Transverse Beam Emittance Measurements at the High Repetition Rate Linac (HRRL)

2012 Spring Seminar Class Presentation

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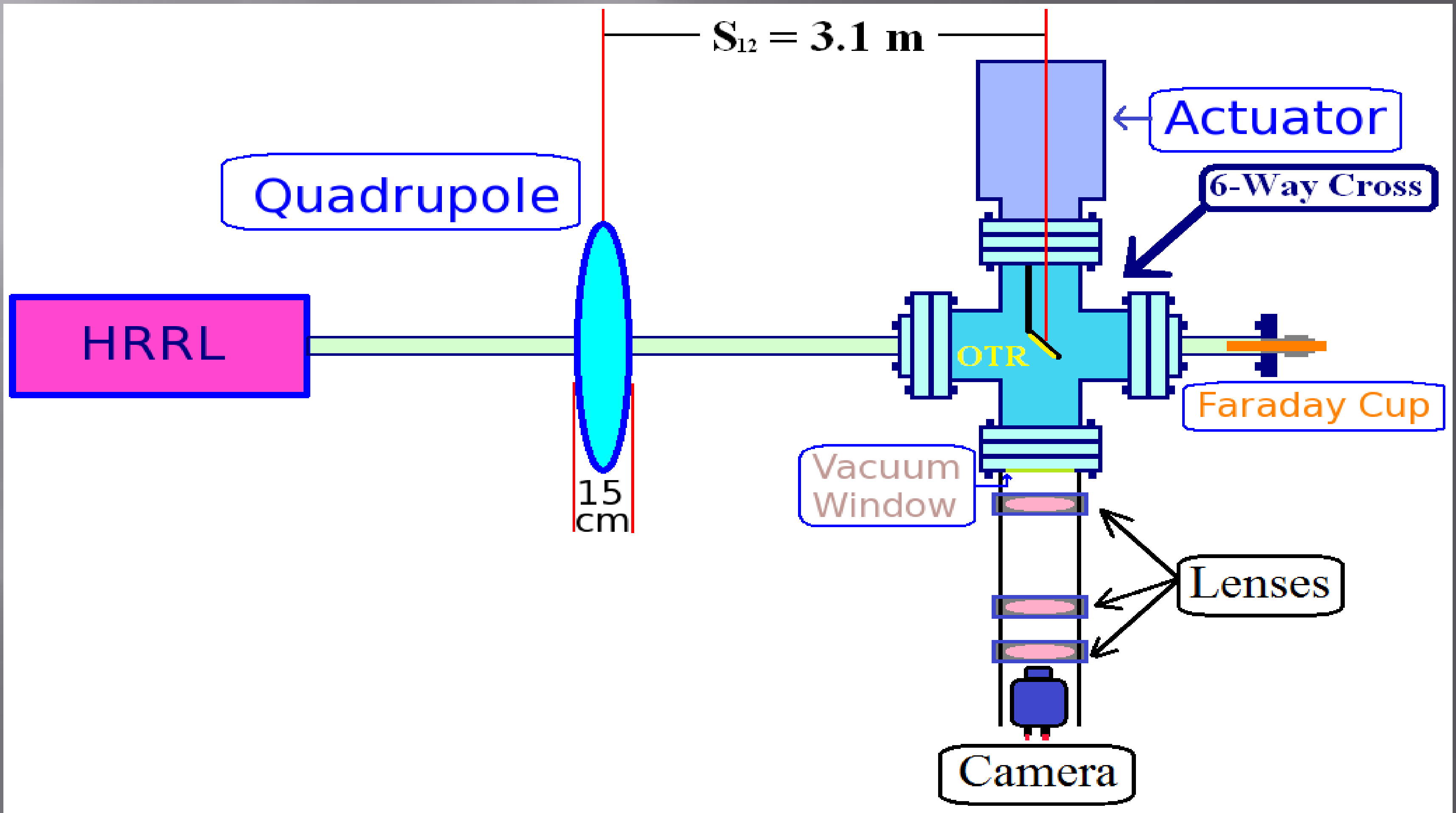
Motivation & Goals

- Optimize electron beam profile for users at the end of beamline
- To control the electron beam size and beam divergence on the positron converting target
- To compare simulations and measured results during the positron source generation.

Over view

Optical Transition Radiation (OTR): Transition radiation is emitted when a charge moving at a constant velocity cross a boundary between two materials (Al, vacuum) with different dielectric constant.

OTR is diagnostic tool to measure emittance, Twiss parameters . We can observe electron beam with OTR screen.



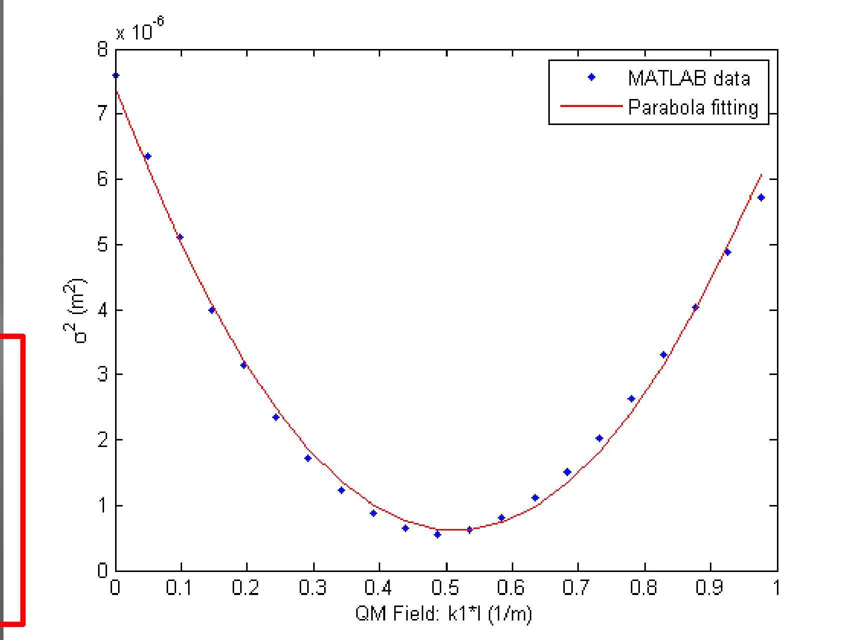
Theory of Quadrupole Scanning

Beam size at the screen relation to the quadrupole strength and effective length:

$$\sigma_{screen,11} = \sigma^2_{screen,x} = A(kL - B)^2 + C = A(kL)^2 - 2AB(kL) + (C + AB^2)$$

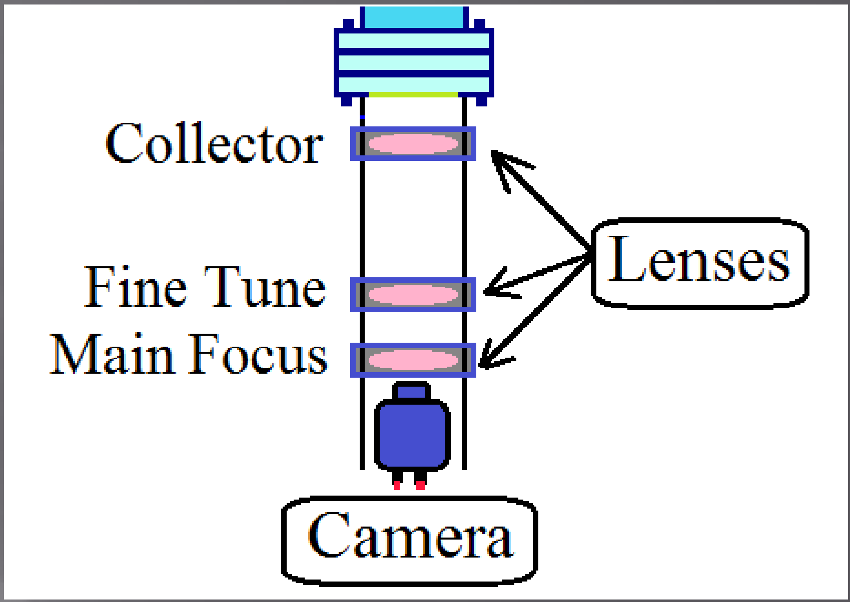
By varying quadrupole magnetic field strength *kL*, we can change beam size on the OTR screen. We make projection to the *x*, *y* axes, then fit them with Gaussian fittings to extract rms values, then plot σ^2 vs. *kL* and fit parabola to find *A*, *B*, and *C*. Then, we can get emittance.

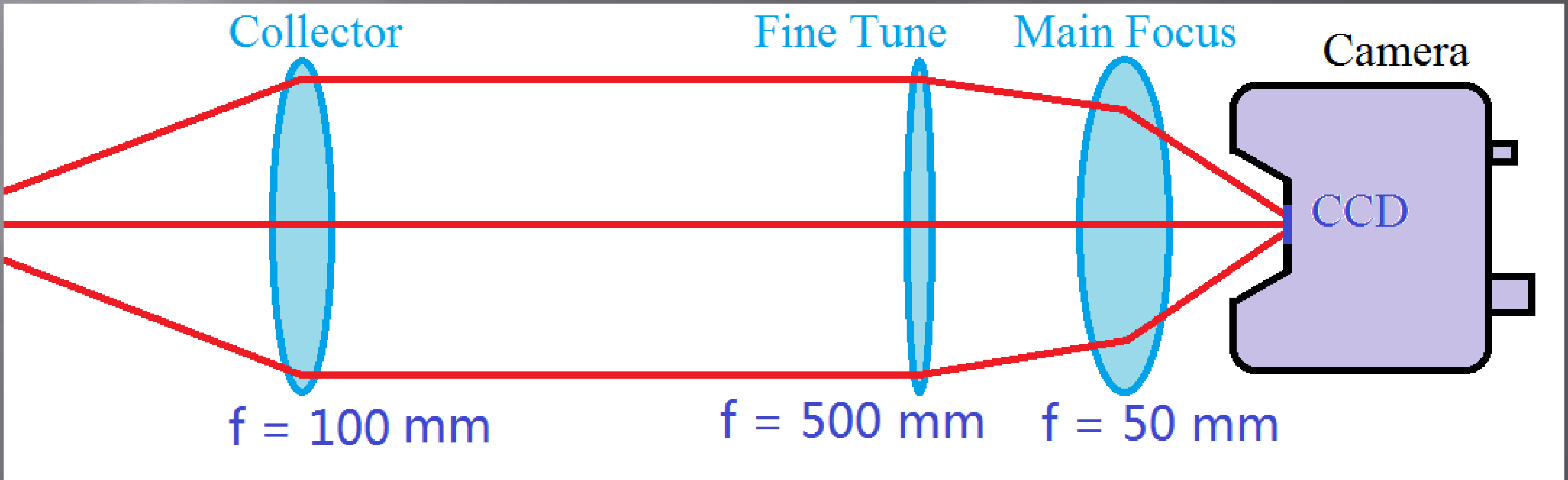
$$\varepsilon = \sqrt{AC}, \quad \beta = \sqrt{\frac{A}{C}}, \quad \alpha = -B\sqrt{\frac{A}{C}}, \quad \gamma = \frac{1 + \frac{A}{C}B^2}{\sqrt{\frac{A}{C}}}$$



Equipments and setup

- OTR light comes out with $4/\gamma$ angle.
- Collector lens: has the middle focal length, collects most of the light from the source.
- Fine Tune lens: has the biggest focal length, act as fine tune of magnification.
- Main Focus Lens: has the smallest focal length, has biggest focusing strength, so act as main focus of light and focuses light to CCD.



