Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

Commissioning and First Results of the Electron Beam Profiler in the Main Injector at Fermilab

Randy Thurman-Keup

2017 International Beam Instrumentation Conference

August 23, 2017

Introduction

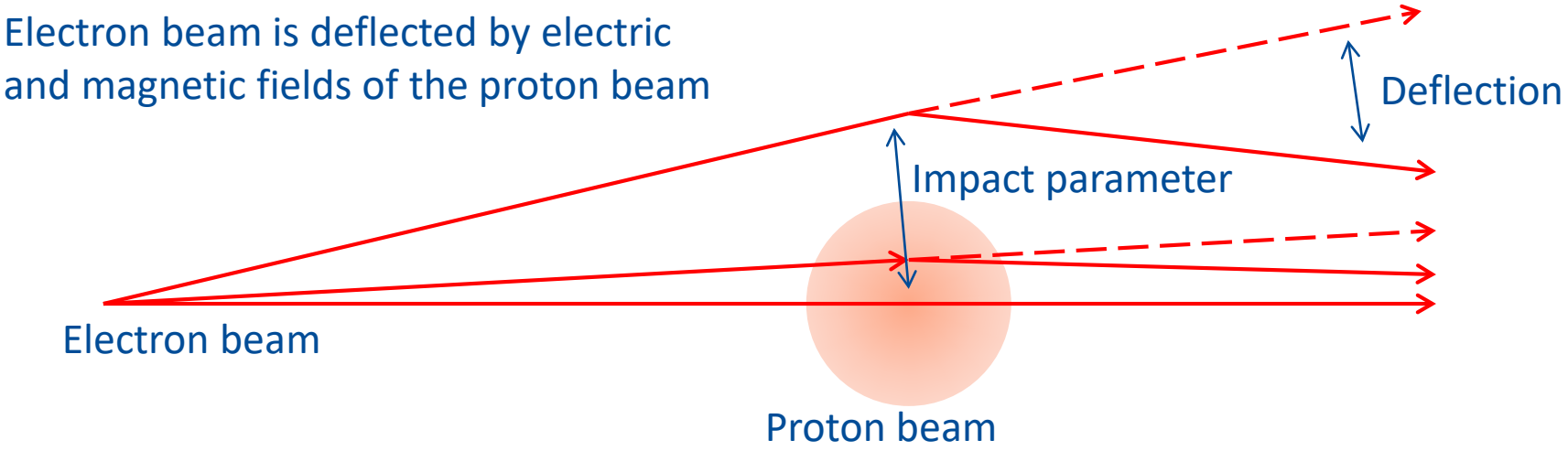
- Fermilab is a particle physics laboratory running a variety of neutrino physics experiments as well as precision physics experiments involving muons
  - Nova; BooNE family; g-2; Mu2e; *DUNE (future)*
- All these experiments are supplied by protons from Main Injector (MI) or Booster
- MI is last in a chain of accelerators
  - H- source
  - Linac (400 MeV extraction energy)
  - Booster synchrotron (8 GeV extraction energy)
  - Recycler (accumulates typically 5 x 10^{13} protons)
  - MI (120 GeV extraction energy)
- Acceleration sequence repeats every 1.3 seconds
- MI parameters
  - 588 rf buckets at ~53 MHz (~19 ns/bucket)
  - ~10^{11} protons per bucket
  - ~700 kW

Motivation

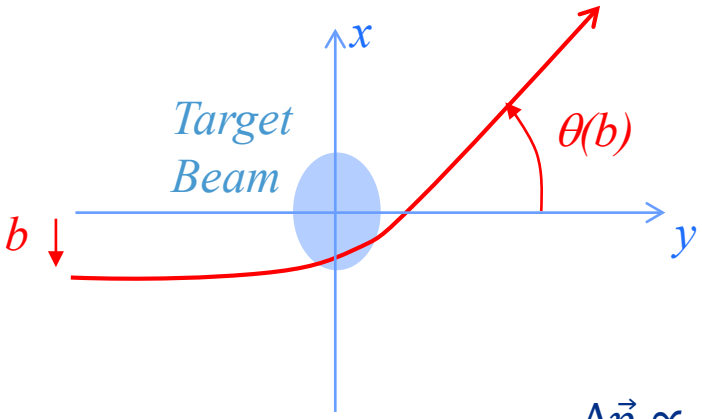
- Long range plan calls for MI beam power in excess of 2 MW
- Presently only have residual gas Ionization Profile Monitor in MI
- Wanted additional non-invasive profile monitor
  - Gas Fluorescence Detectors
  - Gas Jets
  - Probe Beams
- Probe beam concept has existed since at least 1970
  - Paul D. Goldan, *Collisionless Sheath – An Experimental Investigation*, Phys. Fluids 13 1055 (1970).
  - C.H. Stallings, *Electron Beam as a Method of Finding the Potential Distribution in a Cylindrically Symmetric Plasma*, J. Appl. Phys. 42 (1971) 2831.
- Tests at CERN with an ion probe beam
- Operational version in use at SNS in their accumulator ring

