Transverse Beam Emittance Measurements at the HRRL Linac

Term Project for Linear Accelerator Physics Course

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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**

Motivation & Goals

- To figure out whether the HRRL linear accelerator can supply the sufficient electron beam quality to generate the positron source.
- To establish magnet lattices for the user services by measuring Twiss parameters
- 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.

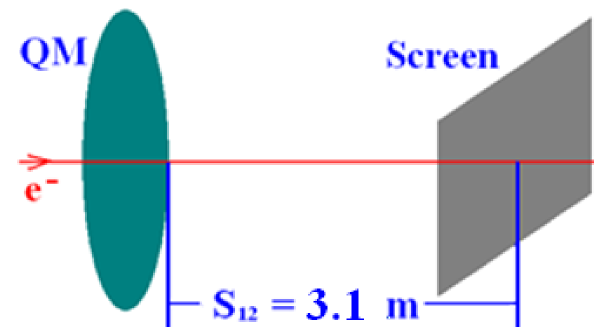
→ We want to measure the transverse beam emittance right after the HRRL linac.

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 Scanning

Transfer matrix of a quadrupole magnet:



$$Q = \begin{pmatrix} \cos\sqrt{k}L & \frac{1}{\sqrt{k}}\sin\sqrt{k}L \\ -\sqrt{k}\sin\sqrt{k}L & \cos\sqrt{k}L \end{pmatrix}$$

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

Transfer matrix of a drift space between quadrupole and screen:

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

Transfer matrix of the scanned region is:

$$M = SQ = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} \cos\sqrt{k}L & \frac{1}{\sqrt{k}}\sin\sqrt{k}L \\ -\sqrt{k}\sin\sqrt{k}L & \cos\sqrt{k}L \end{pmatrix}$$

$$= \begin{pmatrix} S_{11}\cos\sqrt{k}L - S_{12}\sqrt{k}\sin\sqrt{k}L & S_{11}\frac{1}{\sqrt{k}}\sin\sqrt{k}L + S_{12}\cos\sqrt{k}L \\ S_{21}\cos\sqrt{k}L - S_{22}\sqrt{k}\sin\sqrt{k}L & S_{21}\frac{1}{\sqrt{k}}\sin\sqrt{k}L + S_{22}\cos\sqrt{k}L \end{pmatrix}$$

Theory of Quadrupole Scanning

$$M=\begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22}\end{pmatrix}=\begin{pmatrix} S_{11}\cos\sqrt{k}L-S_{12}\sqrt{k}\sin\sqrt{k}L & S_{11}\frac{1}{\sqrt{k}}\sin\sqrt{k}L+S_{12}\cos\sqrt{k}L \\ S_{21}\cos\sqrt{k}L-S_{22}\sqrt{k}\sin\sqrt{k}L & S_{21}\frac{1}{\sqrt{k}}\sin\sqrt{k}L+S_{22}\cos\sqrt{k}L\end{pmatrix}$$

M is related with the beam matrix σ as:

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

Since:

$$\sigma_x=\sqrt{\varepsilon_x\beta_x},\ \sigma_{x'}=\sqrt{\varepsilon_x\gamma_x},\ \sigma_{xx'}=-\varepsilon_x\alpha_x$$

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

σ matrix can be written:

$$\boxed{\sigma_{quad,x}=\begin{pmatrix} \sigma_{quad,x} & \sigma_{quad,xx'} \\ \sigma_{quad,xx'} & \sigma_{quad,x'}\end{pmatrix}=\varepsilon_{rms,x}\begin{pmatrix} \beta_x & -\alpha_x \\ -\alpha_x & \gamma_x\end{pmatrix}}$$

Theory of Quadrupole Scanning

$$\sigma_{quad,x} = \begin{pmatrix} \sigma_{quad,x} & \sigma_{quad,xx'} \\ \sigma_{quad,xx'} & \sigma_{quad,x'} \end{pmatrix} = \varepsilon_{rms,x} \begin{pmatrix} \beta_x & -\alpha_x \\ -\alpha_x & \gamma_x \end{pmatrix}$$

$$\sigma_{screen,x} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \varepsilon_{rms,x} \begin{pmatrix} \beta_x & -\alpha_x \\ -\alpha_x & \gamma_x \end{pmatrix} \begin{pmatrix} m_{11} & m_{21} \\ m_{12} & m_{22} \end{pmatrix}$$

Drop off subscript "rms" on emittace and *x* in Twiss parameters.

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

Using σ matrix relations:

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

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

Theory of Quadrupole Scanning

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

$$= m_{11}^2\sigma_{11} + 2m_{12}m_{11}\sigma_{12} + m_{12}^2\frac{\sigma_{12}^2}{\sigma_{11}} + m_{12}^2\frac{\varepsilon_x^2}{\sigma_{11}}$$

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

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

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

Theory of Quadrupole Scanning

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

Remember:

$$m_{11} = S_{11}\cos\sqrt{k}L - S_{12}\sqrt{k}\sin\sqrt{k}L \qquad m_{12} = S_{11}\frac{1}{\sqrt{k}}\sin\sqrt{k}L + S_{12}\cos\sqrt{k}L$$

$$a = \sigma_{11},\ \ b = \frac{\sigma_{12}}{\sigma_{11}},\ c = \frac{\varepsilon^2}{\sigma_{11}}$$

$$\boxed{\sigma_{screen,x}^2 = a\left(m_{11} + bm_{12}\right)^2 + cm_{12}^2}$$

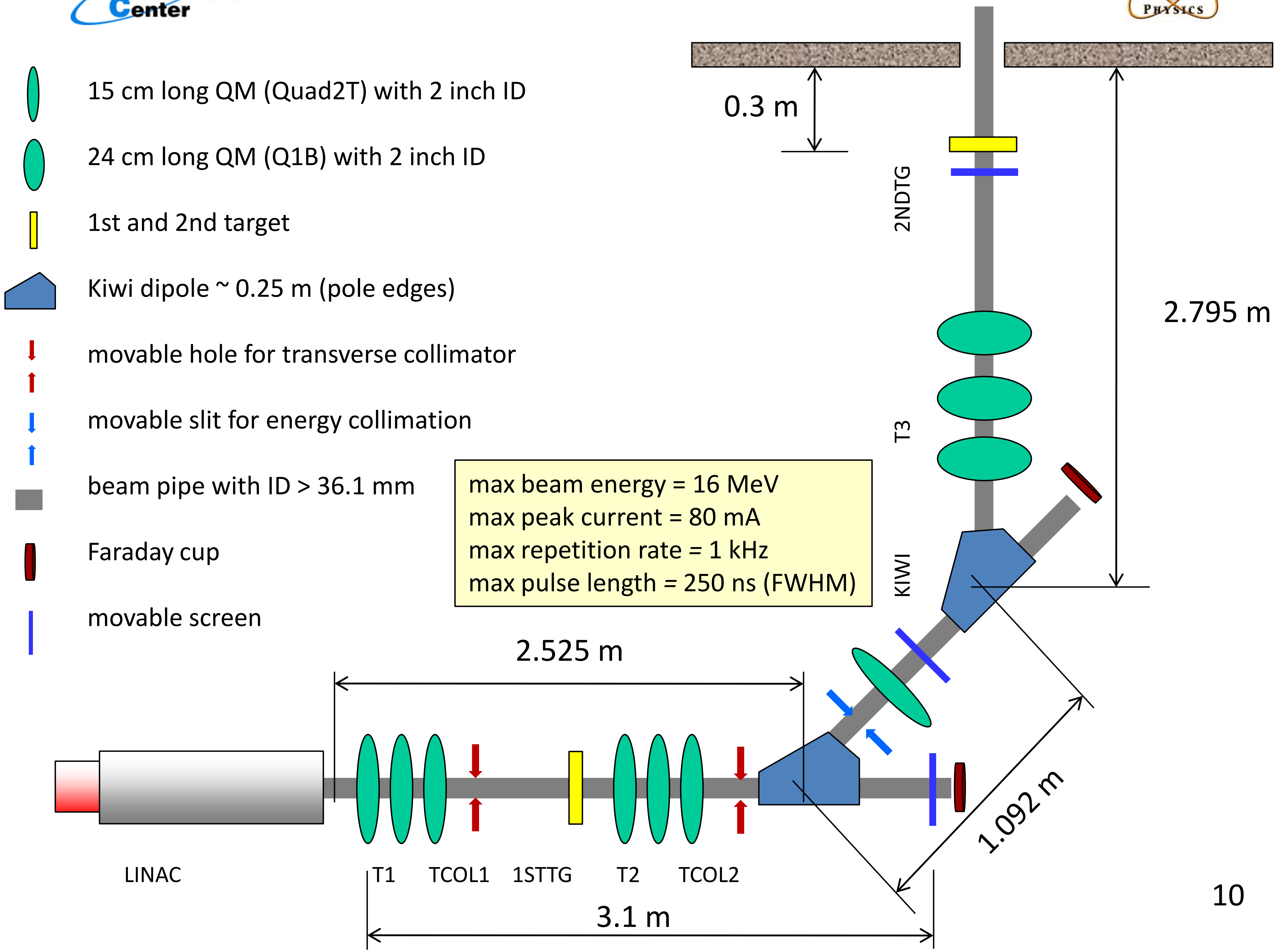
$$\sigma_{11} = \varepsilon\beta, \quad \sigma_{12} = -\varepsilon\alpha$$

$$\boxed{\varepsilon = \sqrt{ac}, \qquad \beta = \sqrt{\frac{a}{c}}, \quad \alpha = -b\sqrt{\frac{a}{c}}, \quad \gamma = \frac{1 + \frac{a}{c}b^2}{\sqrt{\frac{a}{c}}}}$$