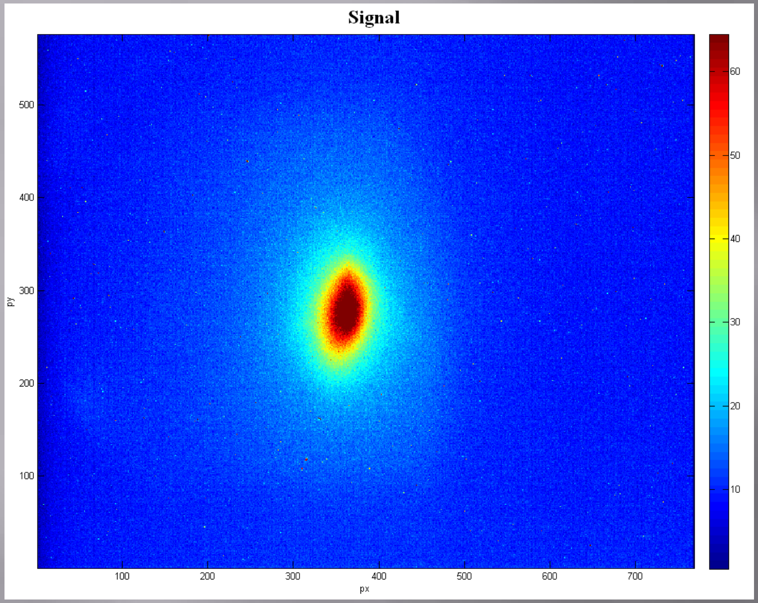


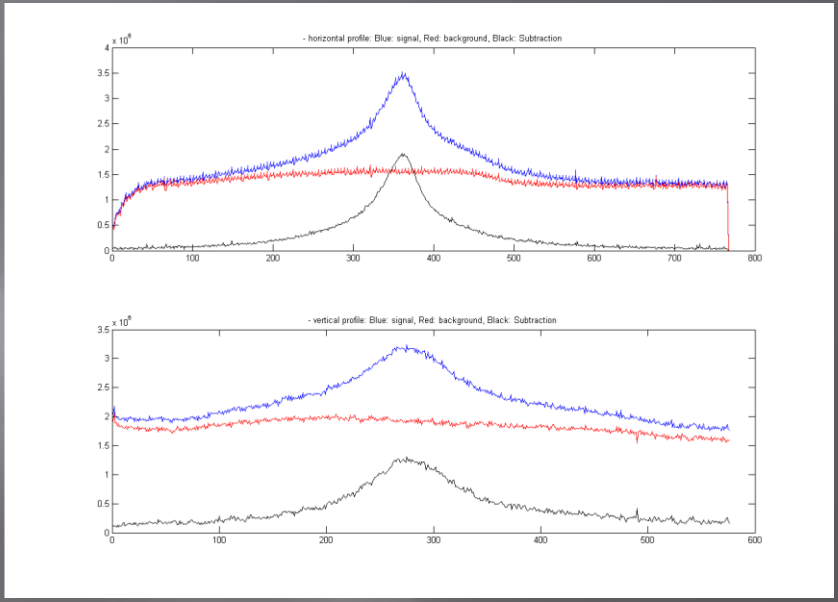
Tuning HRRL and Scanning

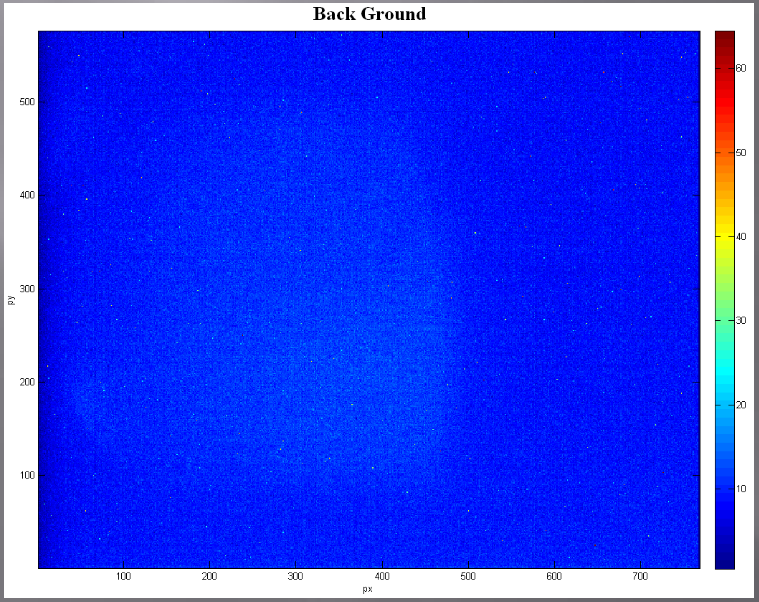
Scan Q1 from -5 Amp to 5 Amp in 51 steps, at 0.2 increments.