Electron Beam Profiler Concept

- Device to measure the transverse profile of the proton beam in the Main Injector (MI) using a beam of electrons
- *Deflection vs. Impact parameter* provides information about the transverse proton beam size in the direction of the impact parameter



Theory



Assume $\gamma \gg 1$, no magnetic field, $\rho \neq f(z)$

$$\vec{F}(\vec{r}) \propto \int d^2\vec{r}'\rho(\vec{r}')\frac{(\vec{r}-\vec{r}')}{|\vec{r}-\vec{r}'|^2} \qquad \Delta\vec{p} = \int_{-\infty}^{\infty} dt\ \vec{F}\big(\vec{r}(t)\big)$$

Assume deflection is very small such that $\vec{r} \approx \{b, vt\}$

$$\Delta\vec{p} \propto \int_{-\infty}^{\infty} dx' \int_{-\infty}^{\infty} dy'\ \rho(x',y') \int_{-\infty}^{\infty} dt\ \frac{\{b-x', vt-y'\}}{(b-x')^2+(vt-y')^2}$$

$$\Delta\vec{p} \propto \int_{-\infty}^{\infty} dx' \int_{-\infty}^{\infty} dy'\,\rho(x',y')\,\mathrm{sgn}(b-x')\{1,0\}$$

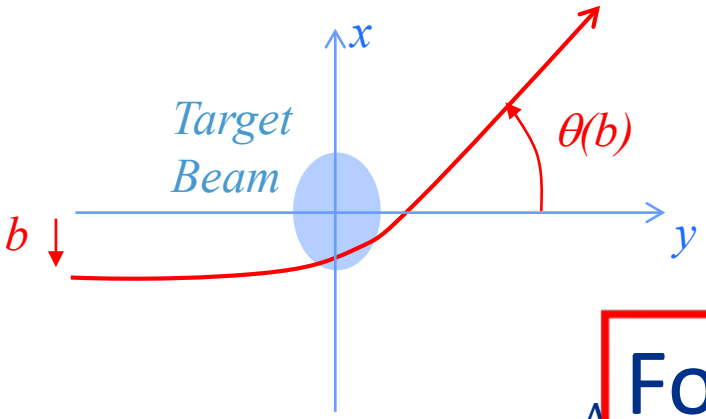
Assume again that deflection is very small such that $\vec{p} \approx \{0, p\}$ and $\theta \approx \frac{|\Delta\vec{p}|}{|\vec{p}|}$

$$\theta(b) \propto \int_{-\infty}^{\infty} dx' \int_{-\infty}^{\infty} dy'\,\rho(x',y')\,\mathrm{sgn}(b-x') \longrightarrow \frac{d}{db}\mathrm{sgn}(b-x') \propto \delta(b-x')$$

$$\frac{d\theta(b)}{db} \propto \int_{-\infty}^{\infty} dy'\,\rho(b,y') \Longleftarrow \text{x profile} \qquad \rho = 2D\ gaussian \Longrightarrow \qquad \frac{d\theta(b)}{db} = Gaussian(b)$$

$$\theta(b) = \mathrm{erf}(b)$$

Theory



Assume $\gamma \gg 1$, no magnetic field, $\rho \neq f(z)$

$$\vec{F}(\vec{r}) \propto \int d^2\vec{r}'\rho(\vec{r}')\frac{(\vec{r}-\vec{r}')}{|\vec{r}-\vec{r}'|^2} \qquad \Delta\vec{p} = \int_{-\infty}^{\infty} dt\ \vec{F}(\vec{r}(t))$$

Assume deflection is very small such that $\vec{r} \approx \{b, vt\}$

$$\Delta \propto \frac{\{b-x', vt-y'\}}{-x')^2+(vt-y')^2}$$

For Gaussian bunch

$$\theta(b) = \mathrm{erf}(b)$$

$$\Delta\vec{p} \propto \int_{-\infty}^{\infty} dx' \int_{-\infty}^{\infty} dy'\,\rho(x',y')\,\mathrm{sgn}(b-x')\{1,0\}$$

