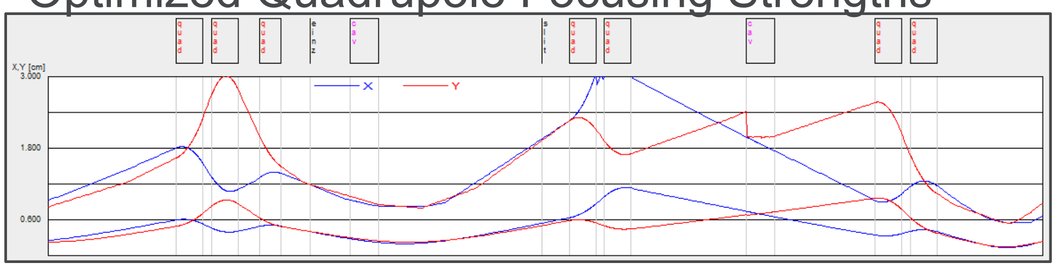
ACCELERATOR BEAMLINE

PII to Booster Line (P2B)

Simulation with Recorded Quadrupole Strengths



Optimized Quadrupole Focusing Strengths



	Recorded [Gs]	Optimized [Gs]	% Diff
QDP 301	784.35	684.35	-12.7%
	-1300.00	-1000.00	-23.1%
QSP 301	871.88	624.35	-28.4%
QDP 302	-556.25	-556.25	0.0%
	565.63	590.63	4.4%
QDP 303	-730.00	-730.00	0.0%
	840.00	840.00	0.0%

- Beam envelope converges as intended after quad doublet
- 13.6% avg. diff. from optimized values

QUADRUPOLE SCAN TECHNIQUE

Practical for any location with Sequential Quadrupole(s) and BPM

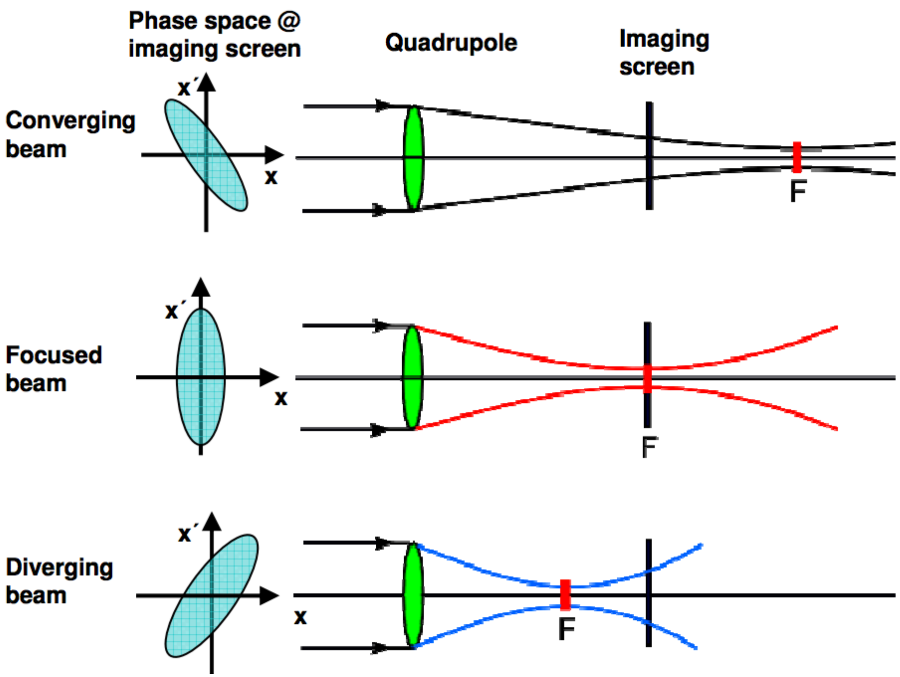
Used for:

- Calculation of beam emittance and Twiss parameters

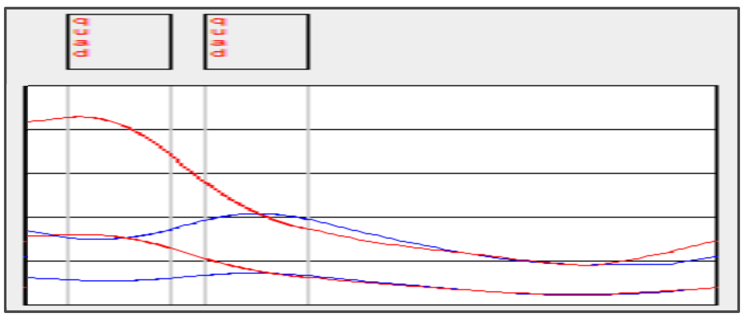
QUADRUPOLE SCAN GEOMETRY

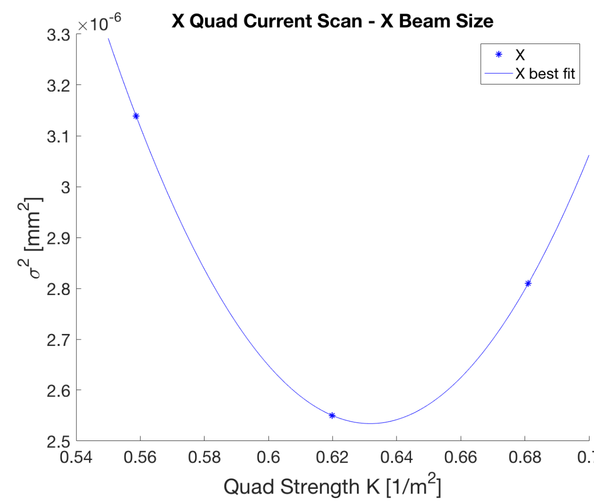
PII to Booster Line (P2B)

Single-Quad Scan



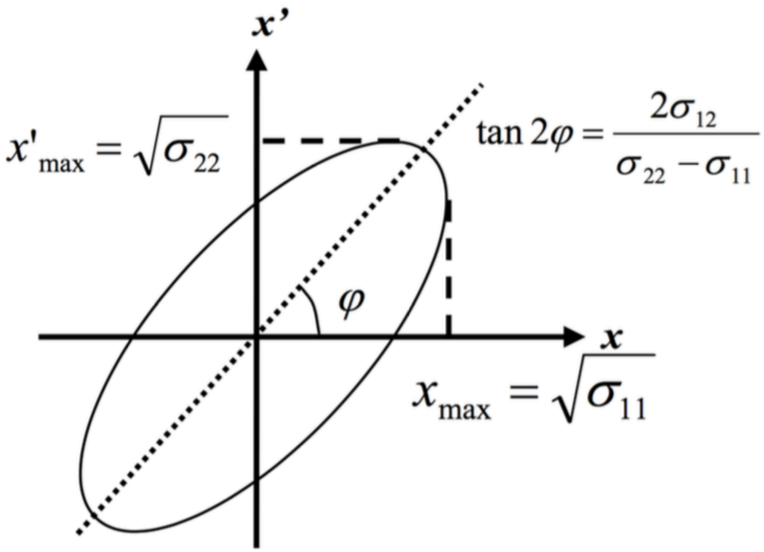
Quad-Doublet Scan





QUADRUPOLE SCAN FORMALISM

Quick overview of the beam matrix and emittance



- Statistical distribution of particles in phase space described by an ellipse
- Beam matrix sigma can describe the geometric properties of this ellipse
- Emittance = area of the ellipse, found by the square root of the beam matrix

$$\sigma = \begin{bmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{bmatrix} = \begin{bmatrix} \sigma_{x^2} & \sigma_{xx'} \\ \sigma_{xx'} & \sigma_{x'^2} \end{bmatrix} = \begin{bmatrix} \langle x^2 \rangle & \langle xx' \rangle \\ \langle xx' \rangle & \langle x'^2 \rangle \end{bmatrix}$$

$$\varepsilon_{rms} = \sqrt{det(\sigma)} = \sqrt{\sigma_{11}\sigma_{22} - \sigma_{12}^2}$$

