Particle Beam Physics Laboratory

# Maximizing 2-D Beam Brightness Using the Round to Flat Beam Transformation in the Ultralow Charge Regime


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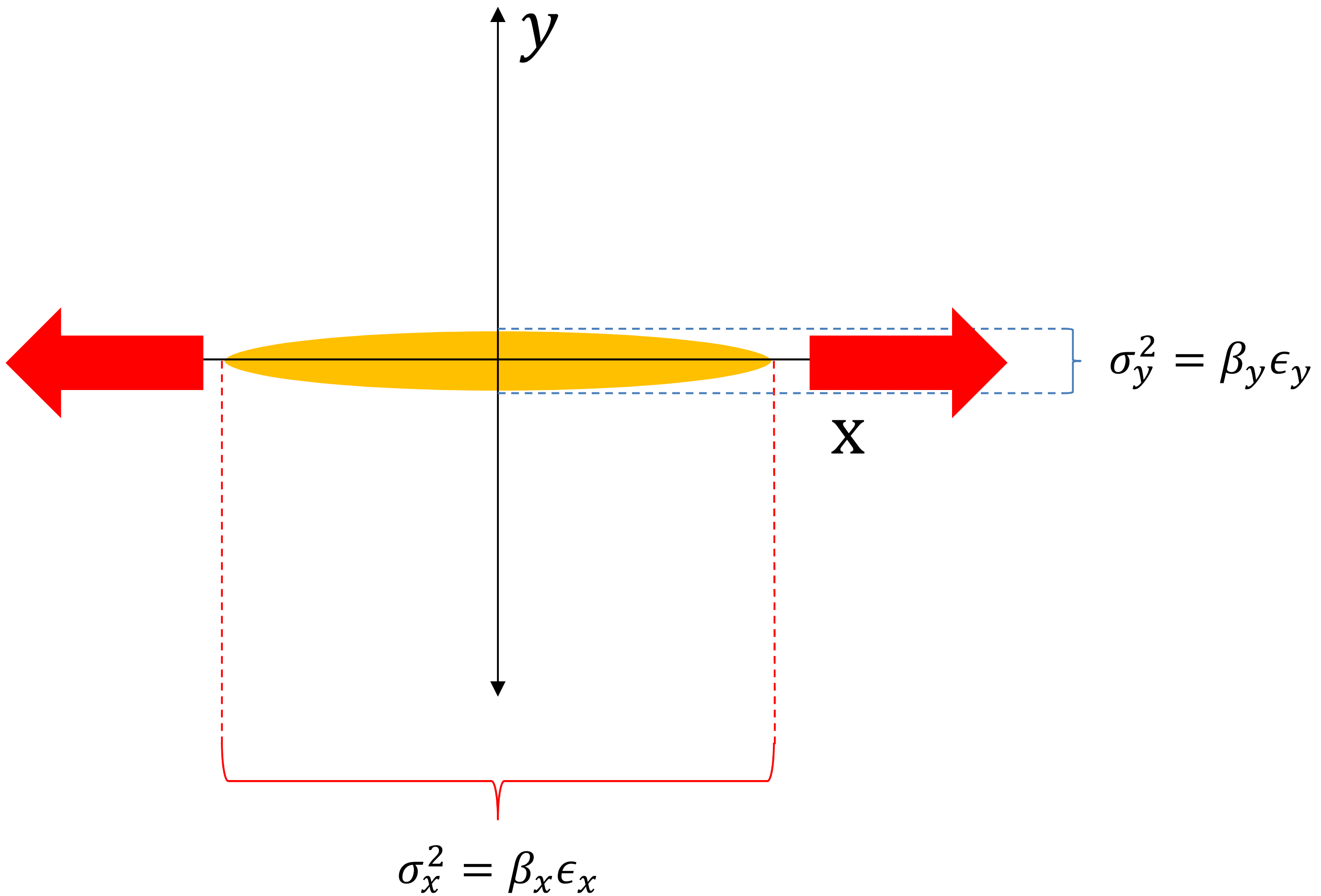
The Center for BRIGHTBEAMS
A National Science Foundation Science & Technology Center

# Outline

- Flat beam introduction
- Motivation & theory
- Flat beam transform at Pegasus
  - Hardware overview
  - Current status
  - Future plans