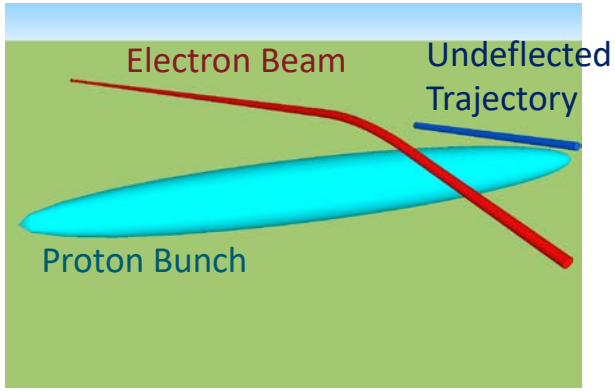
Assume again that deflection is very small such that $\vec{p} \approx \{0, p\}$ and $\theta \approx \frac{|\Delta\vec{p}|}{|\vec{p}|}$

$$\theta(b) \propto \int_{-\infty}^{\infty} dx' \int_{-\infty}^{\infty} dy'\,\rho(x',y')\,\mathrm{sgn}(b-x') \longrightarrow \frac{d}{db}\mathrm{sgn}(b-x') \propto \delta(b-x')$$

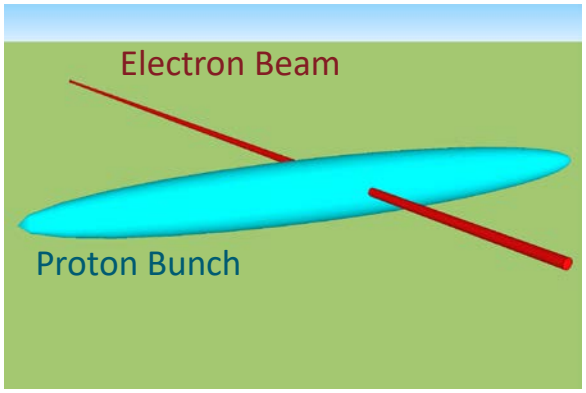
$$\frac{d\theta(b)}{db} \propto \int_{-\infty}^{\infty} dy'\,\rho(b,y') \longleftarrow \text{x profile} \qquad \rho = 2D\ gaussian \Longrightarrow \qquad \frac{d\theta(b)}{db} = Gaussian(b)$$

$$\theta(b) = \mathrm{erf}(b)$$

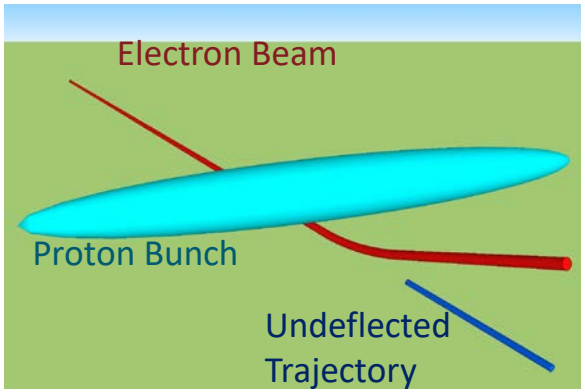
Electron Beam Profiler – Artist's Conception



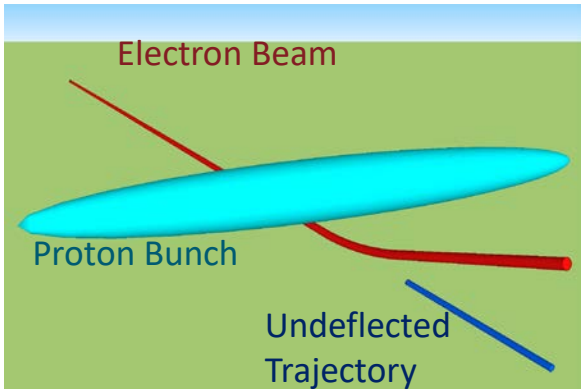
Electron Beam Profiler – Artist's Conception