If $k^{1/2}L << 1 \rightarrow$ Thin lens approximation:

$$m_{11} = S_{11} - S_{12}kL \qquad m_{12} = S_{11}L + S_{12}$$

Layout of the HRRL Beamline

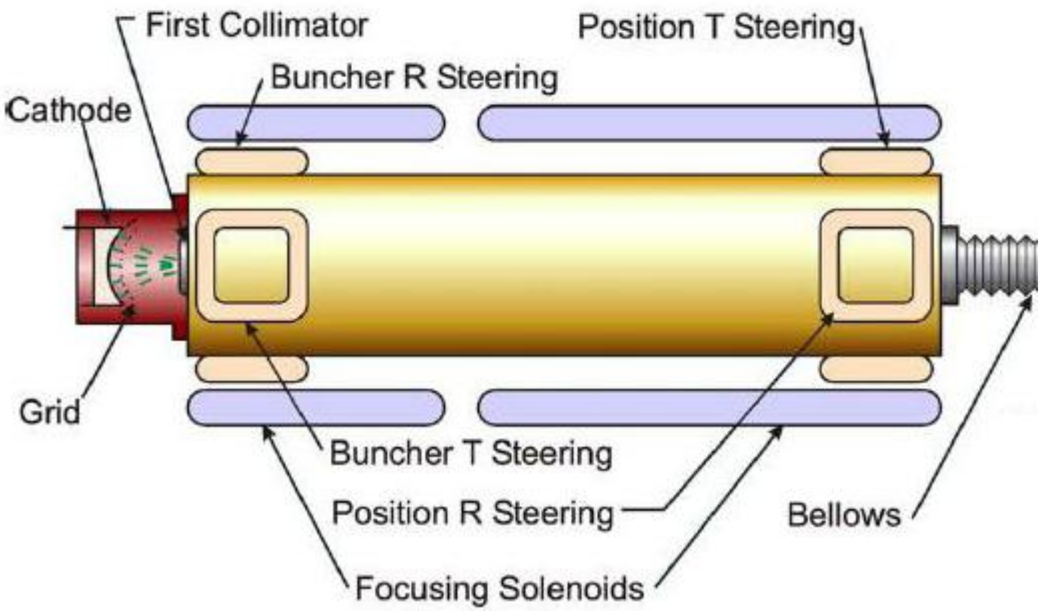


HRRL

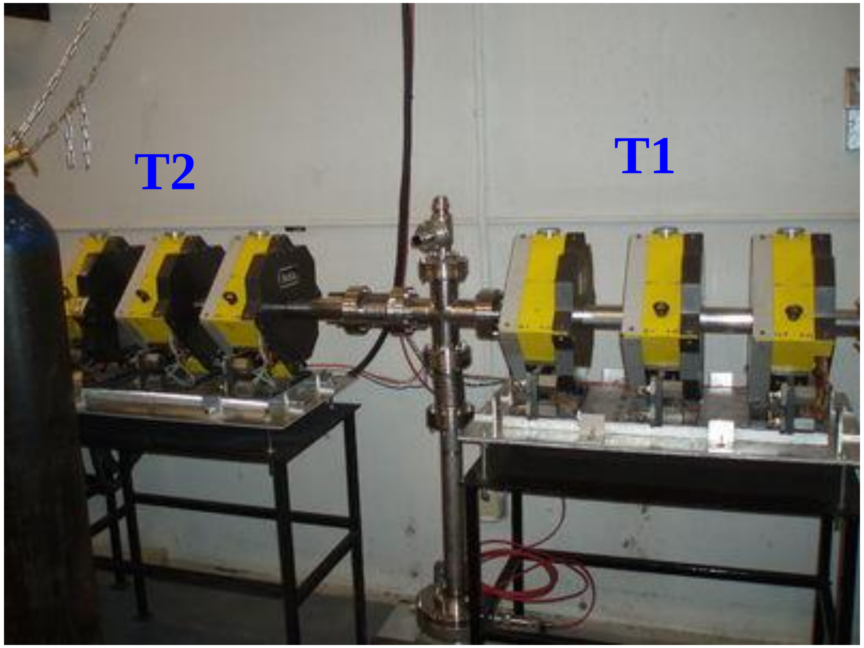
High Repetition Rate Linac (HRRL) is dedicated for positron source.

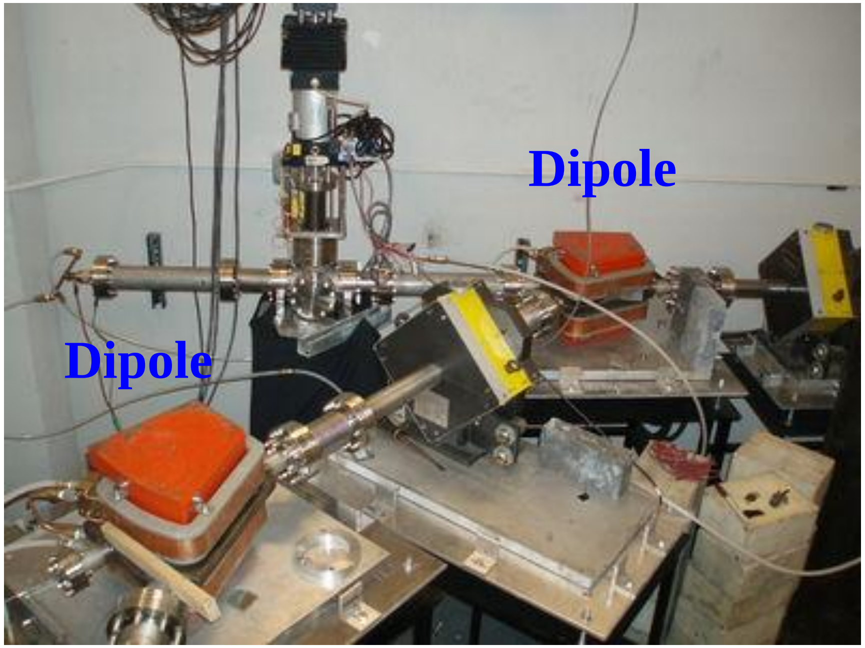
Tungsten target will be install in the near future to create positrons.

HRRL can deliver electron to the downstream.