# Flat Beam Introduction

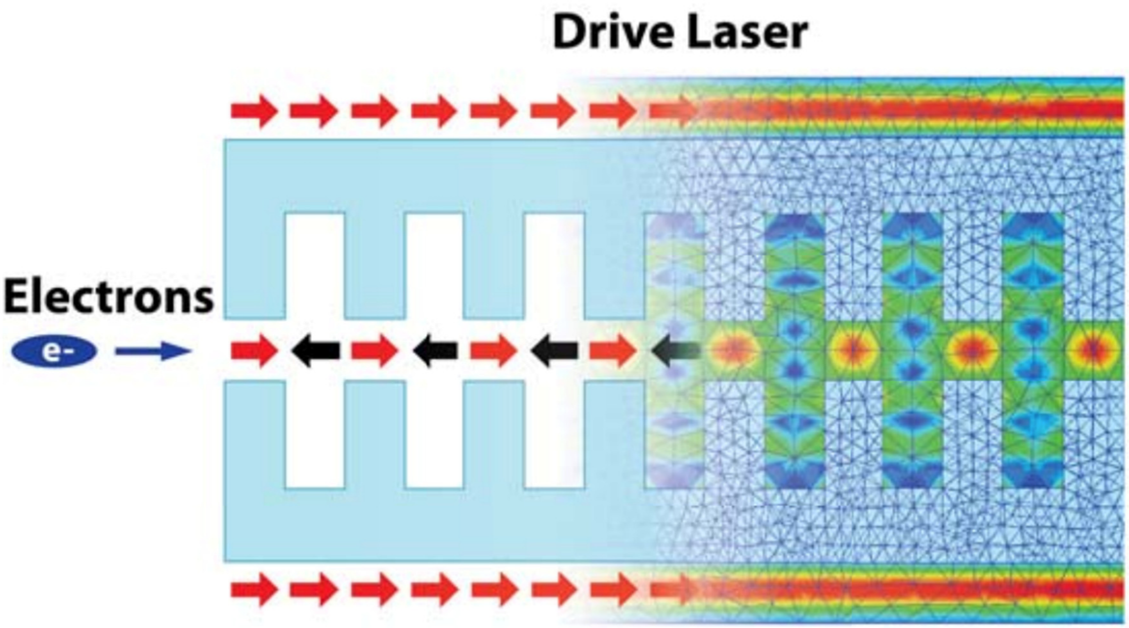
Definition: $\epsilon_x \ll \epsilon_y$ or $\epsilon_y \ll \epsilon_x$



# Practical Motivation

- $B_{4D} = \frac{Q}{\varepsilon_{4D,n}}$ $B_{2D,x} = \frac{Q}{\varepsilon_{x,n}}$
- Theory: $\epsilon_{n,x}$<10 nm
- Dielectric Laser Acceleration, relativistic electron microscopy
- FBT originally developed for electron cooling & colliders [1], [2], [3], [4], [5], [6]
- At Pegasus, new FBT regime: ultralow charge (<1pC)
  - Working for ultra-small emittances (not high emittance ratio)


[1] Ya. Derbenev, University of Michigan, UM-HE-98-04, Feb. 1998
[2] R. Brinkmann et al., Phys. Rev. ST Accel. Beams 4, 053501 (2001)
[3] K.J. Kim, Phys. Rev. ST Accel. Beams **6**, 104002 (2003)
[4] P. Piot et al. Phys. Rev. ST Accel. Beams 9, 031001 (2006)
[5] Y.-E Sun et al. Phys. Rev. ST Accel. Beams 7, 123501
[6] Y. Sun, PhD dissertation, University of Chicago (2005)


K. Soong et al. AIP Conference Proceedings 1507, 516 (2012)

# Theoretical Motivation

- Conserved quantities
  - 4-D Emittance
  - Gromov's non-squeezing theorem
    - Another symplectic invariant

$$Tr((J\sigma^{4D})^2) \propto \epsilon_1^2 + \epsilon_2^2$$

  - Eigenemittance is the lowest limit of projected emittance

**The Symplectic Camel:** *It is impossible to move a ball of radius $\geq 1$ symplectically from one side of the wall to the other.*

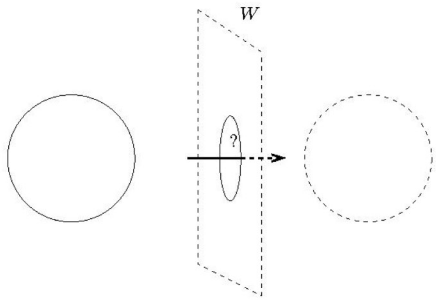



FIGURE 2.3. Can the ball go through the hole?

[6]The name of this problem is a somewhat "in" joke, of the kind appreciated by many mathematicians. The reference is to the saying that it would be easier for a camel to go through the eye of needle than for a rich man to get into heaven. (This saying is probably a mistranslation of a sentence in the bible.)

$$M^T \sigma^{4D} M = \begin{pmatrix} \epsilon_1 & 0 & 0 & 0 \\ 0 & \epsilon_1 & 0 & 0 \\ 0 & 0 & \epsilon_2 & 0 \\ 0 & 0 & 0 & \epsilon_2 \end{pmatrix}$$

$$\epsilon_1 = \frac{1}{2}\sqrt{-\mathrm{tr}[(\Sigma^{4D}J)^2] + \sqrt{\mathrm{tr}^2[(\Sigma^{4D}J)^2] - 16\det(\Sigma^{4D})}}$$

$$\epsilon_2 = \frac{1}{2}\sqrt{-\mathrm{tr}[(\Sigma^{4D}J)^2] - \sqrt{\mathrm{tr}^2[(\Sigma^{4D}J)^2] - 16\det(\Sigma^{4D})}}$$