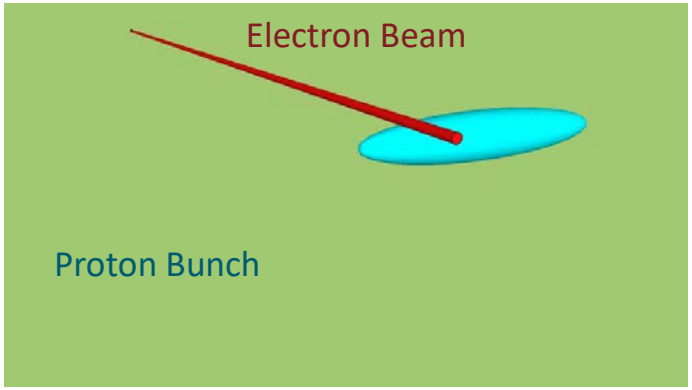


Electron Beam Profiler – Artist's Conception



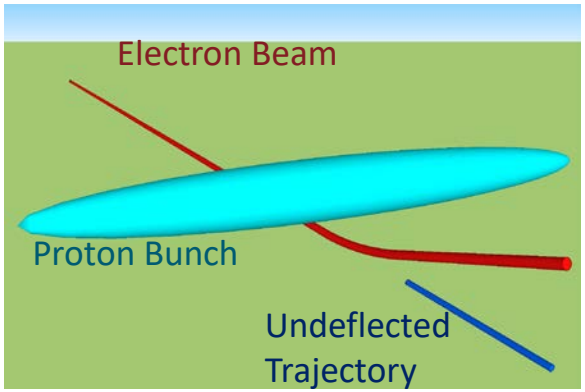
Electron Beam Profiler – Artist's Conception

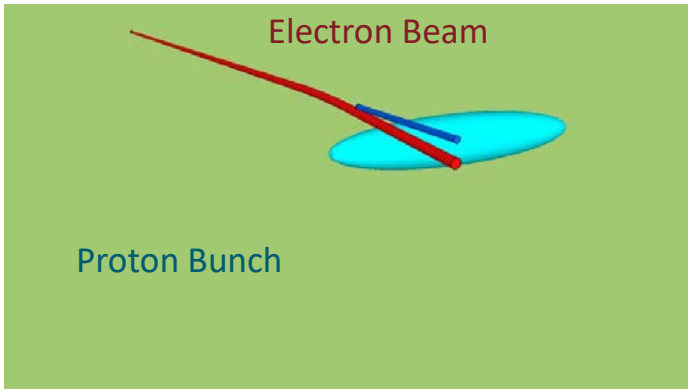




Stationary Electron Beam

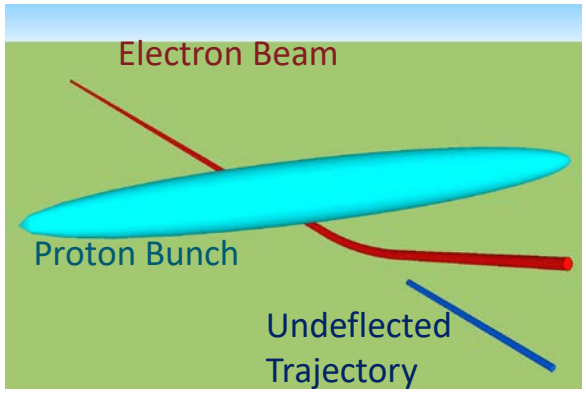
Electron Beam Profiler – Artist's Conception