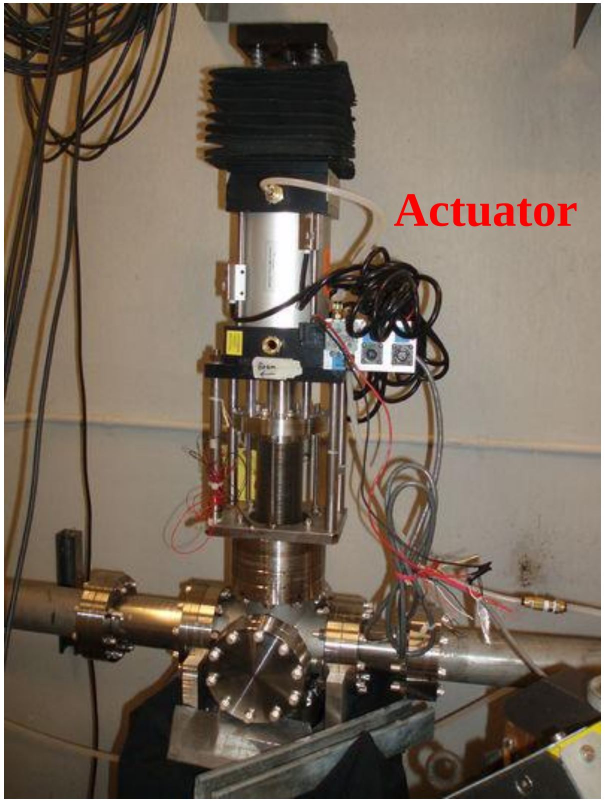


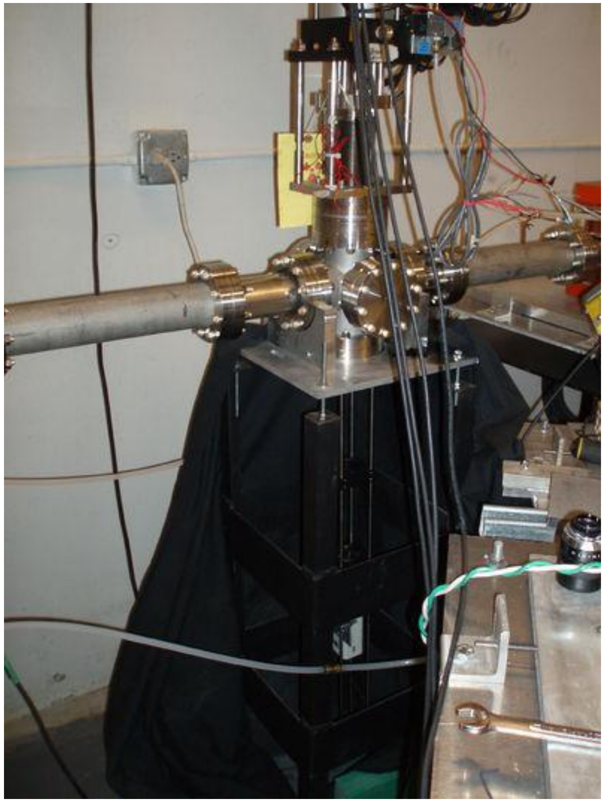
Equipments and setup

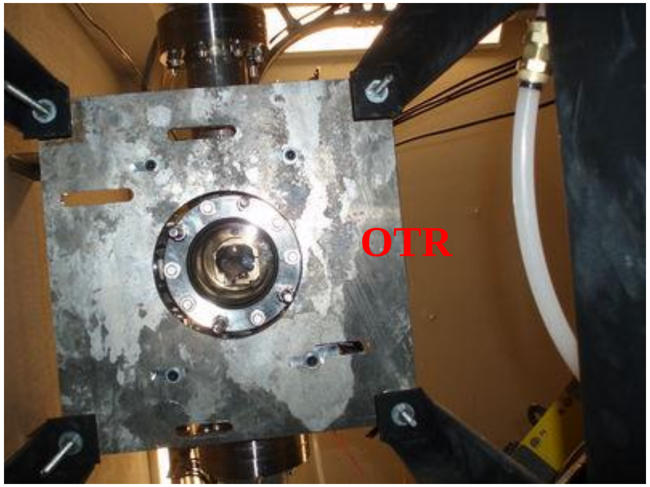




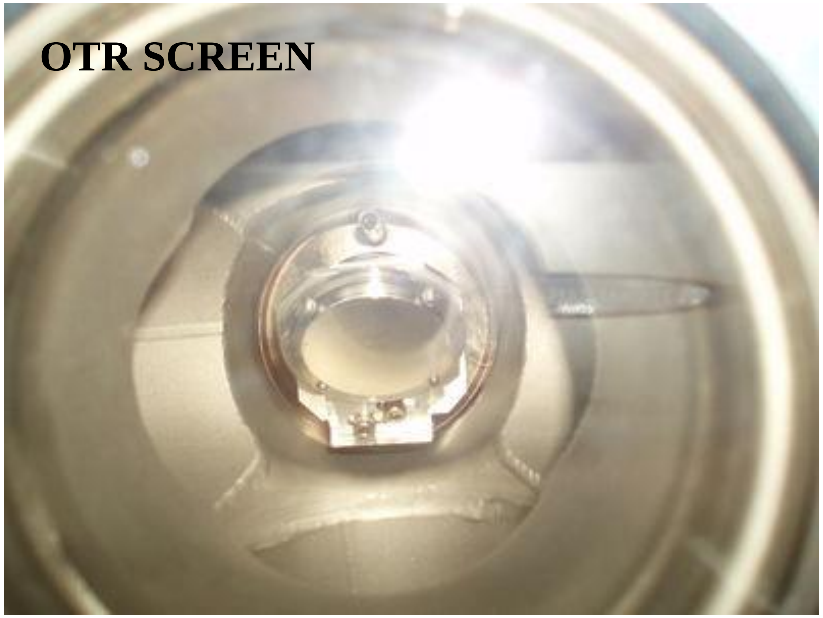
Equipments and setup

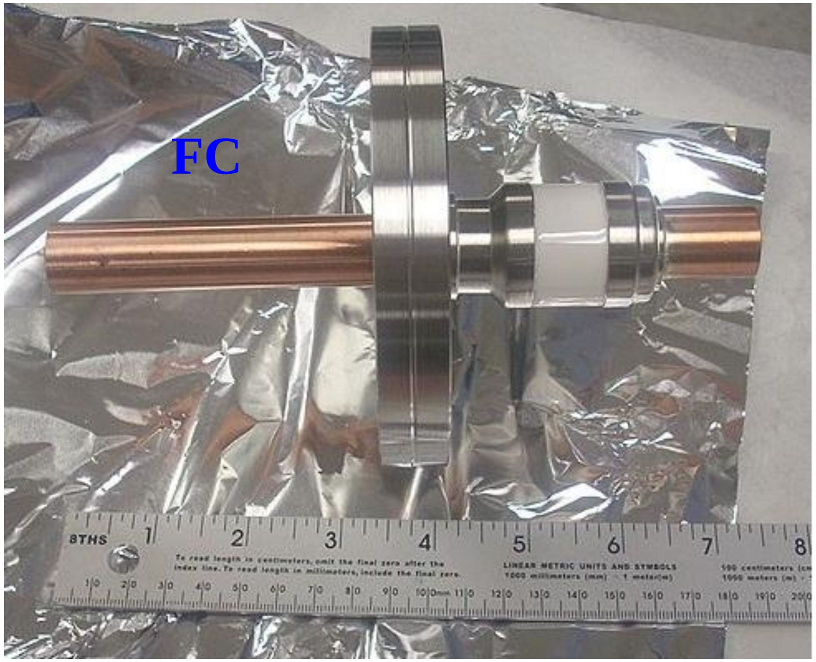


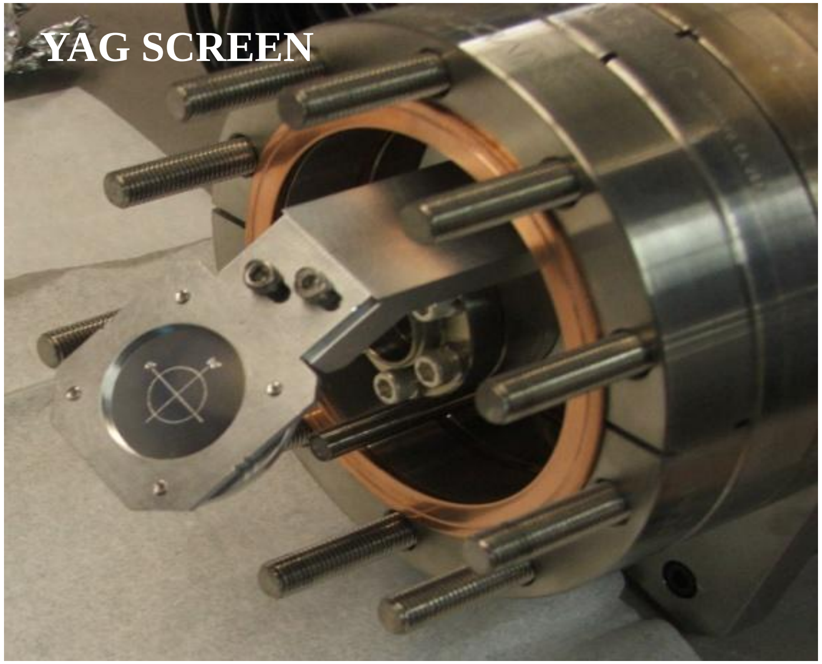




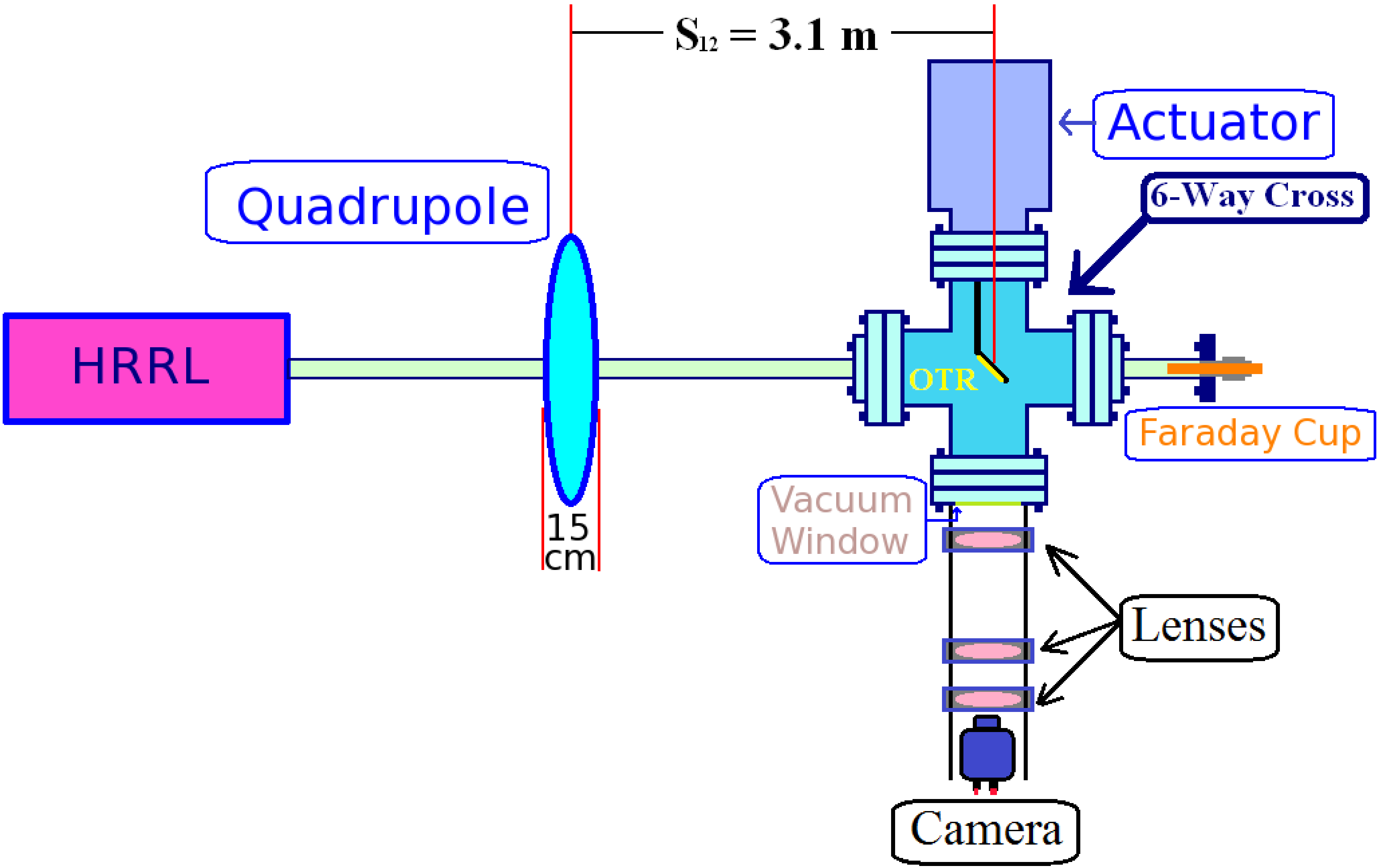
Equipments and setup







Equipments and setup



Equipments and setup

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

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

In our experiment, Pole face is 8 cm long in *z* direction:

$$L_0 = 0.08 \text{ m}$$

Radius of the Bore aperture (center to pole face = 1 inch):

$$R_B = 0.0254 \text{ m}$$

$L_{ef} = L_0 + R_B$ **(this will be updated later with a measured length).**

Quadupole Strength:

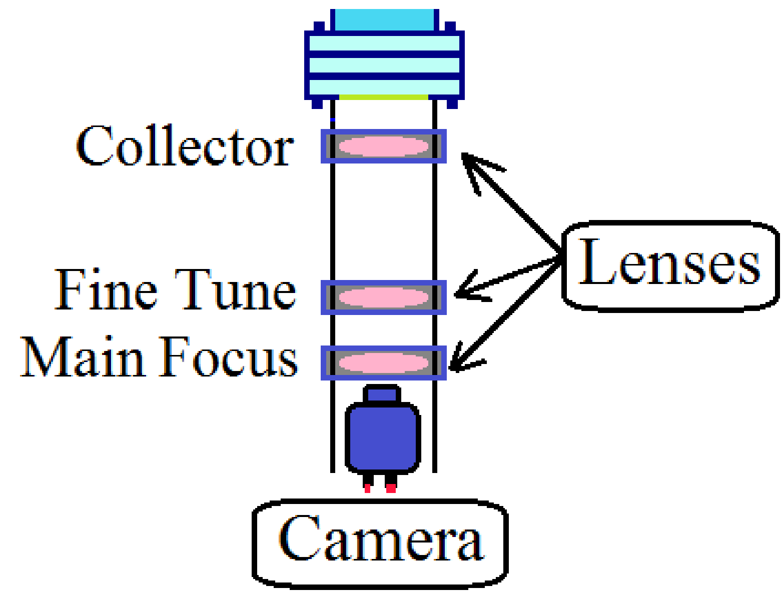
$$k1 = 0.2998 \frac{g[\text{T/m}]}{p[\text{GeV}]} = 0.2998 \frac{\frac{B(I)}{R_B}[\text{T/m}]}{p[\text{GeV}]}$$

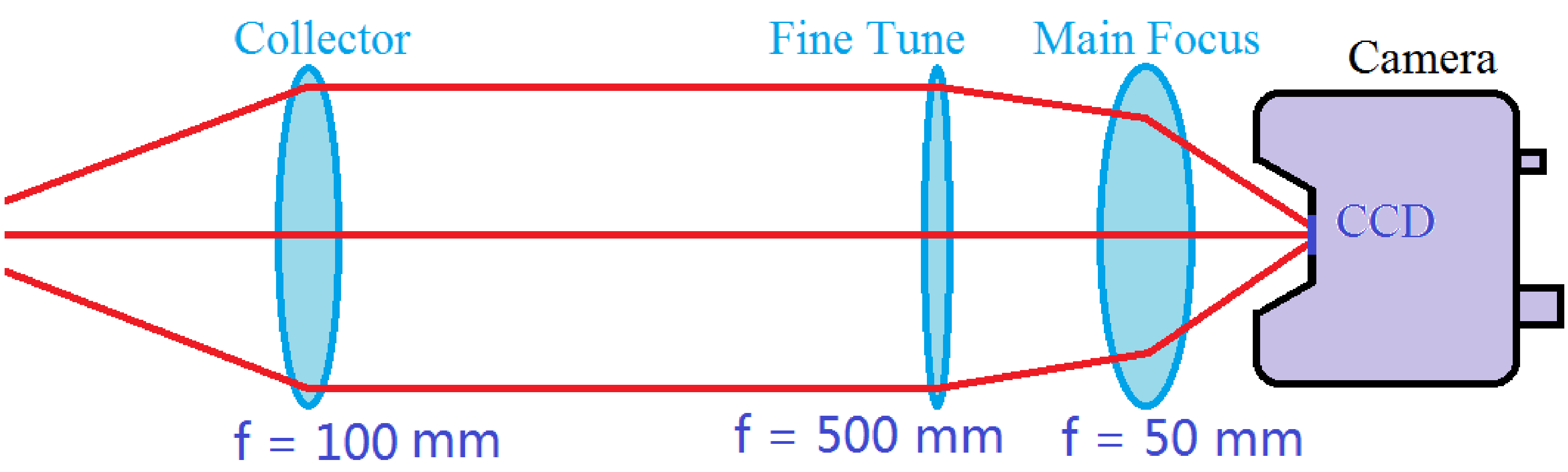
$$B(I) = (3.6 \pm 1.3) \times 10^{-4} + (1945 \pm 2) \times 10^{-6}\, I \ \ (\text{T})$$

$$\text{k}1 = 0.2998 \frac{(3.6 \pm 1.3) \times 10^{-4} + (1945 \pm 2) \times 10^{-6} I}{0.0254\, p}$$

Equipments and setup

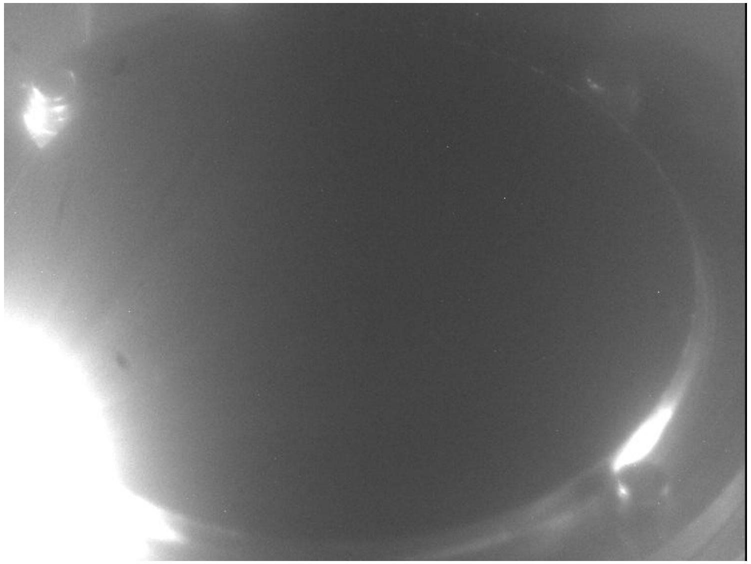
- OTR light comes out with 4/γ angle.
- Collector lens: has the middle focal length, collects most of the light from the source.
- Fine Tune lens: has the biggest focal length, act as fine tune of magnification.
- Main Focus Lens: has the smallest focal length, has biggest focusing strength, so act as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