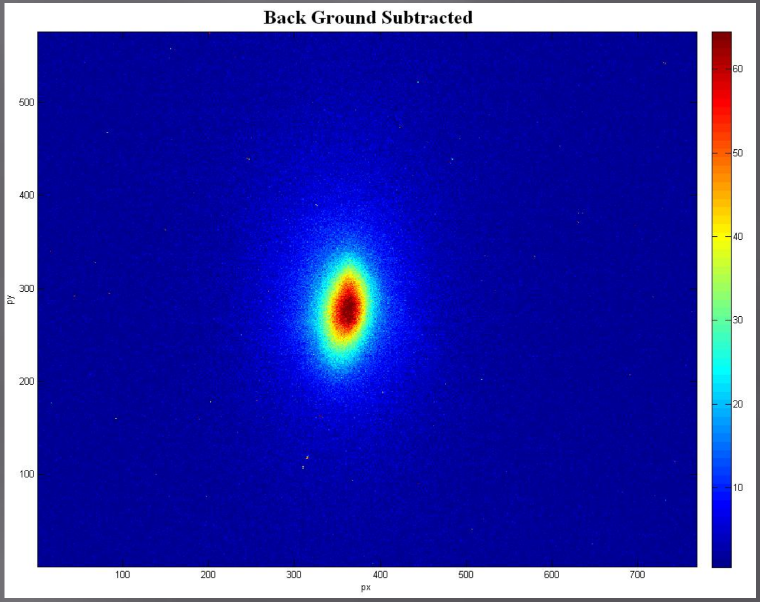
Data Analysis

Back Ground Subtraction:





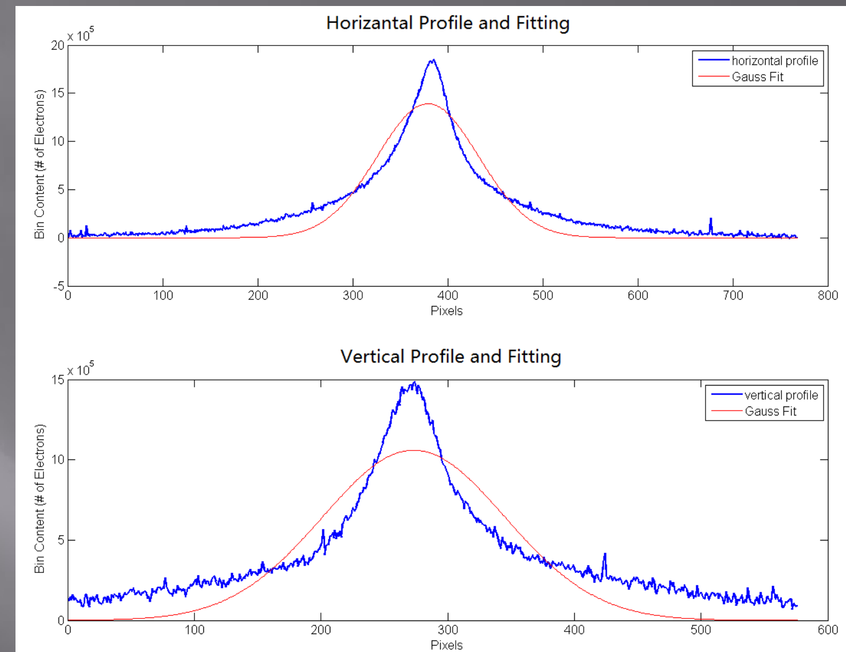


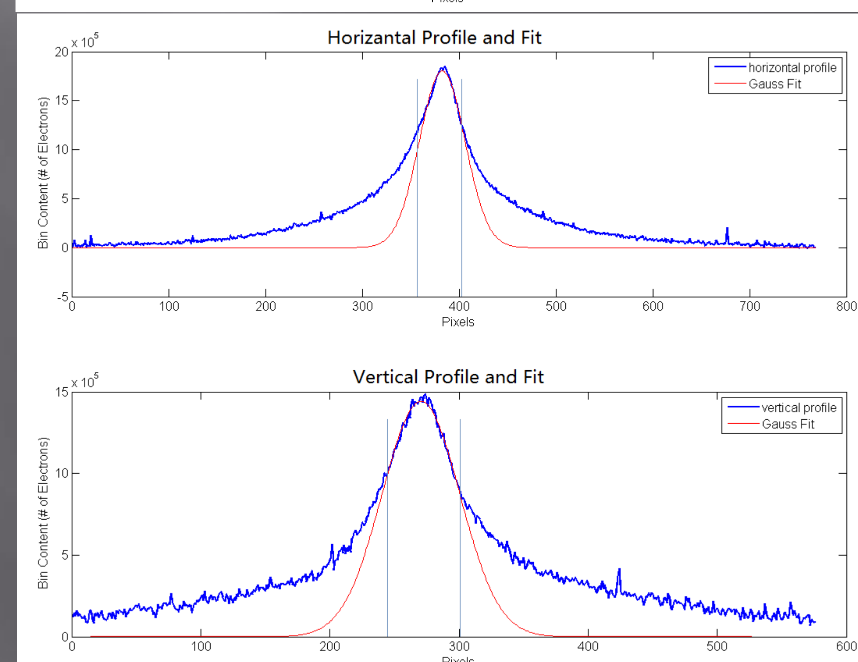


Data Analysis

Problem in Gaussian Fitting

- **Top image: fit for whole pixel area.**
- **Bottom image: fit for the pixel area of: x=[362,404], y=[241,301]**
- **Gaussian fit does not work well for our beam.**