[7] B. Carlsten, PRSTAB, 14, 050706 (2011)

# Skew Quadrupoles-Based FBT

- Flat beam transform strategy:
  - Make one eigenemittance small
  - Retrieve it as projected emittance
- Add angular momentum
  - Beam born into magnetic field
- Skew quadrupole triplet can be tuned to remove angular momentum

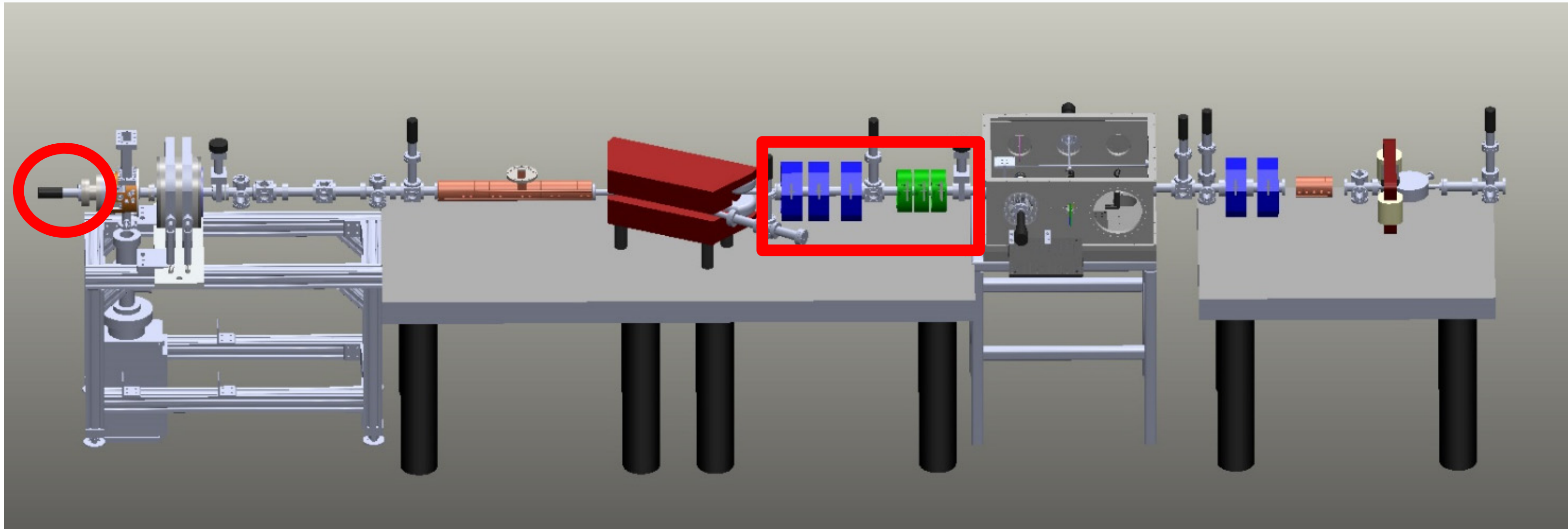
$$\sigma^{4D} = \begin{pmatrix} \sigma_c & 0 & 0 & \mathcal{L} \\ 0 & \sigma_{x'x'} & -\mathcal{L} & 0 \\ 0 & -\mathcal{L} & \sigma_c & 0 \\ \mathcal{L} & 0 & 0 & \sigma_{y'y'} \end{pmatrix}$$

$$\epsilon_{\pm} = \sqrt{\epsilon_u^2 + L^2} \pm L = \epsilon_{eff} \pm L \qquad \epsilon_u = \sqrt{\frac{MTE}{mc^2}\sigma_c^2} \qquad L = \frac{eB_c}{2mc}\sigma_c^2$$

$$\epsilon_- \approx \frac{MTE}{eB_c c} \qquad \epsilon_+ \approx 2L + \epsilon_-$$

$\epsilon_{\pm}$: large and small eigenemittances
$B_c$: magnetic field on cathode
$\sigma_c$: electron spot size at cathode