QUADRUPOLE SCAN FORMALISM

Quick overview of transfer matrices

$$M_{Qf} = \begin{bmatrix} cos(\sqrt{\kappa}s) & \frac{1}{\sqrt{\kappa}}sin(\sqrt{\kappa}s) \\ -\sqrt{\kappa}sin(\sqrt{\kappa}s) & cos(\sqrt{\kappa}s) \end{bmatrix} \quad (1)$$

$$M_{Qd} = \begin{bmatrix} cosh(\sqrt{|\kappa|}s) & \frac{1}{\sqrt{|\kappa|}}sinh(\sqrt{|\kappa|}s) \\ \sqrt{|\kappa|}sinh(\sqrt{|\kappa|}s) & cosh(\sqrt{|\kappa|}s) \end{bmatrix} \quad (2)$$

$$\kappa = \frac{B'}{B\rho} \quad (3) \qquad M_{drift} = \begin{bmatrix} 1 & s \\ 0 & 1 \end{bmatrix} \quad (4)$$

$$M = M_{drift}M_{Qd}M_{drift}M_{Qf} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \quad (5)$$

$$\sigma(s) = M(s)\sigma(s_0)M(s)^T \quad (6)$$

(1)&(2) Transfer matrices for focusing and defocusing quadrupole magnets

(3) Focusing strength of a quadrupole magnet

(4) Transfer matrix for a drift

(5) Complete transfer matrix for quadrupole scan geometry

(6) Beam matrix propagated from point s_0 to point s

QUADRUPOLE SCAN FORMALISM

Quadrupole Scan Calculation

$$\sigma(s) = M(s)\sigma(s_0)M(s)^T \quad (1)$$

$$\sigma_{11}(s) = M_{11}^2\sigma_{11}(s_0) + 2M_{11}M_{12}\sigma_{12}(s_0) + M_{12}^2\sigma_{22}(s_0) \quad (2)$$

$$\begin{bmatrix} \sigma_{11(a)}(s) \\ \sigma_{11(b)}(s) \\ \cdots \\ \sigma_{11(n)}(s) \end{bmatrix} = \underbrace{\begin{bmatrix} M_{11(a)}^2 & 2M_{11(a)}M_{12(a)} & M_{12(a)}^2 \\ M_{11(b)}^2 & 2M_{11(b)}M_{12(b)} & M_{12(b)}^2 \\ \cdots & \cdots & \cdots \\ M_{11(n)}^2 & 2M_{11(n)}M_{12(n)} & M_{12(n)}^2 \end{bmatrix}}_{A} \begin{bmatrix} \sigma_{11}(s_0) \\ \sigma_{12}(s_0) \\ \sigma_{22}(s_0) \end{bmatrix} \quad (3)$$

$$A^T(AA^T)^{-1} \begin{bmatrix} \sigma_{11(a)}(s) \\ \sigma_{11(b)}(s) \\ \cdots \\ \sigma_{11(n)}(s) \end{bmatrix} = \begin{bmatrix} \sigma_{11}(s_0) \\ \sigma_{12}(s_0) \\ \sigma_{22}(s_0) \end{bmatrix} \quad (4)$$

$$\varepsilon_{rms} = \sqrt{det(\sigma)} = \sqrt{\sigma_{11}\sigma_{22} - \sigma_{12}^2} \quad (5)$$

(1) Propagation of beam matrix through quad geometry
- s – BPM location
- s_0 – Start of first quad

(2) First element of resulting beam matrix

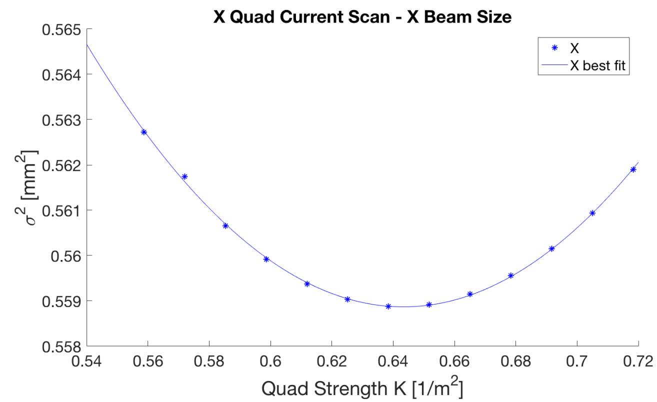
(3) When 3 or more measurements are taken this becomes a fully constrained system of equations with three unknowns