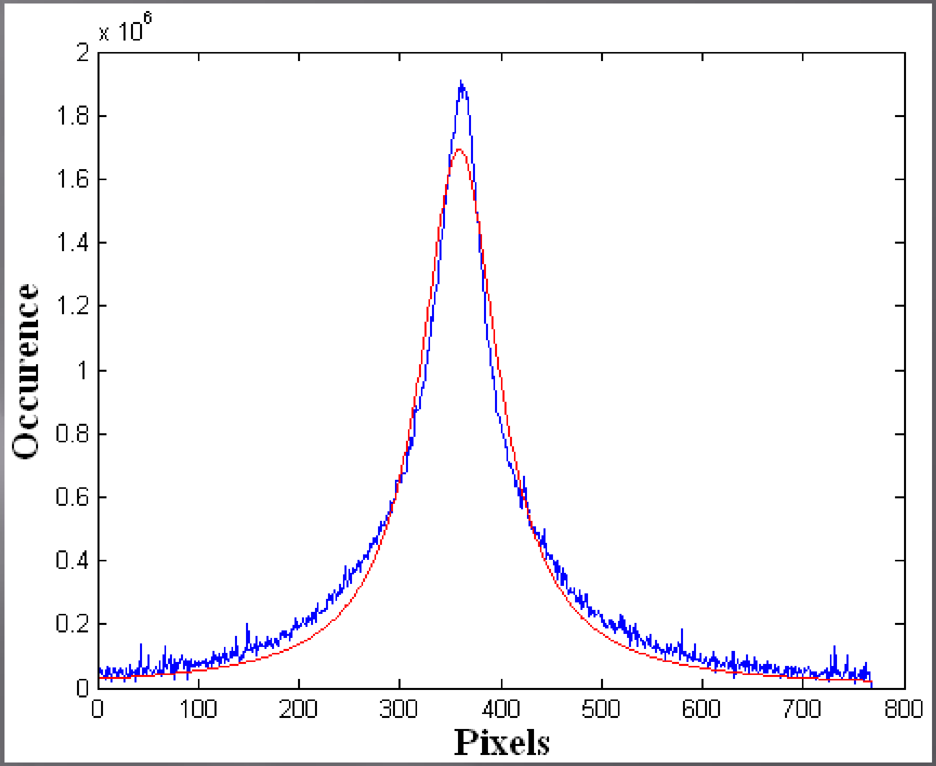




Data Analysis

Lorentzian Fitting:

- **Lorentzian fits better.**
- **RMS not defined for Lorentzian.**
- **Half-width at half-maximum (HWHM) is defined.**
- **HWHM = 45.428 px**



If we apply the relation between rms value of the Gaussian distribution and its FWHM to the Lorentzian distribution, we can roughly extract one sigma (or rms) of the Lorentzian distribution:

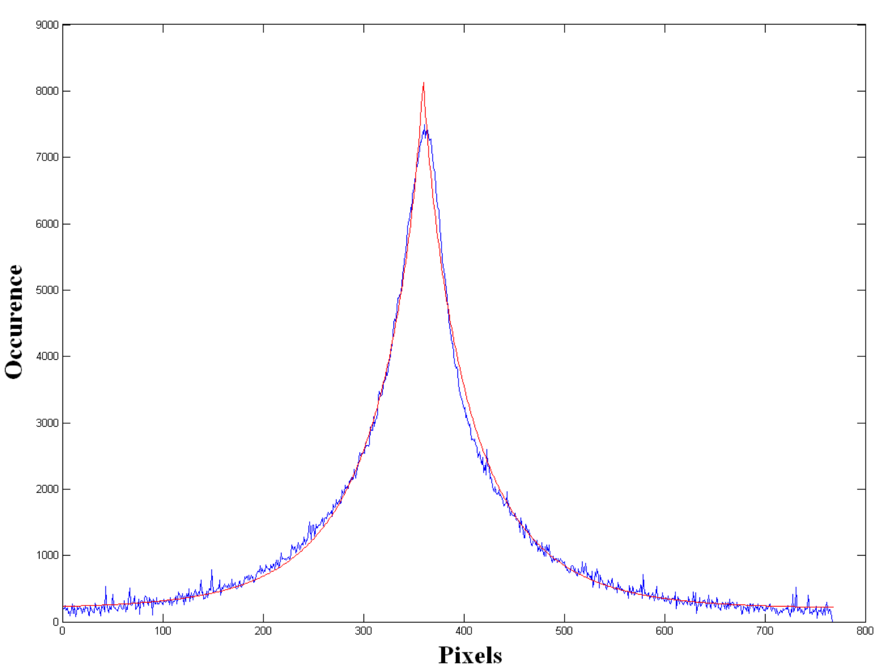
RMS ~ FWHM / 2.3548 = (2*HWHM) / 2.3548 = 38.58 px

Data Analysis

Super-Gaussian Fitting [1]:

$$g(x) = \frac{1}{\sqrt{2\pi}\sigma_0} \exp\left(\frac{-(\mathrm{abs}(x))^N}{2\sigma_0^N}\right) \quad \text{with} \quad \sigma = \sigma_0 \cdot \left(\frac{\pi}{2}\right)^{2/N-1} .$$

- **N = 2 → Normal Gaussian**
- **N < 2 → Super Gaussian**
- **N > 2 → Flat-top shape**
- **Our beams were fitted well with the Super-Gaussian distribution.**
- **σ = 38.56 px**



Super-Gaussian: σ = 38.56 px
Lorentzian: RMS = 38.58 px

Very Close

[1]: "Beam Distributions Beyond RMS", F.-J. Decker, Stanford Linear Accelerator Center, SLAC-PUB-6684, Sep 1994 (A)

Data Analysis

Q = 14.7 pC, E = 14 MeV, macro pulse length = 200 ns FWHM pulse

$$\sigma_x^{\,2} = (3.678 \pm 0.022) + (-4.17 \pm 0.22)k_1L + (5.55 \pm 0.42)(k_1L)^2$$