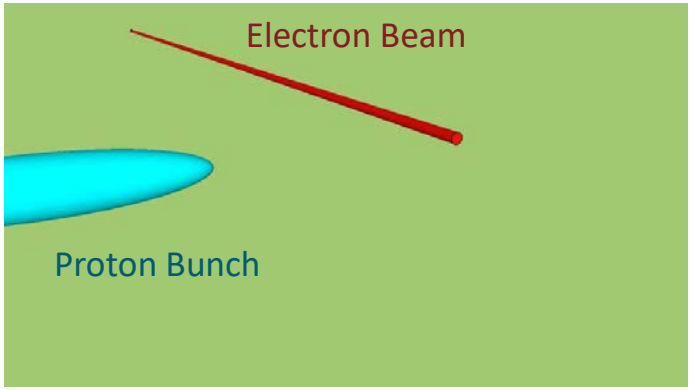




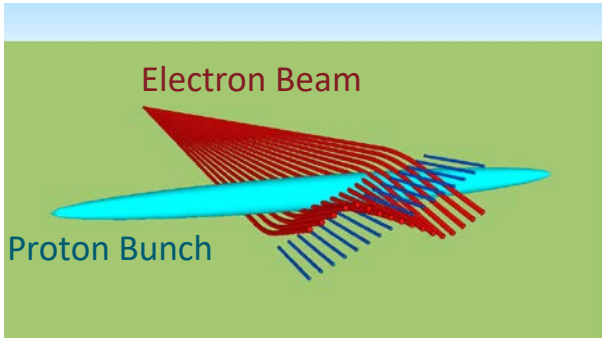
Stationary Electron Beam

Electron Beam Profiler – Artist's Conception





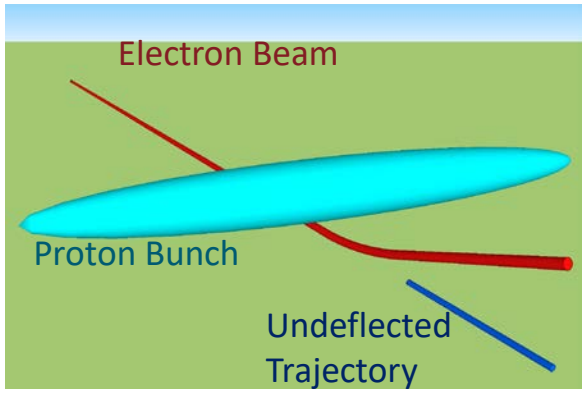
Stationary Electron Beam

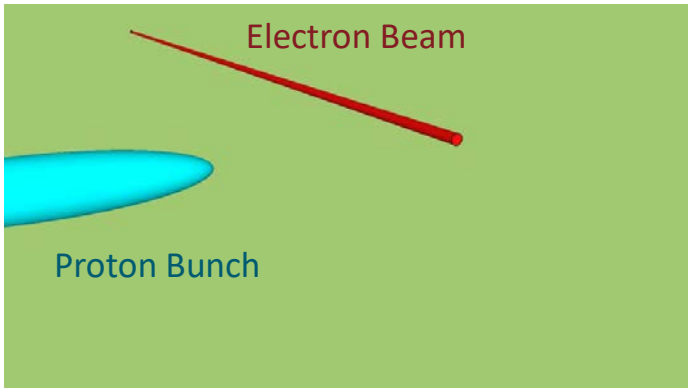


Single Shot Sweep

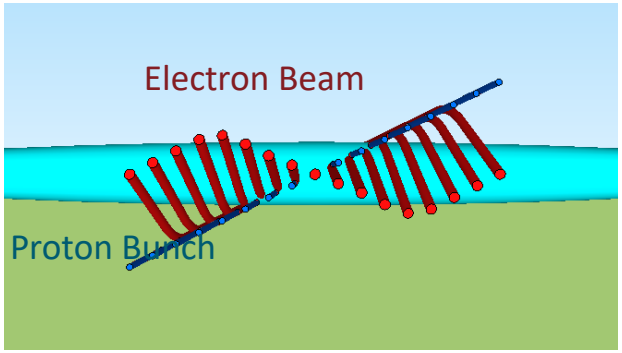
Need bunch length >> sweep time
MI rms bunch length < 2-3 ns

Electron Beam Profiler – Artist's Conception





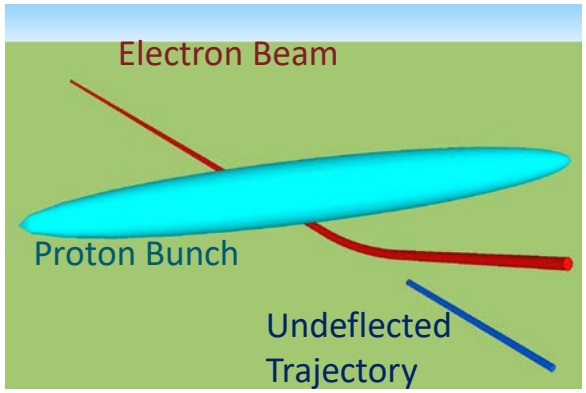
Stationary Electron Beam

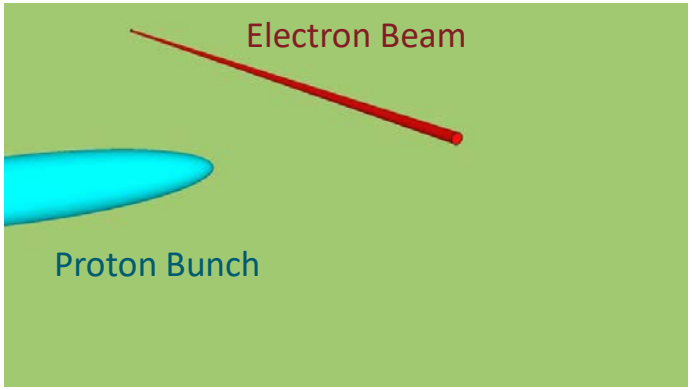


Single Shot Sweep

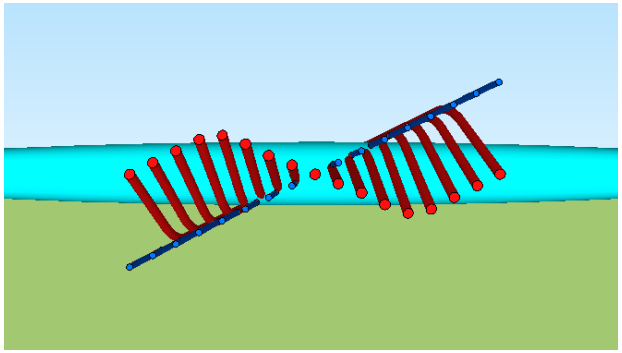
Need bunch length >> sweep time
MI rms bunch length < 2-3 ns