# Flat Beam at Pegasus



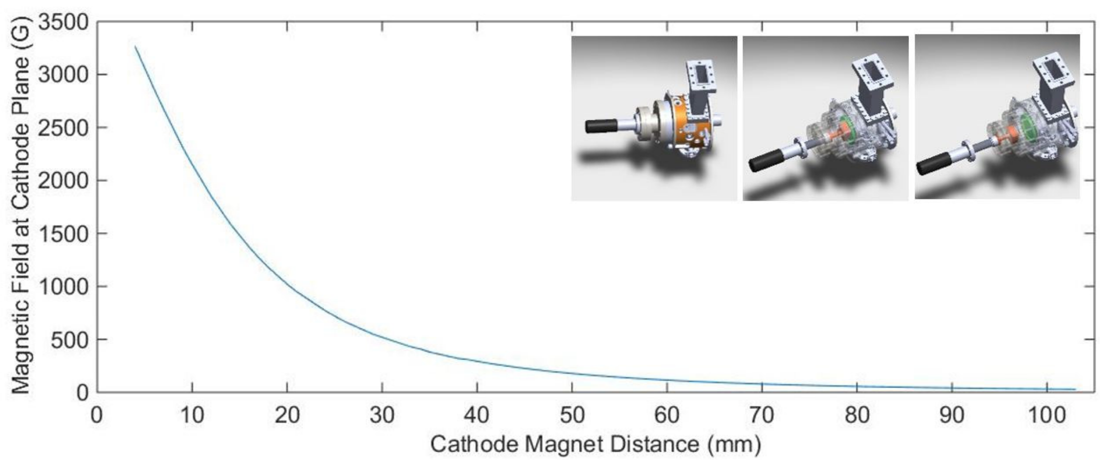
**Pegasus General Information**

1.6 cell RF photoinjector

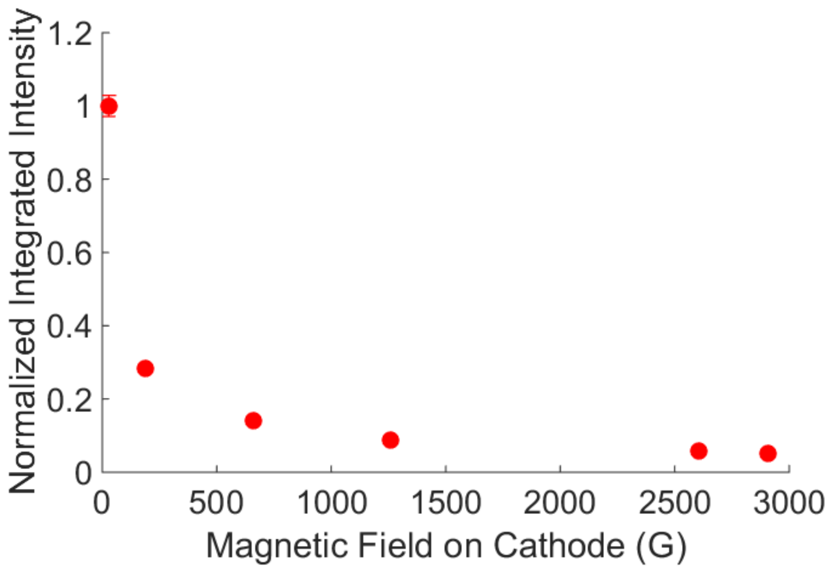
Beam energies of up to 12 MeV

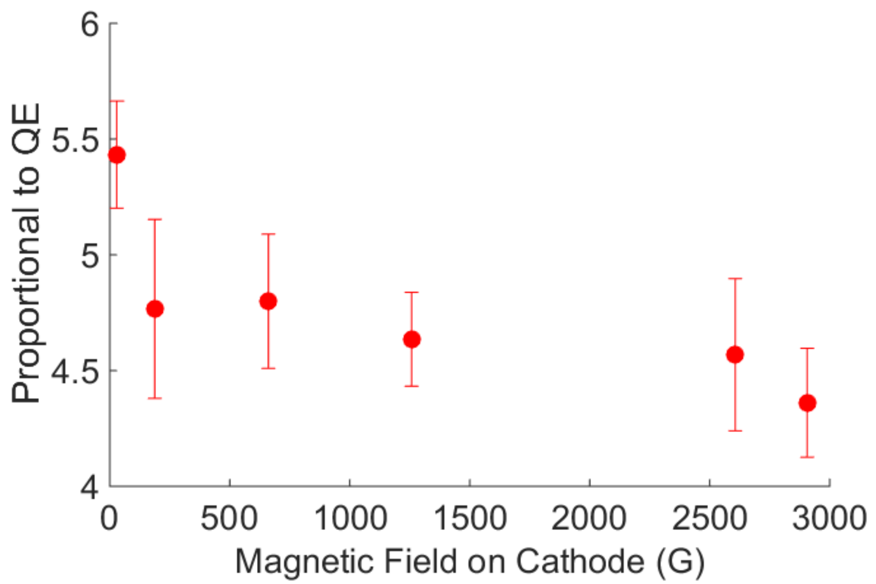
Generally, for flat beam experiment, run around 3.5 MeV

100 fs bunch length



# Effect of Magnetized Cathode




- Dark current decreases rapidly with magnetic field on cathode
- QE also decreases by ~20%
  - Possible explanations related to dark current