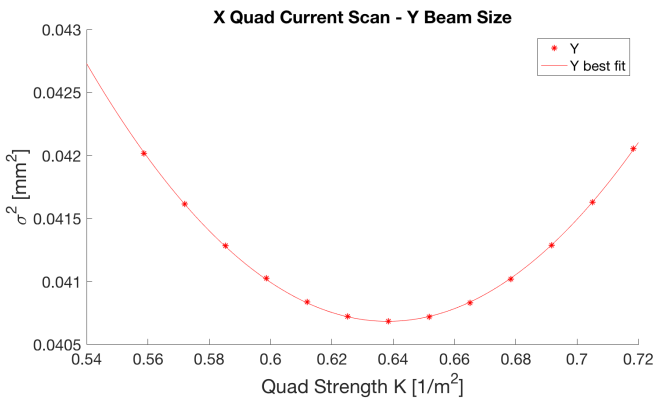
(4) A Moore-Penrose pseudoinverse as a least squares fit can be used to find the matrix elements

(5) Emittance calculation

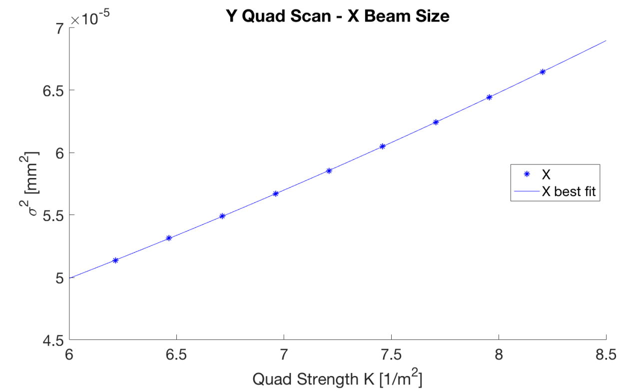
QUADRUPOLE SCAN TEST SIMULATION

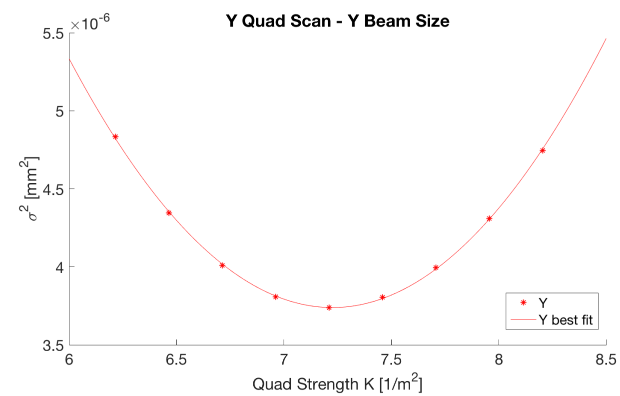
Comparison of symmetric and asymmetric scans about beam waist





	TRACK	Calculation	% Diff
$4\varepsilon_{xNrms}$ [cm mrad]	0.0277	0.0274	1.0%
$4\varepsilon_{yNrms}$ [cm mrad]	0.0461	0.0462	0.21%