Electron Beam Profiler – Artist's Conception

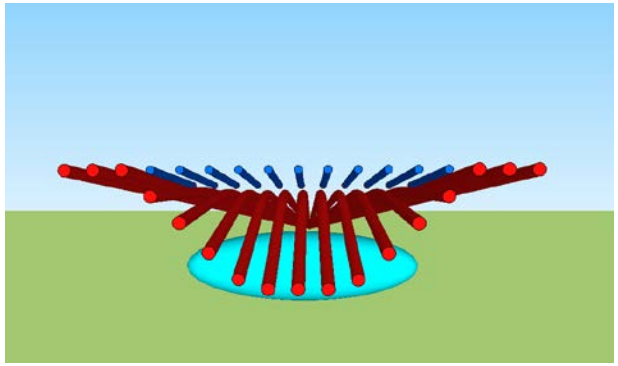




Stationary Electron Beam



Single Shot Sweep

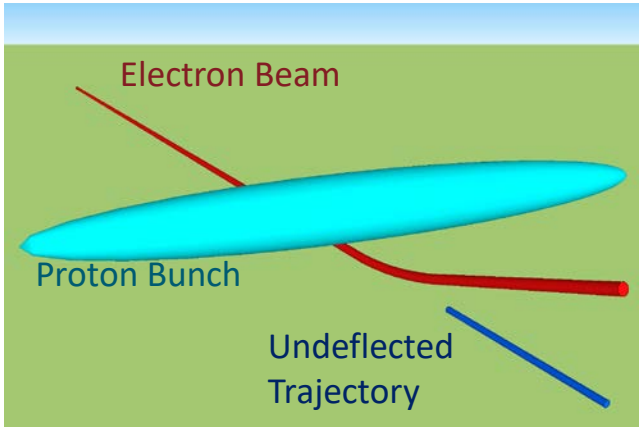


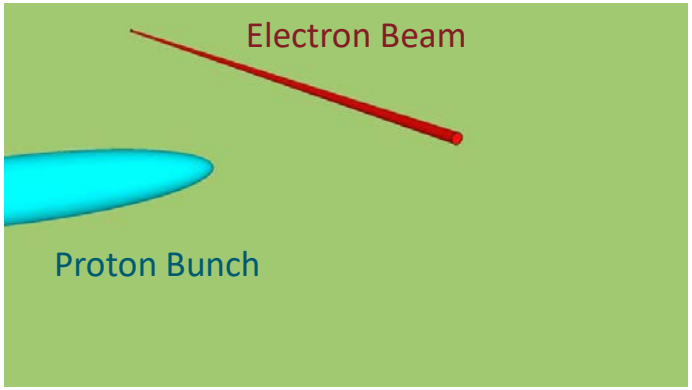
Raster Scan

Need bunch length >> sweep time
MI rms bunch length < 2-3 ns

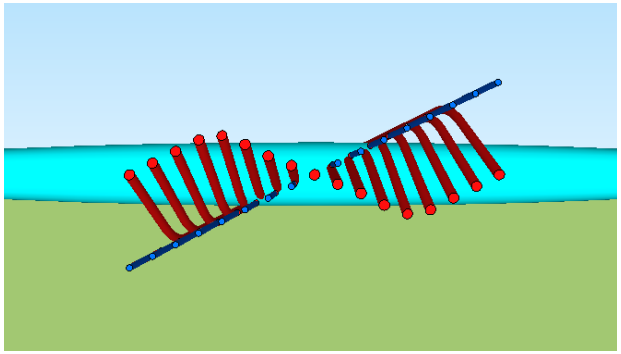
Fermilab

Electron Beam Profiler – Artist's Conception



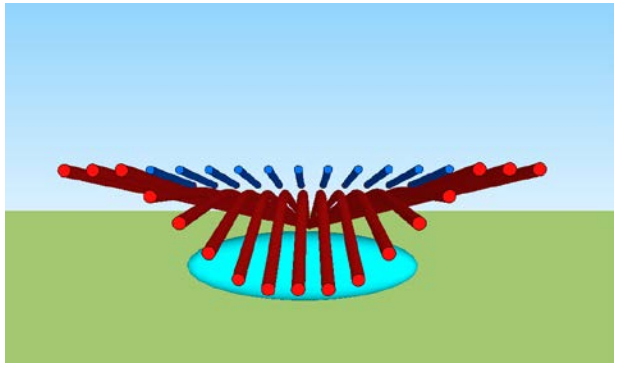


Stationary Electron Beam



Single Shot Sweep

Need bunch length >> sweep time