# Skew Quadrupole Optimization

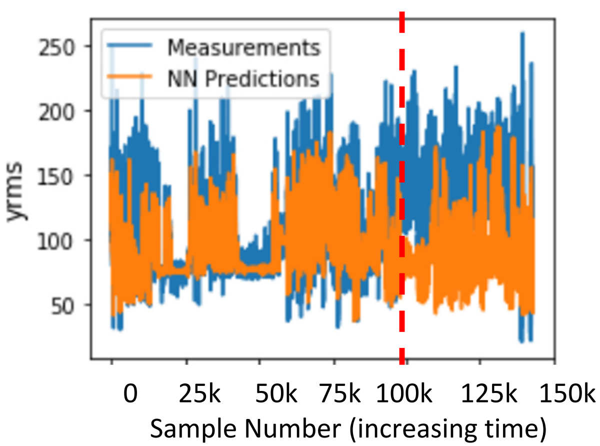
## Manual Optimization

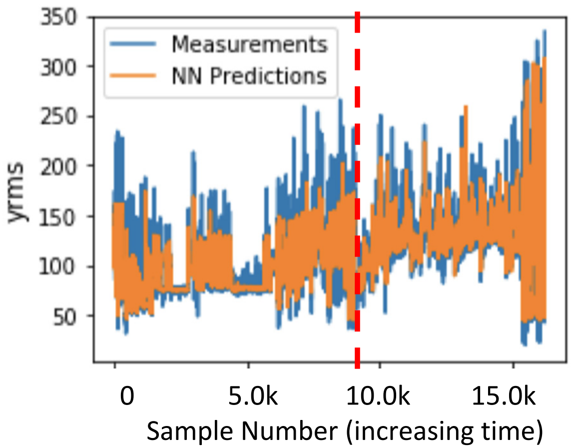
- Maximized up-right aspect ratio on screen downstream
- After focus upstream
- Based on results in particle tracking simulations

## Machine Learning

- Machine model able to tune quad gradients with same efficacy as manual tuning
- Model very consistent within a day
- Somewhat consistent day-to-day

Collaboration with SLAC NATIONAL ACCELERATOR LABORATORY

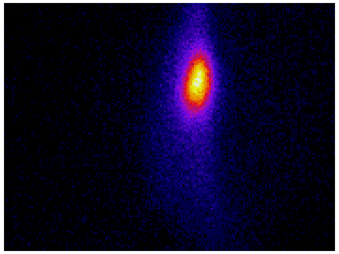


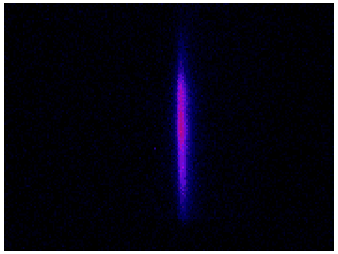

Neural network (NN) predictions of spot size measurements. Data after red line was taken on a new day.

Left: NN was trained only on data from before the red dashed line. Right: NN was trained on data from all days.