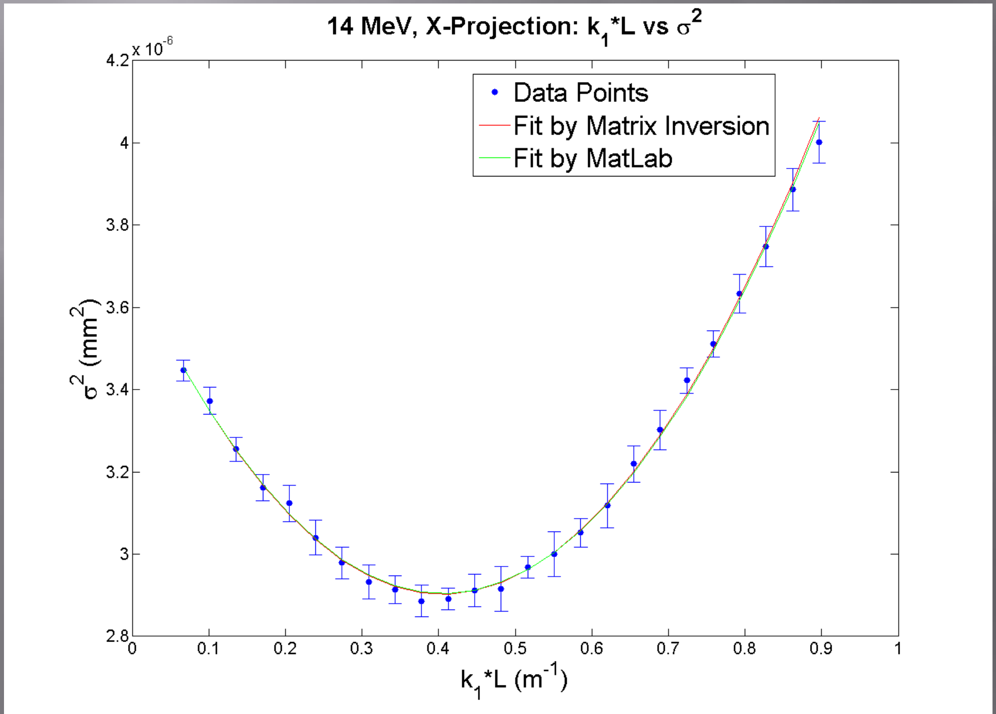
$$\sigma_y^{\,2} = (2.843 \pm 0.044) + (1.02 \pm 0.52)k_1L + (3.8 \pm 1.2)(k_1L)^2$$

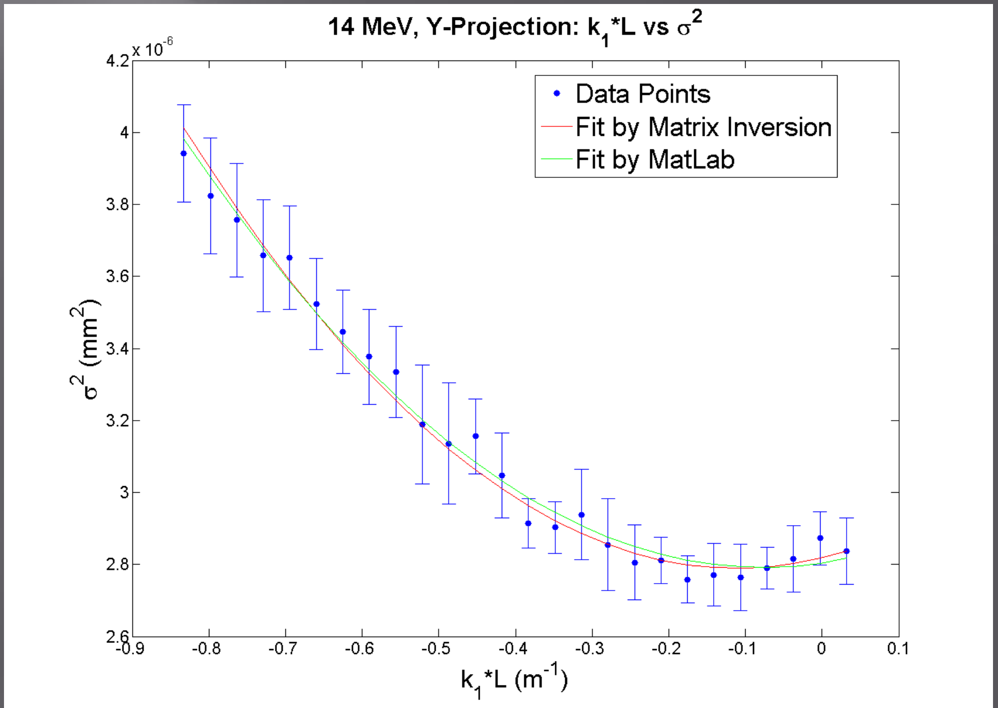
Positive scan, X-projection

- ε_x = 0.417 ± 0.023 μm
- ε_{nx} = 11.43 ± 0.64 μm
- β_x = 1.39 ± 0.07 m
- α_x = 0.97 ± 0.07 rad

Positive scan, Y-projection

- ε_y = 0.338 ± 0.065 μm
- ε_{ny} = 9.30 ± 1.8 μm
- β_y = 1.17 ± 0.19 m
- α_y = 0.22 ± 0.10 rad





Thanks for listening !

Questions ?

Suggestions ?

Outline

- Motivation
- Term Project Goals
- Layout of the HRRL Linear Accelerator
- Quadrupole Scanning based Emittance Measurement
- Steps for Emittance Measurements, Equipments, and Setup
- Tuning of the HRRL Linac for the Quadrupole Scanning
- Data Acquisition and Analysis
- Measured Emittance
- Conclusions

Steps for Emittance Measurements

- Installation of Imaging System
- Alignment of Beampipe and Beam Trajectory
- Tuning of the HRRL linac to deliver the max charge to Faraday Cup (FC).
- Optimization of the HRRL linac to generate high quality electron beam
- Data Acquisition and Analysis
- Estimation of emittance and Twiss Parameters

Theory of Quadrupole Magnet Scanning

Transfer matrix of a quadrupole magnet under thin lens approximation:

$$\mathbf{Q} = \begin{pmatrix} 1 & 0 \\ -kL & 1 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix}$$

Here $kl > 0$ for x-plane, and $kl < 0$ for y-plane.