MI rms bunch length < 2-3 ns

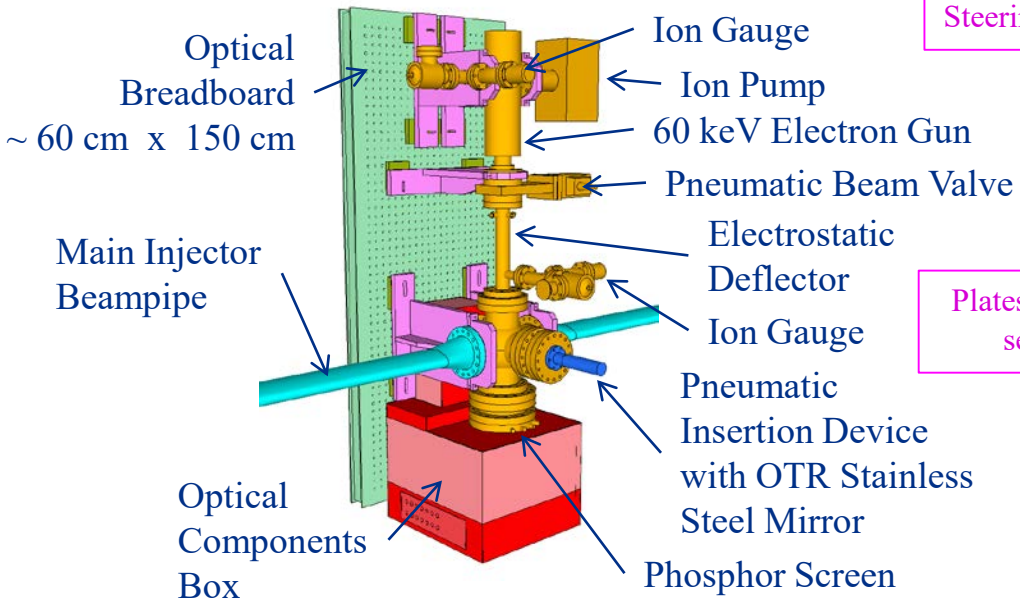


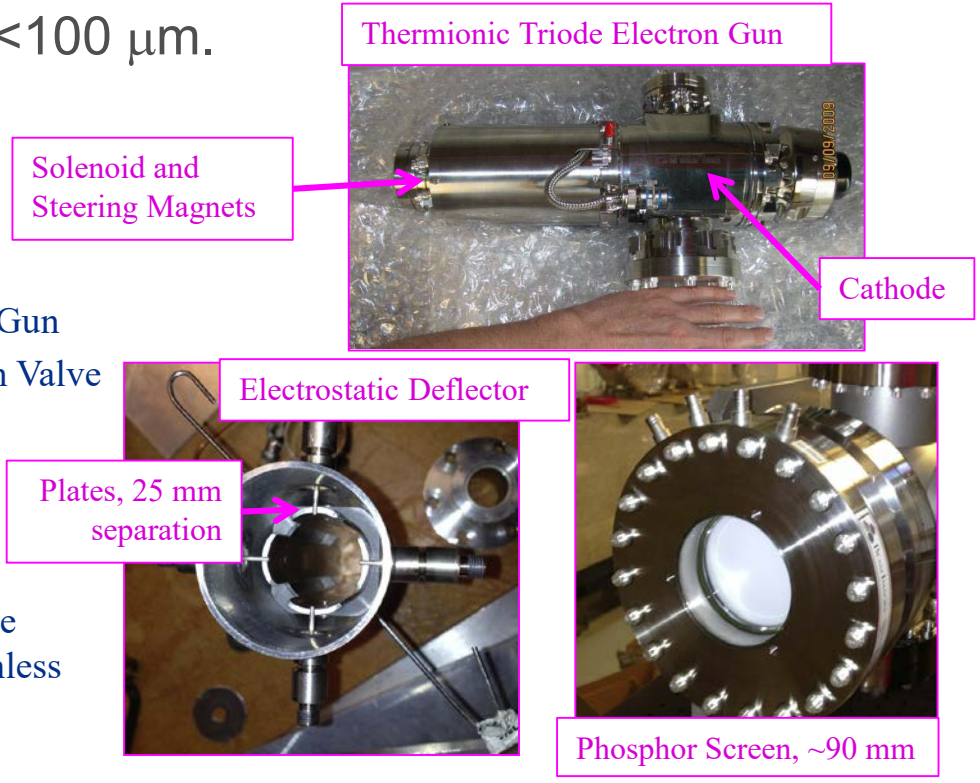
Raster Scan

Possibility of longitudinal slicing of transverse profile

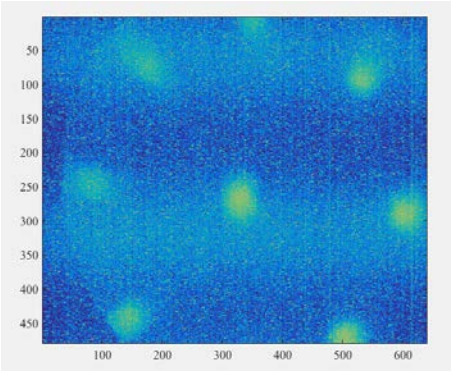
Electron Gun Beamline

- Electron Gun from Kimball Physics
  - Up to 60 keV, 6 mA, thermionic gun with a LaB_6 cathode
  - Can be gated from 2 μs to DC at a 1 kHz rate
  - Contains a focusing solenoid and four independent magnet poles for steering / focusing