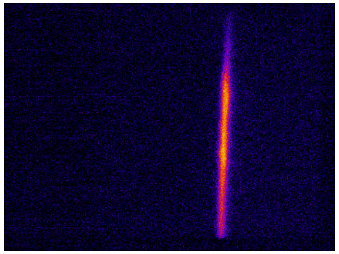
# Flat Beam First Evidence



Screen 9.2cm from third skew quad



Screen 70.2cm from third skew quad



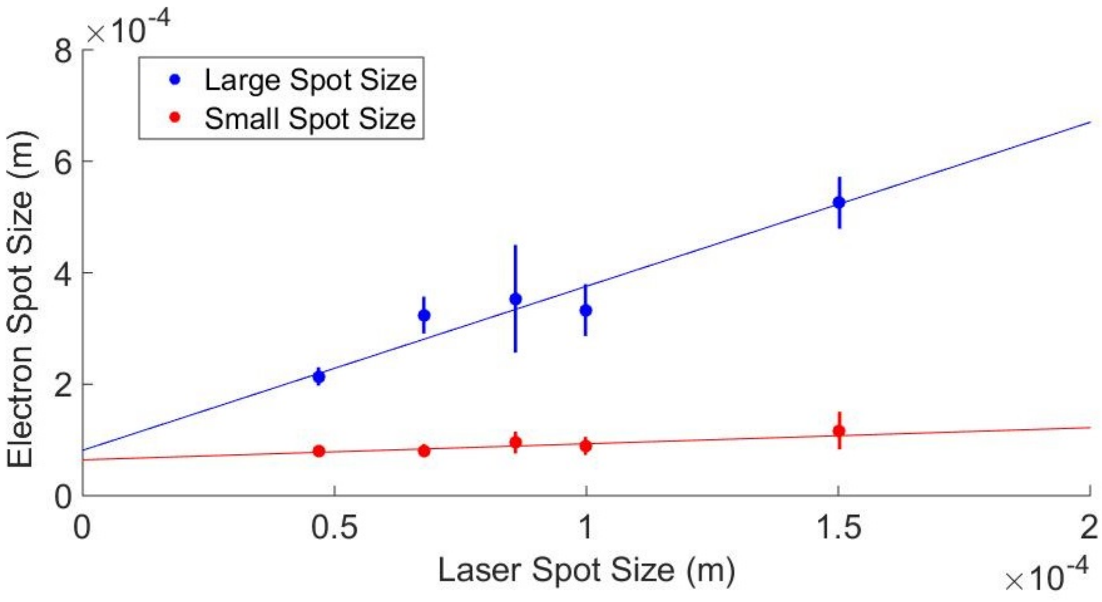
Screen 144.6cm from third skew quad

For angular momentum dominated beam

$$\epsilon_+ \sim \sigma_c^2$$

$$\epsilon_- \approx \frac{MTE}{eB_c c}$$

$$\sigma_f \sim \sqrt{\epsilon}$$



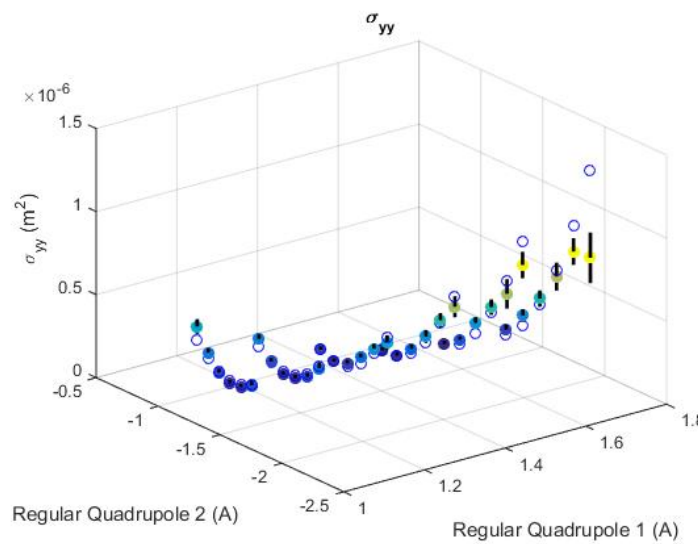
# Two Quadrupole Magnet Scans

- Following Prat and Aiba (2014) [8]

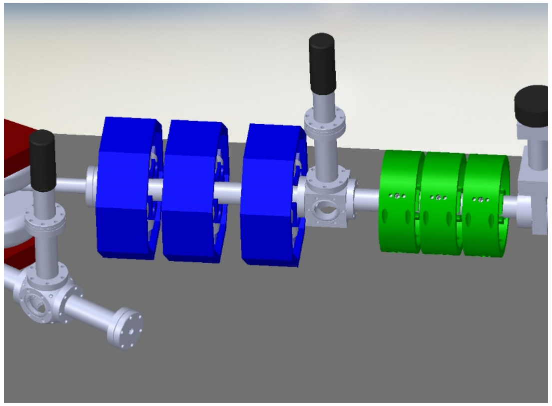
$$\langle x^2\rangle_s = R_{11}^2\langle x^2\rangle_{s_0} + R_{12}^2\langle x'^2\rangle_{s_0} + 2R_{11}R_{12}\langle xx'\rangle_{s_0},$$

$$\langle y^2\rangle_s = R_{33}^2\langle y^2\rangle_{s_0} + R_{34}^2\langle y'^2\rangle_{s_0} + 2R_{33}R_{34}\langle yy'\rangle_{s_0},$$

$$\langle xy\rangle_s = R_{11}R_{33}\langle xy\rangle_{s_0} + R_{12}R_{33}\langle x'y\rangle_{s_0} + R_{11}R_{34}\langle xy'\rangle_{s_0} + R_{12}R_{34}\langle x'y'\rangle_{s_0}.$$




$$\langle xy\rangle = \frac{-2\langle x^2\rangle_{45}+\langle x^2\rangle+\langle y^2\rangle}{2} = \frac{+2\langle y^2\rangle_{45}-\langle x^2\rangle-\langle y^2\rangle}{2}$$