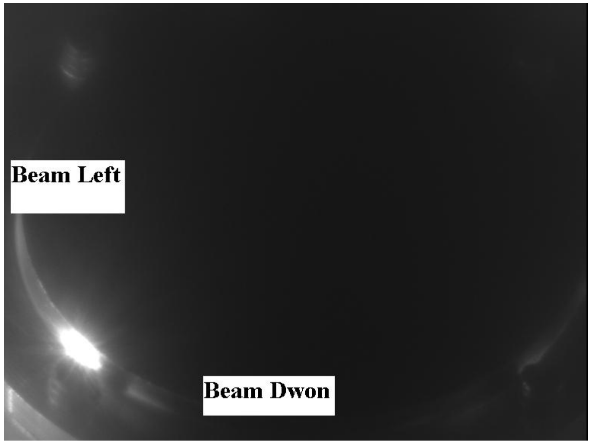


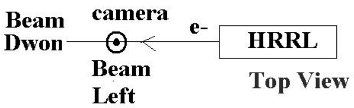


Tuning HRRL and Scanning

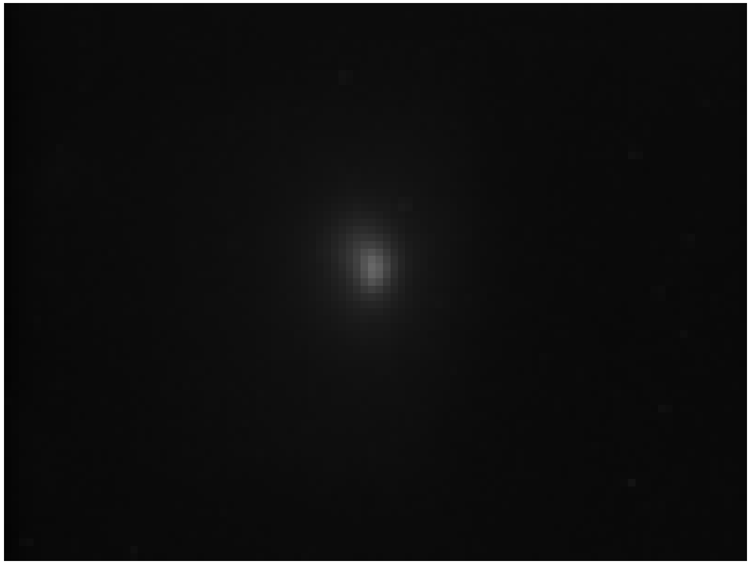
OTR Screen with side light on



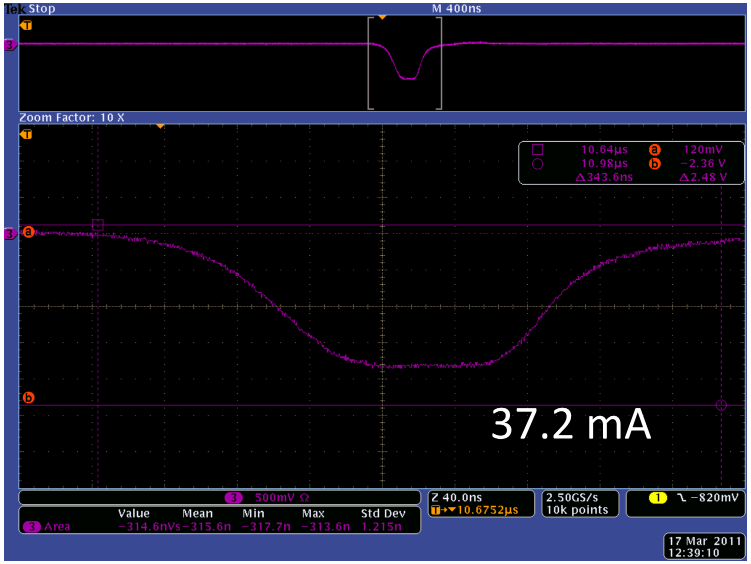




Electron beam the OTR

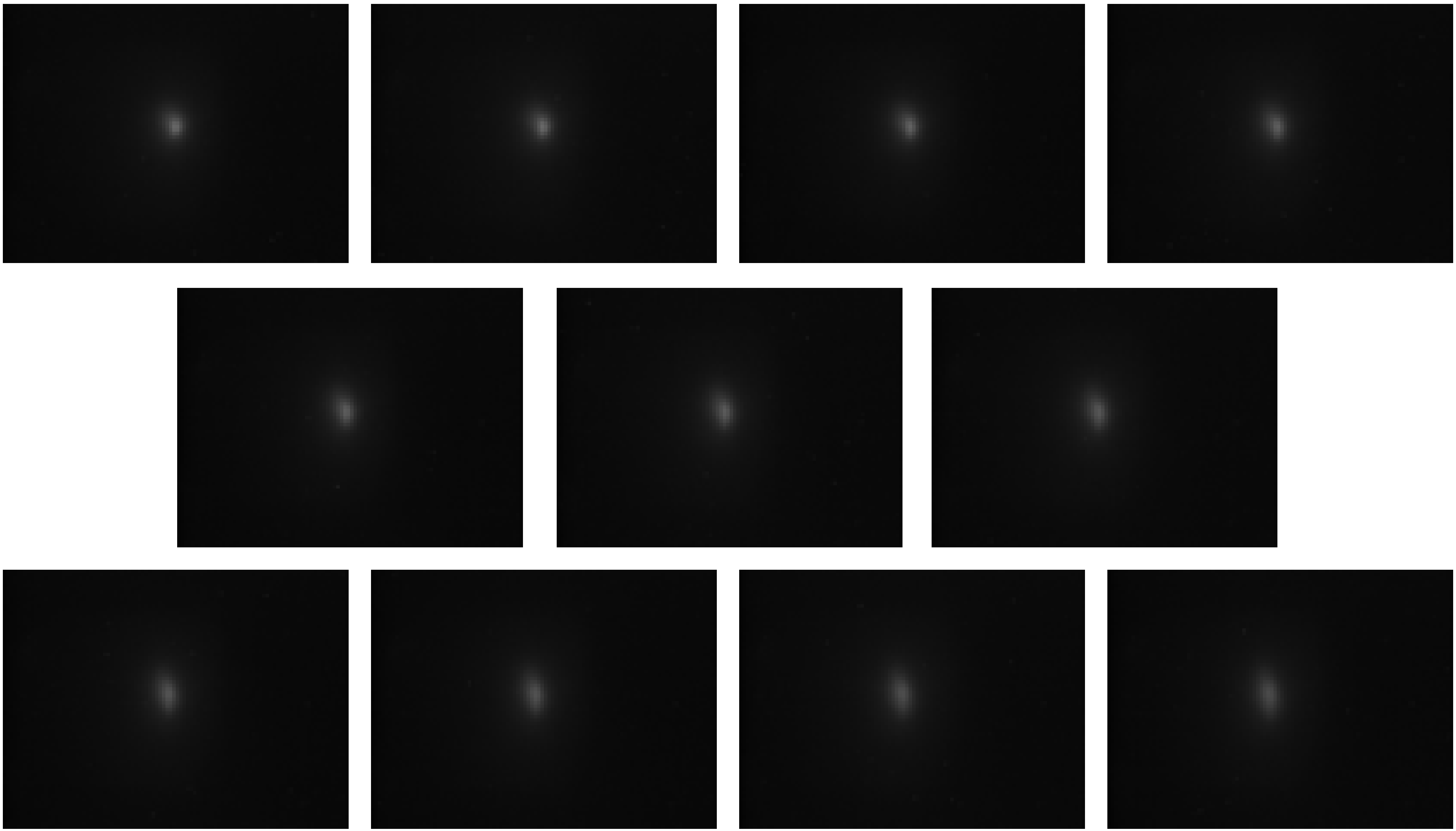


Scope image on the FC



Tuning HRRL and Scanning

Scan Q1 from 0 Amp to 2 Amp in 11 steps.



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.