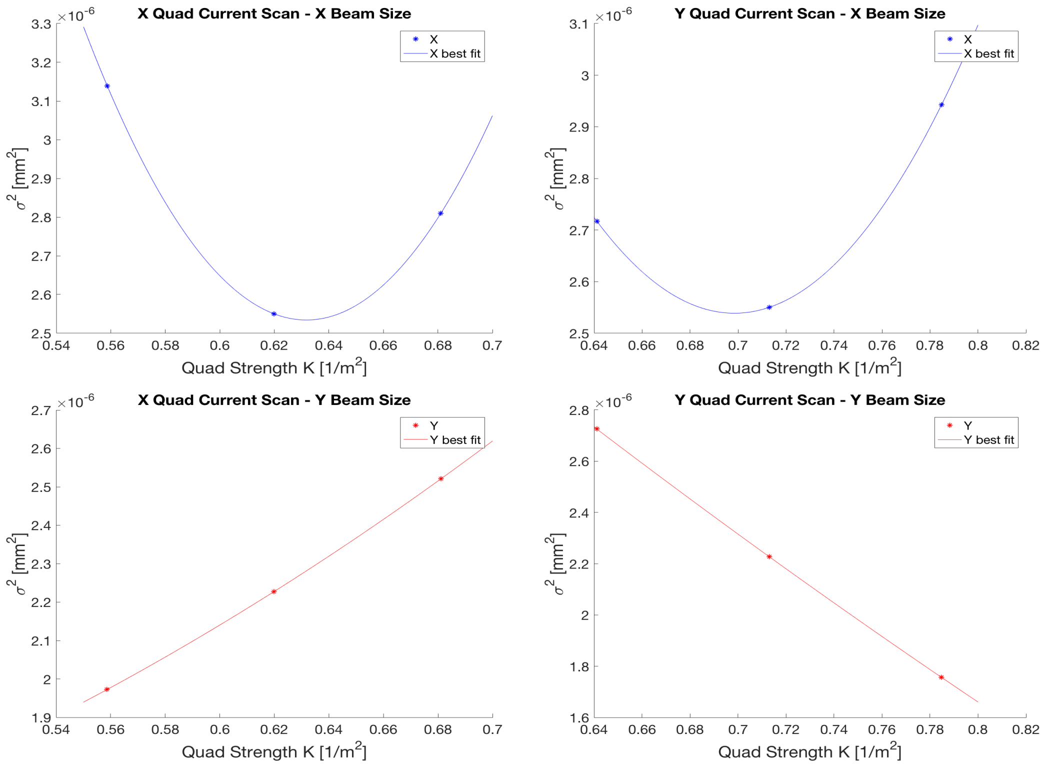




	TRACK	Calculation	% Diff
$4\varepsilon_{xNrms}$ [cm mrad]	0.0277	0.0223	19.4%
$4\varepsilon_{yNrms}$ [cm mrad]	0.0461	0.0458	0.7%

QUADRUPOLE SCAN DATA ANALYSIS

Analysis of March 10th quadrupole scan data



	TRACK	Calculation X Scan	% Diff	Calculation Y Scan	% Diff
$4\varepsilon_{xNrms}$ [cm mrad]	0.0630	0.00813	87.1%	0.0183	71.0%
$4\varepsilon_{yNrms}$ [cm mrad]	0.0650	0.0120	81.5%	0.00627	90.4%

- Inconsistency between TRACK and calculated emittance
- Calculated emittance is smaller than at Pepper-pot!

Conclusion:

- Because three points are not enough to statistically determine a quadratic fit these calculations do not yield accurate results

CONCLUSIONS AND FUTURE STUDIES

Optimizations:

- Run LEBT quadrupoles at lower current to prevent early emittance growth

Quadrupole Scan:

- Quad scans should be swept over the beam waist and include as many data points as possible for greatest accuracy
- Because scanning over a quad doublet the data from each quad could be combined in x and y to minimize the number of data points needed for each

ACKNOWLEDGEMENTS

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- Special thanks to the Lee Teng Fellowship and Argonne National Laboratory.

REFERENCES

- Rudolph, J. "Slice Emittance Measurement Techniques." Helmholtz Zentrum Berlin.
- Crandall et al, "TRACE 3-D Documentation" Los Alamos National Laboratory.

Images:

- https://www.phy.anl.gov/airis/layout.html
- Nagatomo et al, "Development of a Pepper-pot Emittance Meter for Diagnostics of Low-energy Multiply Charged Heavy Ion Beams Extracted from an ECR Ion Source." *Rev. Sci. Inst.* 87.2 (2016)

THANK YOU FOR LISTENING