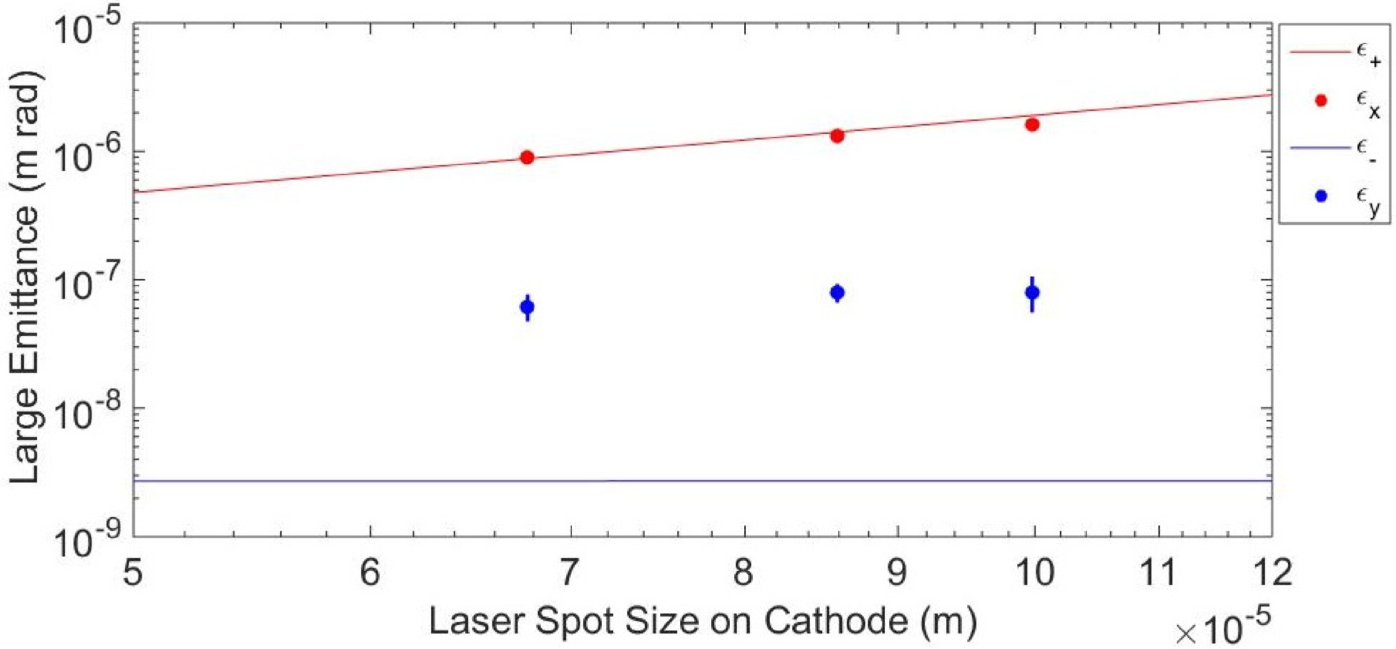


- Can fit the remaining terms with a sufficient number of shots

[8] Phys. Rev. ST Accel. Beams **17**, 052801, 2014

# Preliminary Fitted Emittances

- Large emittance scales as initial spot size squared
- Small emittance approximately constant
  - Smaller than thermal emittance of equivalent round beam (i.e. 80 nm with 100 um rms spot size on cathode)
  - Emittance Ratio >20
  - Small emittance an order of magnitude larger than expected



# Single Shot Emittance Measurement

- Theory:

$$\langle x^2 \rangle = \frac{\sum_{ij} I_{ij} x_{ij}^2}{\sum_{ij} I_{ij}},$$

$$\langle xx' \rangle = \frac{\sum_{ij} I_{ij} x_{ij} \bar{x'}_{ij}}{\sum_{ij} I_{ij}},$$

$$\langle x'^2 \rangle = \frac{\sum_{ij} I_{ij} (\bar{x'}^2_{ij} + \sigma^2_{x'_{ij}})}{\sum_{ij} I_{ij}},$$

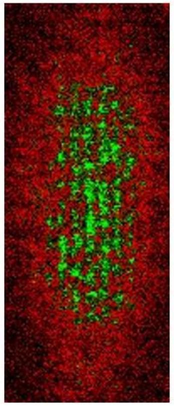
$$\langle xy \rangle = \frac{\sum_{ij} I_{ij} x_{ij} y_{ij}}{\sum_{ij} I_{ij}},$$

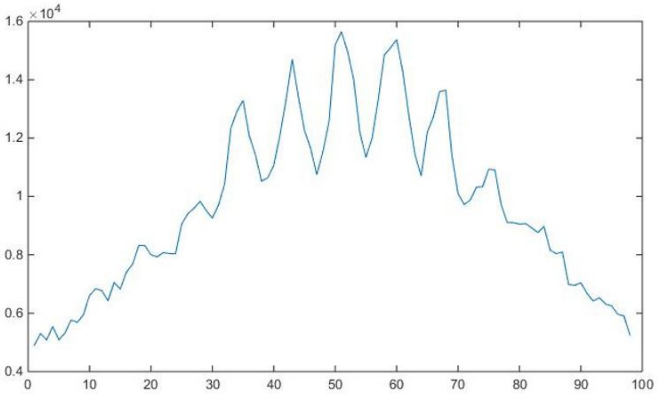
$$\langle xy' \rangle = \frac{\sum_{ij} I_{ij} x_{ij} \bar{y'}_{ij}}{\sum_{ij} I_{ij}},$$

$$\langle x'y \rangle = \frac{\sum_{ij} I_{ij} \bar{x'}_{ij} y_{ij}}{\sum_{ij} I_{ij}},$$

$$\langle x'y' \rangle = \frac{\sum_{ij} I_{ij} (\bar{x'}_{ij} \bar{y'}_{ij} + \sigma^2_{x'y'_{ij}})}{\sum_{ij} I_{ij}},$$