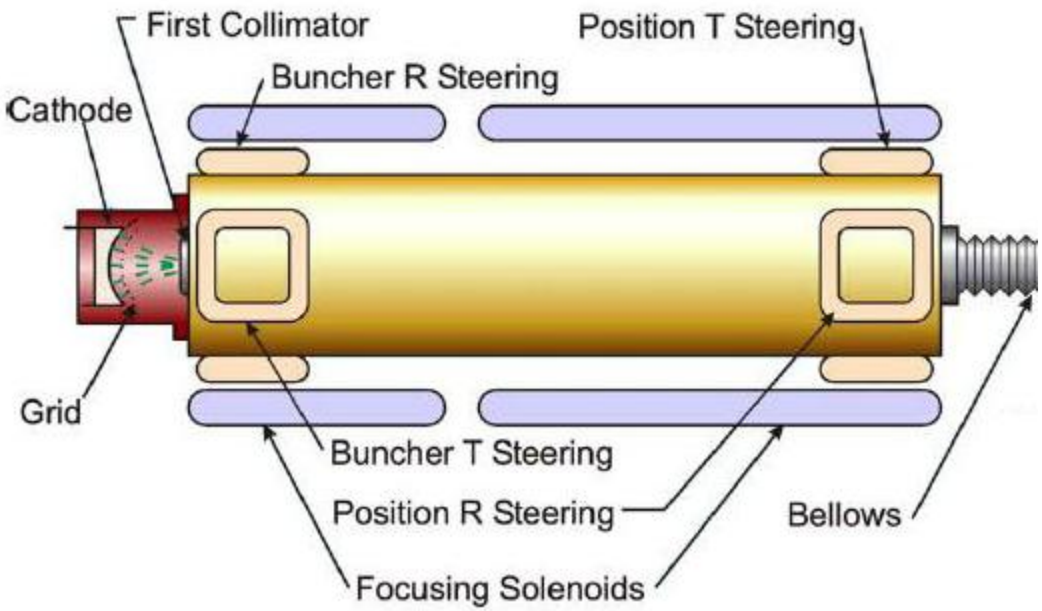
- On March 17th, 2011, we could optimize steerers, solenoids in linac to get a round electron beam shape and almost no steering at the quadrupole.

Tuning HRRL and Scanning

- **Tuned by Dr. Kim on the March 17th**

Control Unit	Setting
Solenoid 1	6.8 A
Solenoid 2	10.4 A
Gun Ver	-0.2 A
Gun Hor	+0.4 A
Output Hor	-1.4 A
Output Ver	-0.5 A
Gun HV	+9.75 (knob Setting)
Gun Grid Voltage	5.25 (Knob Setting)
RF Frequency	2855.816 MHz
Modulator HV Power Supply	4.42 (Knob Setting)
RF Macro Pulse Length (FMHM)	200 ns
e- Beam Energy	14 MeV

HRRL


First Collimator
Position T Steering
Buncher R Steering
Cathode
Grid
Buncher T Steering
Position R Steering
Bellows
Focusing Solenoids

Tuning HRRL and Scanning

- **Tuned by Sadiq Setiniyaz on the March 18th**

Control Unit	Setting
Solenoid 1	5.4 A
Solenoid 2	5.5 A
Gun Ver	-0.2 A
Gun Hor	+0.4 A
Output Hor	-0.5 A
Output Ver	-0.5 A
Gun HV	+9.75 (knob Setting)
Gun Grid Voltage	5.25 (Knob Setting)
RF Frequency	2855.8163MHz
Modulator HV Power Supply	5.25 (Knob Setting)
RF Macro Pulse Length (FMHM)	200 ns
e- Beam Energy	12.74 MeV

Data Analysis

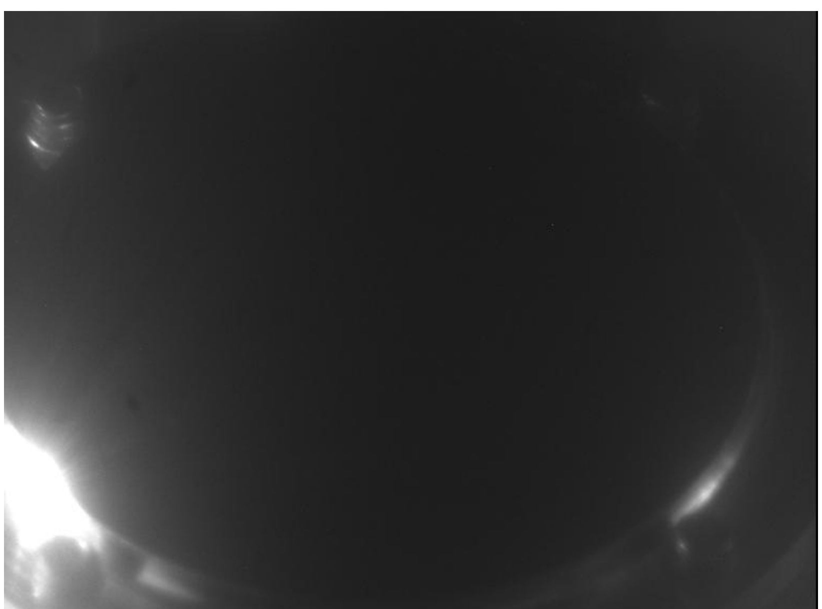
- Diameter! 1/2” progressive scan camera
- Monochrome and Bayer color versions
- 782 (h) x 582 (v) 8.37 μm square pixels
- 60 fps with full resolution
- 250 fps with 1/8 partial scan
- Vertical binning (CV-A10GE) for higher frame rates and sensitivity
- High speed shutter from 1/60 to 1/300,000 second
- 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

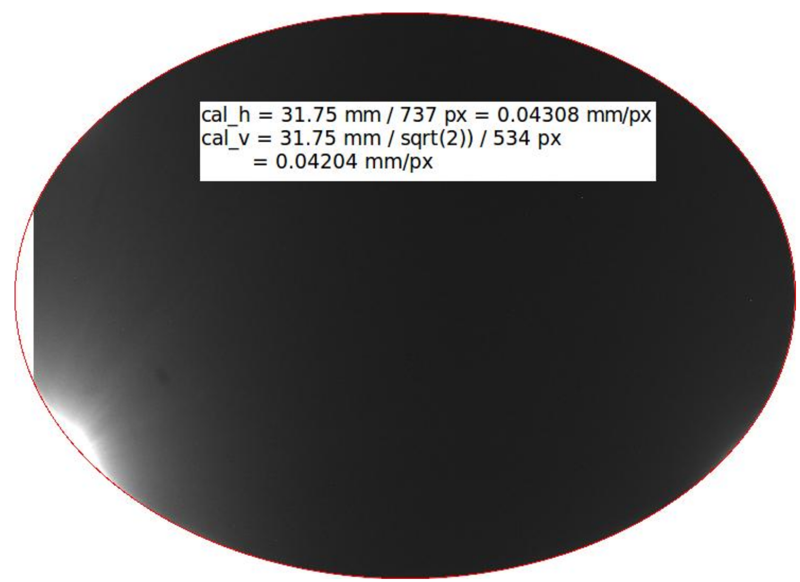
Data Analysis

- Diameter of the OTR is 1.25”, which is 31.75 mm.
- Horizontal Scaling = 31.75 mm/(# of pixels)
- Vertical Scaling = 31.75 mm*cos(π/4)/(# of pixels)

<u>Scaling factors of the data on Mar 17th</u>

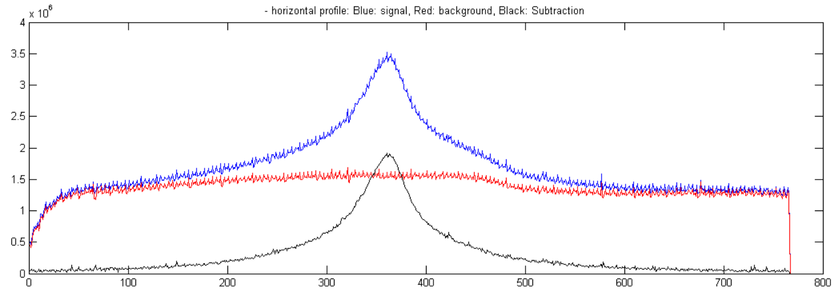
Vertical Scaling (mm/px)	Horizontal Scaling (mm/px)
0.04308	0.04204
0.04320	0.04228
0.04349	0.04181
0.04323	0.04196
0.04337	0.04212
Average	Average
0.04327 0.00016	0.04204 0.00018

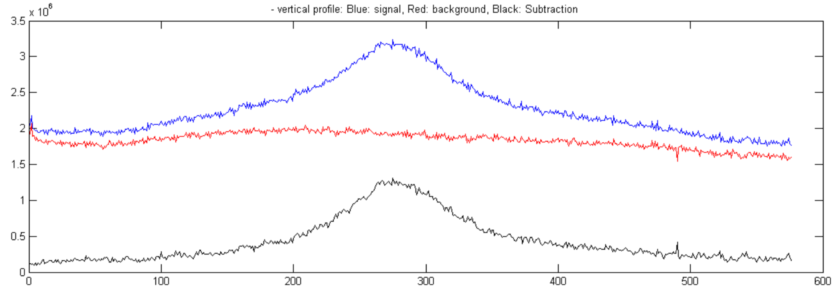




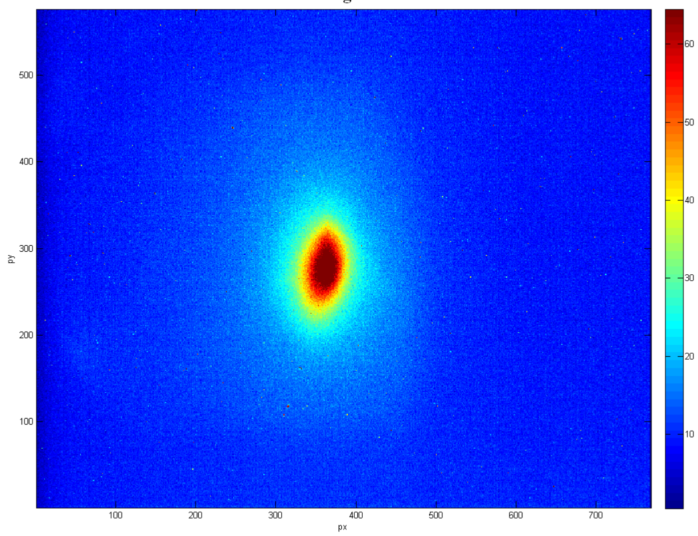
Data Analysis

Back Ground Subtraction:

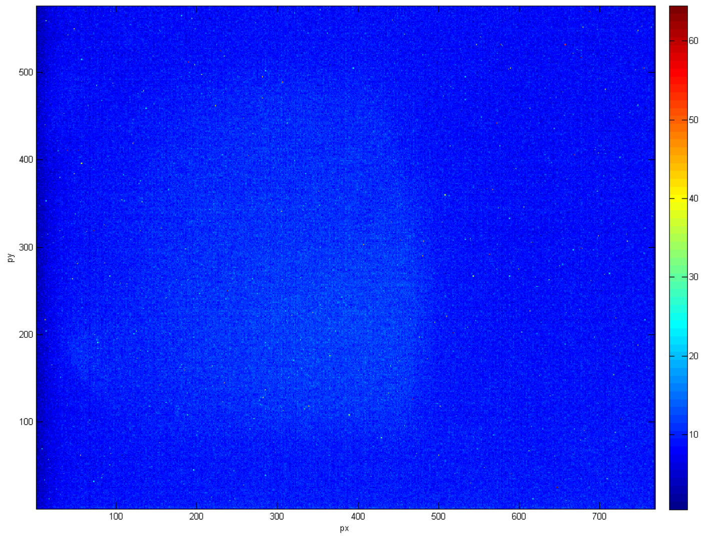




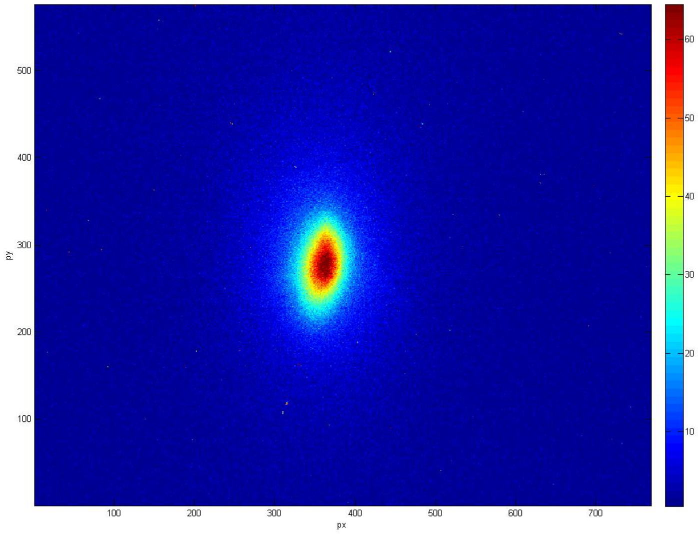
Signal



Back Ground



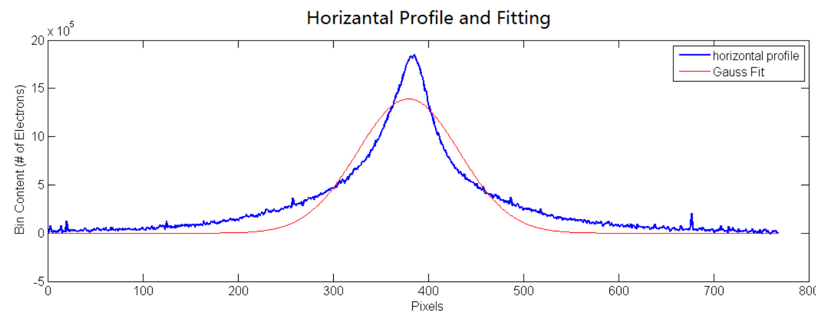
Back Ground Subtracted

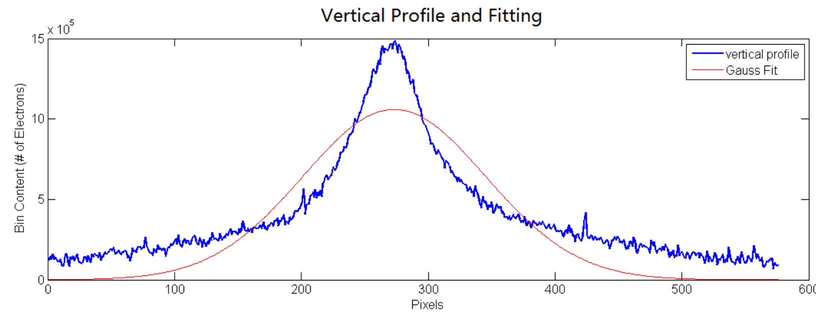


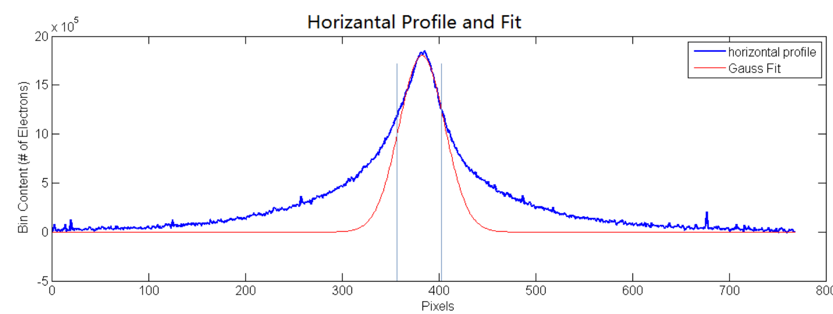
Data Analysis

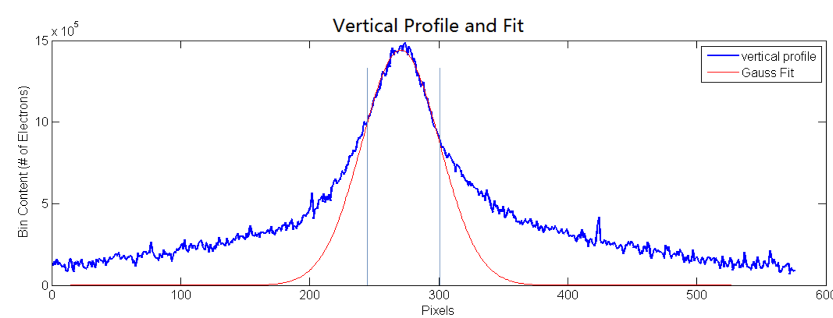
Problem in Gaussian Fitting

- **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.**





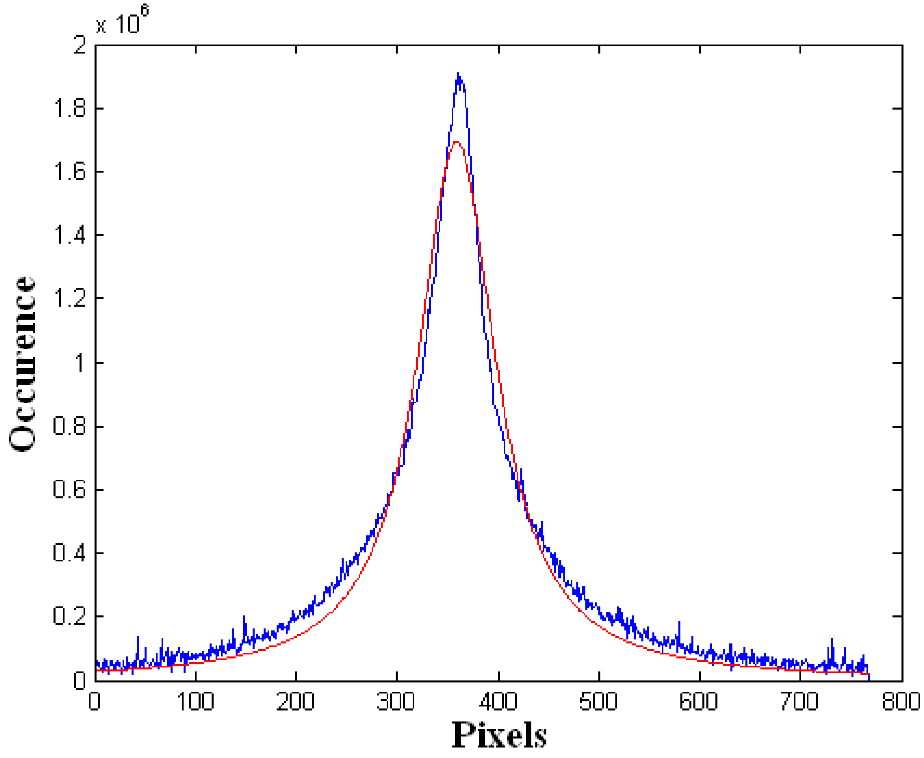




Data Analysis

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:

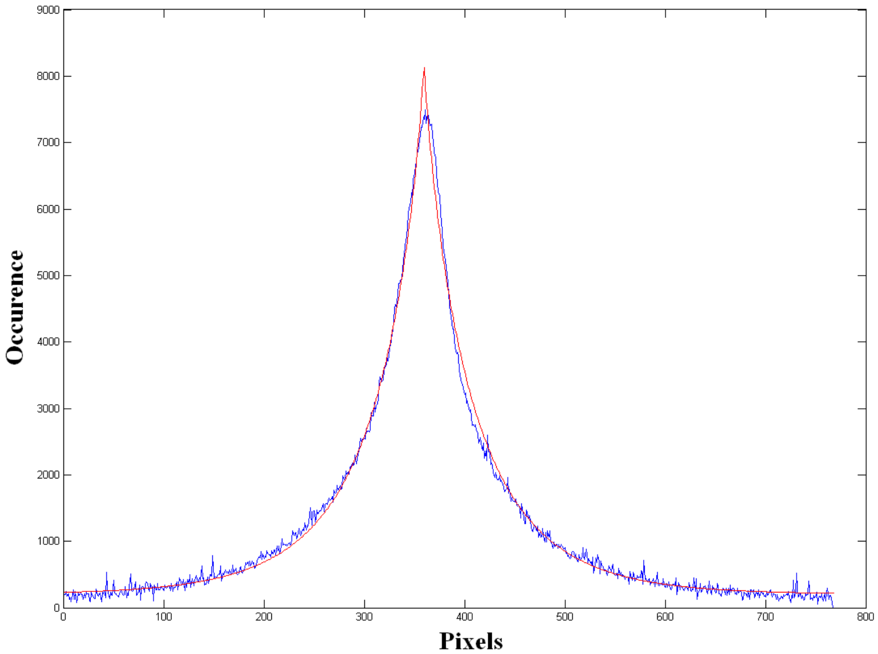
RMS ~ FWHM / 2.3548 = (2*HWHM) / 2.3548 = 38.58 px

Data Analysis

Super-Gaussian Fitting:

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

- **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

Calculating single bunch charge:

S-band linac has RF frequency of 2856 MHz. The period then is:

$$T_{RF} = \frac{1}{f_{RF}} = \frac{1}{2856MHz} = 350\ ps$$

Pulse width of the RF macro-pulse : Δ*t*
Number of bunches within a pulse: *N*

$$N \times T_{RF} = \Delta t \Longrightarrow N = \frac{\Delta t}{T_{RF}}$$

Peak current of the pulse: I_{peak}

Total Charge in a pulse: $Q_t = I_{peak} \times \Delta t$

Charge in a single bunch: $Q_s = \frac{Q_t}{N}$

$$Q_s = \frac{I_{peak} \times \Delta t}{\frac{\Delta t}{T_{RF}}}$$

$$Q_s = I_{peak} \times T_{RF}$$

$$Q_s = I_{peak} \times 350\ ps$$

Data Analysis

Mar 17th, 2011

Q = 14.7 pC, E = 14 MeV

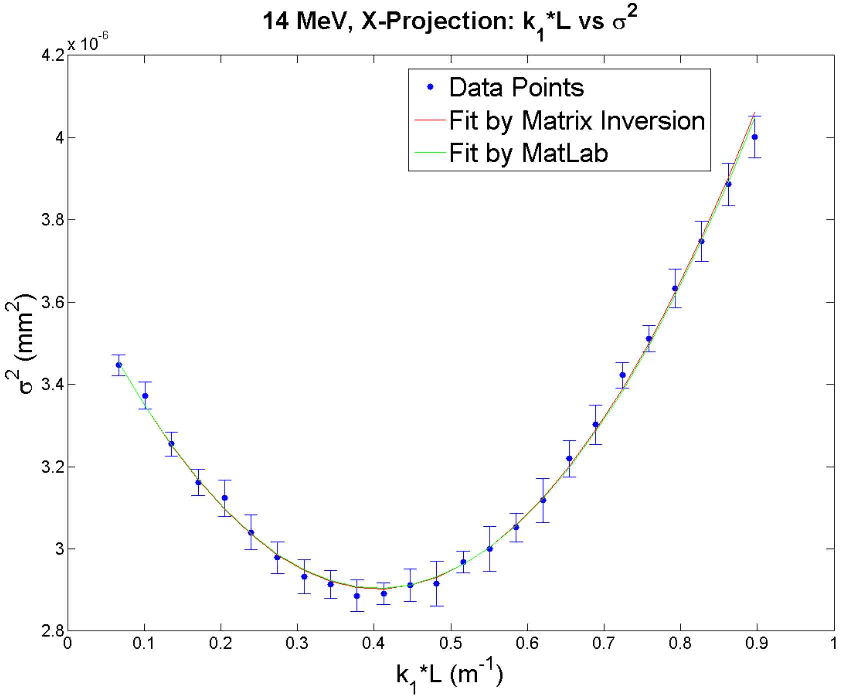
macro pulse length = 200 ns FWHM pulse

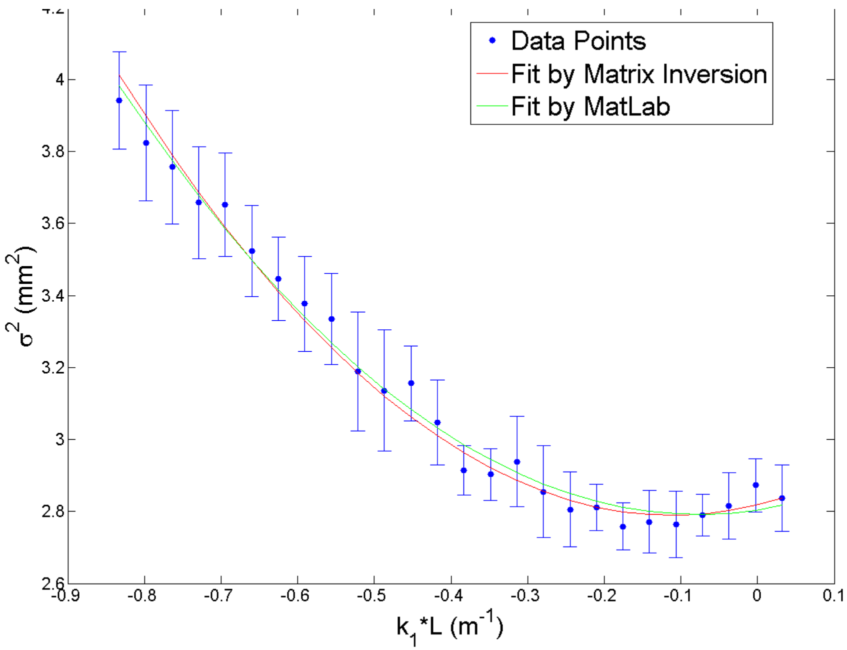
Positive scan, X-projection

- ε_x = 0.388 ± 0.008 μm
- ε_{nx} = 10.64 ± 0.023 μm
- β_x = 1.29 ± 0.03 m
- α_x = 0.94 ± 0.03 rad

Positive scan, Y-projection

- ε_y = 0.266 ± 0.018μm
- ε_{ny} = 7.30 ± 0.05 μm
- β_y = 0.918 ± 0.068 m
- α_y = 0.19 ± 0.06 rad





Conclusions

We could establish all hardware and software to measure beam emittance at the HRRL accelerator.

Electron beam from HRRL is not Gaussian. But it is super Gaussian or Lorentzian.

The transverse normalized rms emittances we measured are:

$$\varepsilon_{nx} = 10.658 \quad 0.034\ \mu\mathrm{m}, \quad \varepsilon_{ny} = 7.370 \quad 0.024\ \mu\mathrm{m}$$

for Q = 14.7 pC, E = 14 MeV.

OTR works properly to measure emittance of the HRRL accelerator.

Therefore, it seems that beam quality of the HRRL accelerator is sufficient to generate the positron beams.

Future Work

Do emittance measurement with different energies and energy spreads.

Do emittance with different peak currents or single bunch charges.

Apply Iris to get better signal to noise ratio in beam imaging system.

New ways to subtract back ground.

Tune beam again, see if we can tune beam to Gaussian distribution.

Development of an EPICS and MATLAB based automatic emittance measurement tool.

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Thanks for listening !

Questions ?

Suggestions ?