Transfer matrix of a drift space between quadrupole and screen:

$$\mathbf{S} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} = \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix}$$

Transfer matrix of the scanned region is:

$$\mathbf{M} = \mathbf{S}\,\mathbf{Q} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -kL & 1 \end{pmatrix} = \begin{pmatrix} S_{11} - kLS_{12} & S_{12} \\ S_{21} - kLS_{22} & S_{22} \end{pmatrix}$$

Theory of Quadrupole Magnet Scanning

$$\mathbf{M} = \mathbf{S}\mathbf{Q} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -kL & 1 \end{pmatrix} = \begin{pmatrix} S_{11} - kLS_{12} & S_{12} \\ S_{21} - kLS_{22} & S_{22} \end{pmatrix}$$

M is related with the beam matrix σ as:

$$\sigma_{\text{screen}} = \mathbf{M}\sigma_{\text{quad}}\mathbf{M}^{\text{T}} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \begin{pmatrix} \sigma_{quad11} & \sigma_{quad12} \\ \sigma_{quad21} & \sigma_{quad22} \end{pmatrix} \begin{pmatrix} m_{11} & m_{21} \\ m_{12} & m_{22} \end{pmatrix}$$

Since:

$$\sigma_x = \sqrt{\varepsilon_x \beta}, \sigma_{x'} = \sqrt{\varepsilon_x \gamma}, \sigma_{xx'} = -\varepsilon_x \alpha$$

$$\sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{pmatrix} = \begin{pmatrix} \sigma_x^2 & \sigma_{xx'} \\ \sigma_{xx'} & \sigma_{x'}^2 \end{pmatrix}$$

σ matrix can be written:

$$\boxed{\sigma_{quad} = \begin{pmatrix} \sigma_{quad,x} & \sigma_{quad,xx'} \\ \sigma_{quad,xx'} & \sigma_{quad,x'} \end{pmatrix} = \varepsilon_{rms,x} \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}}$$

Theory of Quadrupole Magnet Scanning

$$\sigma_{quad} = \begin{pmatrix} \sigma_{quad,x} & \sigma_{quad,xx'} \\ \sigma_{quad,xx'} & \sigma_{quad,x'} \end{pmatrix} = \varepsilon_{rms,x} \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}$$

$$\sigma_{screen} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \varepsilon_{rms,x} \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix} \begin{pmatrix} m_{11} & m_{21} \\ m_{12} & m_{22} \end{pmatrix}$$

Drop off subscript "rms" on emittace.

$$\sigma_{screen11} = \sigma^2_{screen,x} = \varepsilon_x \left(m_{11}^2 \beta - 2 m_{12} m_{11} \alpha + m_{12}^2 \gamma \right)$$

Using σ matrix relations:

$$\varepsilon\beta = \sigma_{11}, \varepsilon\alpha = -\sigma_{12}, \varepsilon\gamma = \varepsilon \frac{1+\alpha^2}{\beta} = \frac{\varepsilon^2}{\varepsilon} \frac{1+\alpha^2}{\beta} = \frac{\varepsilon^2 + \sigma_{12}^2}{\sigma_{11}}$$

$$\sigma^2_{screen,x} = m_{11}^2 \sigma_{11} + 2 m_{12} m_{11} \sigma_{12} + m_{12}^2 \frac{\varepsilon_x^2 + \sigma_{12}^2}{\sigma_{11}}$$

Theory of Quadrupole Magnet Scanning

$$\sigma^2_{screen,x} = m_{11}^2\sigma_{11} + 2m_{12}m_{11}\sigma_{12} + m_{12}^2\frac{\varepsilon_x^2 + \sigma_{12}^2}{\sigma_{11}}$$

$$= \left(m_{11}^2\sigma_{11} + 2m_{12}m_{11}\sigma_{12} + m_{12}^2\frac{\sigma_{12}^2}{\sigma_{11}}\right) + m_{12}^2\frac{\varepsilon_x^2}{\sigma_{11}}$$

$$= \sigma_{11}\left(m_{11}^2 + 2m_{12}m_{11}\frac{\sigma_{12}}{\sigma_{11}} + m_{12}^2\frac{\sigma_{12}^2}{\sigma_{11}^2}\right) + m_{12}^2\frac{\varepsilon_x^2}{\sigma_{11}}$$

$$= \sigma_{11}\left(m_{11} + m_{12}\frac{\sigma_{12}}{\sigma_{11}}\right)^2 + m_{12}^2\frac{\varepsilon_x^2}{\sigma_{11}}$$

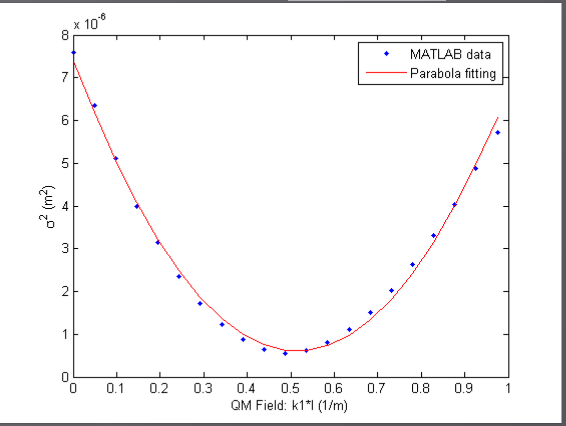
Remember: $m_{11} = S_{11} - kLS_{12}$ $\quad m_{12} = S_{12}$

$$\sigma^2_{screen,x} = \sigma_{11}\left((S_{11} - kLS_{12}) + S_{12}\frac{\sigma_{12}}{\sigma_{11}}\right)^2 + S_{12}^2\frac{\varepsilon_x^2}{\sigma_{11}}$$

$$\sigma^2_{screen,x} = \sigma_{11}S_{12}^2\left(kL - \left(\frac{S_{11}}{S_{12}} + \frac{\sigma_{12}}{\sigma_{11}}\right)\right)^2 + S_{12}^2\frac{\varepsilon_x^2}{\sigma_{11}}$$