- TEM grids
- In progress: current status
  - Similar to quad scan
  - Smaller than cathode emittance of equivalent round beam
- Geometry of grids/pepper pots will preclude full 4-D reconstruction
- Small emittance still larger than expected

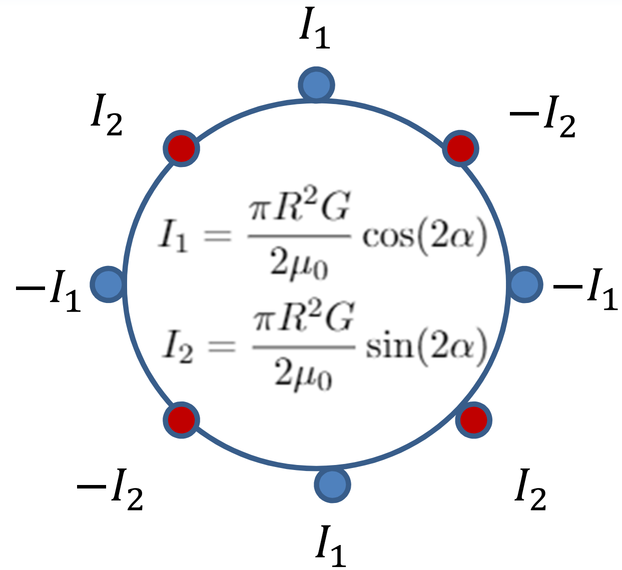


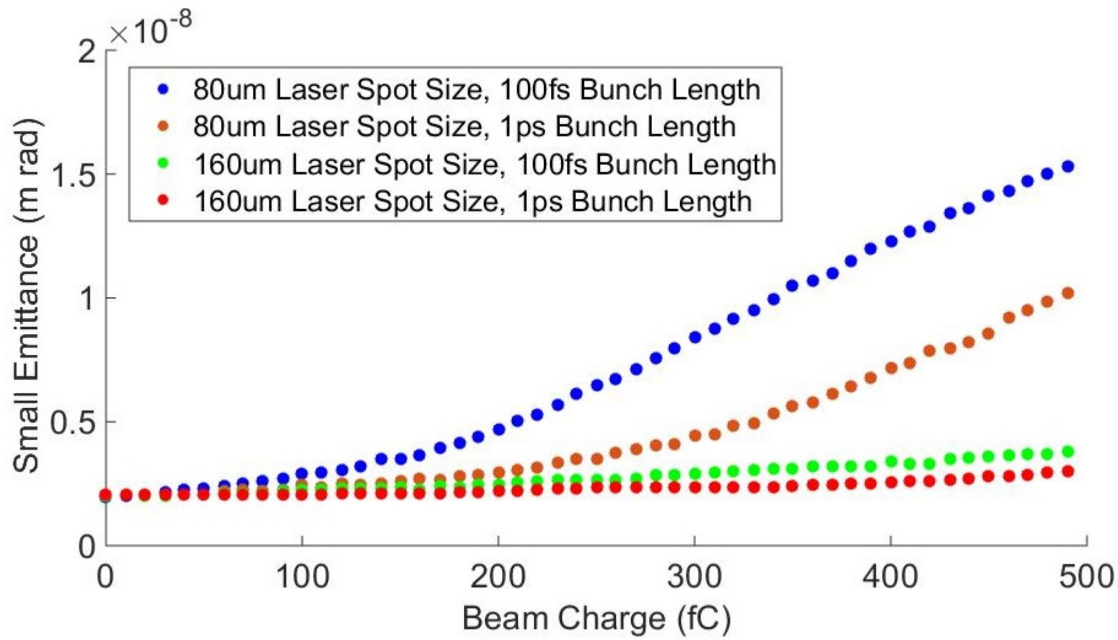



[9] M. Zhang, Report No. FERMILAB-TM-1988, 1996.
[10] D. Marx, J. Giner Navarro, D. Cesar, J. Maxson, B. Marchetti, R. Assmann, and P. Musumeci Phys. Rev. Accel. Beams 21, 102802, 2018

# Small Emittance Measurement

- Possible explanations:
  - Extraneous quadrupole
  - Measurement Limitations
    - Quad Scans
    - TEM Grids
  - And others…



# Conclusion

- Flat beam transform theory and motivation
- Hardware considerations
- Optimization
  - Manual
  - Machine learning
- Flat beam verification
  - Three screen measurement
  - Spot sizes
- Effect of Magnetized Cathode
- Measurement
  - Quadrupole scans
  - TEM grid-based measurement
- Future work
  - Removing extraneous quadrupole moments
- Questions?

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# Extraneous Quadrupoles & Correction

- Simulations and preliminary measurements suggest that additional quadrupole moments exist in our beam
- Need to be cancelled to be able to obtain single nanometer emittances
- Two quadrupoles 45 degrees relative to each other make an arbitrarily rotated quadrupole.