Theory of Quadrupole Magnet Scanning

$$\sigma^2_{screen,x} = \sigma_{11} S_{12}^2 \left(kL - \left(\frac{S_{11}}{S_{12}} + \frac{\sigma_{12}}{\sigma_{11}} \right) \right)^2 + S_{12}^2 \frac{\varepsilon_x^2}{\sigma_{11}}$$



Introducing constants A, B and C:

$$A = \sigma_{11} S_{12}^2, \quad B = \left(\frac{S_{11}}{S_{12}} + \frac{\sigma_{12}}{\sigma_{11}} \right), \quad C = S_{12}^2 \frac{\varepsilon_x^2}{\sigma_{11}}.$$

$$\boxed{\sigma_{screen,11} = \sigma^2_{screen,x} = A(kL - B)^2 + C = A(kL)^2 - 2AB(kL) + (C + AB^2)}$$

$$\varepsilon_x^2 = \frac{C\sigma_{11}}{S_{12}^2} = \frac{C\sigma_{11} S_{12}^2}{S_{12}^4} = \frac{AC}{S_{12}^4}$$

$$\boxed{\varepsilon = \frac{\sqrt{AC}}{S_{12}^2}}$$

By varying quadrupole magnetic field strength k1, we can change beam size on the OTR screen ($\sigma^2_{screen,x}$). We make projection to the *x*, *y* axes, then fit them with Gaussian fittings to extract rms values, then plot σ^2 vs k1L and fit parabola to find *A*, *B*, and *C*. Then, we can get emittance.

Data Analysis

- Diameter! 1/2” progressive scan camera
- Monochrome and Bayer color versions
- 782 (h) x 582 (v) 8.37 µm square pixels
- 60 fps with full resolution
- 250 fps with 1/8 partial scan
- Vertical binning (CV-A10GE) for higher frame rates and sensitivity
- High speed shutter from 1/60 to 1/300,000 second
- 8 or 10-bit output
- Edge pre-select, and pulse width trigger modes
- Auto shutter and smear-less mode
- Auto-Iris lens video output, auto shutter and AGC allow a wider light range
- Programmable GPIO module
- Comprehensive software suite and SDK (SDK Light) for Windows XP

$$\gamma = \frac{1 + \alpha^2}{\beta}, \quad \text{or} \quad \beta\gamma - \alpha^2 = 1.$$

$$\alpha = -\frac{1}{2}\beta'$$

Tuning HRRL and Scanning

- When we turned on the HRRL, we put the beam at the center of the screen by steerers. But the beam position on the screen was continuously steered during the quadrupole scanning, which was induced by the mis-steered orbit at the quadrupole.

- Looking at the beam position on the screen and by the beam current on FC, we tried to align beam line. The goal was to center the beam on the center of the screen, and maximize the FC charge as high as we can.

- To maximize the charge and to position the beam image at the center of the screen, the vacuum pipes and the first dipole were realigned.

- On March 16th, 2011, we reduced the mis-steering at the quadrupole by tuning steerers in the linac.

- On March 17th, 2011, we could optimize steerers, solenoids in linac to get a round electron beam shape and almost no steering at the quadrupole.

Theory of Quadrupole Scanning

Transfer matrix of a quadrupole magnet under thin lens approximation:

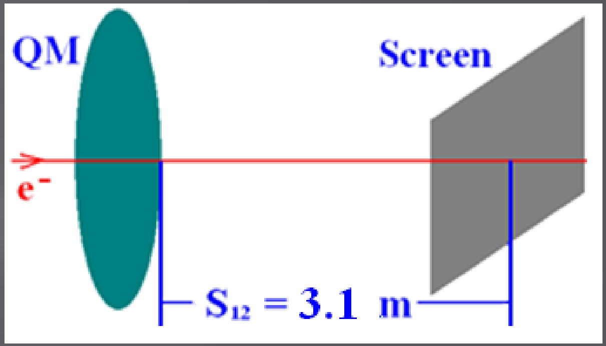
$$Q = \begin{pmatrix} 1 & 0 \\ -kL & 1 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix}$$

k is the quadrupole strength, L is quadrupole width, f is the focal length .

Here $kl > 0$ for x-plane, and $kl < 0$ for y-plane.

Transfer matrix of a drift space between quadrupole and screen:

$$S = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} = \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix}$$



l is distance between quadrupole magnet and screen.

Transfer matrix of the scanned region is:

$$M = SQ = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -kL & 1 \end{pmatrix} = \begin{pmatrix} S_{11} - kLS_{12} & S_{12} \\ S_{21} - kLS_{22} & S_{22} \end{pmatrix}$$

Theory of Quadrupole Scanning

Effective Length: The length of the magnet taken into consideration of the fringe of the quadrupole magnet.

In simple words: For different quadrupole current the fringe takes up different portion of the total B-field.

$$L_{effective} = \frac{\int_a^b \mathrm{B}dx}{L_{quad}}$$

L_{quad}: Quadrupole pole face width. Two integration ends "a" and "b" are far points where we start and end magnetic field mapping.