  - Minimum working spot size is <100 μm.





Imaging Optics



Phosphor Screen
LED Calibration

Calibration
OTR

f = 125 mm

Selectable Neutral Density
Filters (ND 1,2,3) and
Ver / Hor Polarizers

Image
Intensifier

COHU CCD camera
plus C-mount
objective lens

Motorized Focusing Stage

Phosphor

f = 40 mm

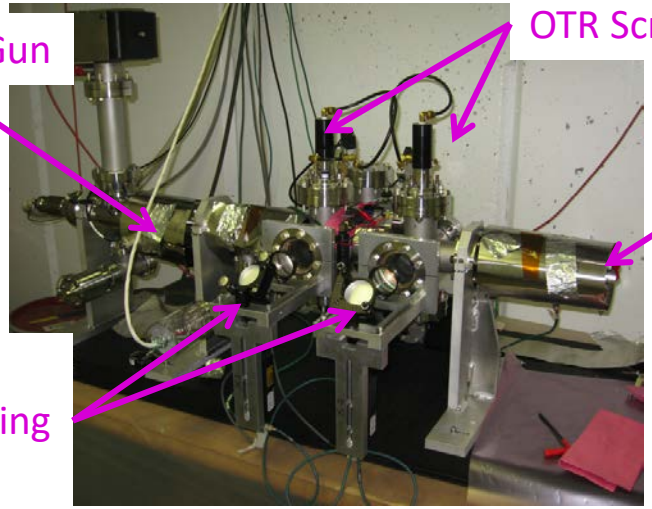
f = 40 mm

RS-170 video capture
via computer in service
building

Mirror on Motorized Stage selects OTR or Phosphor

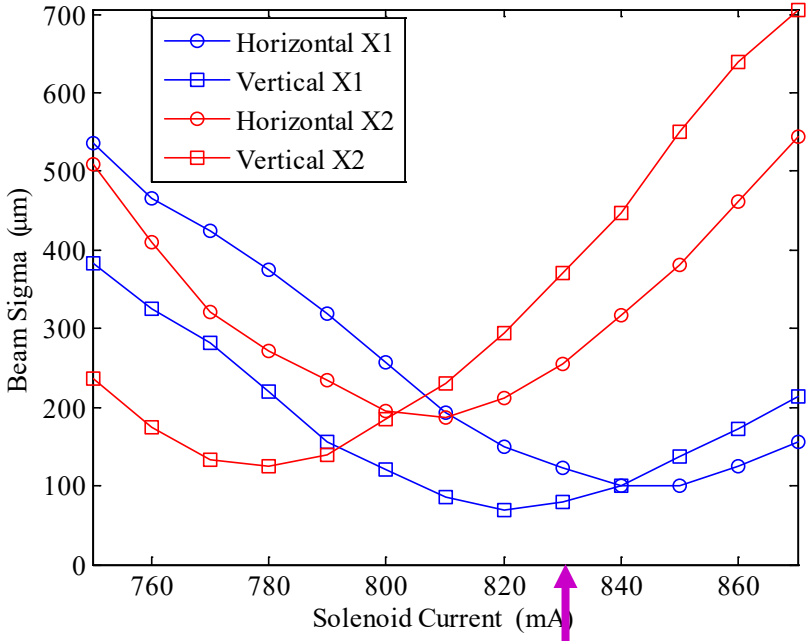
Motorized Focusing Stage

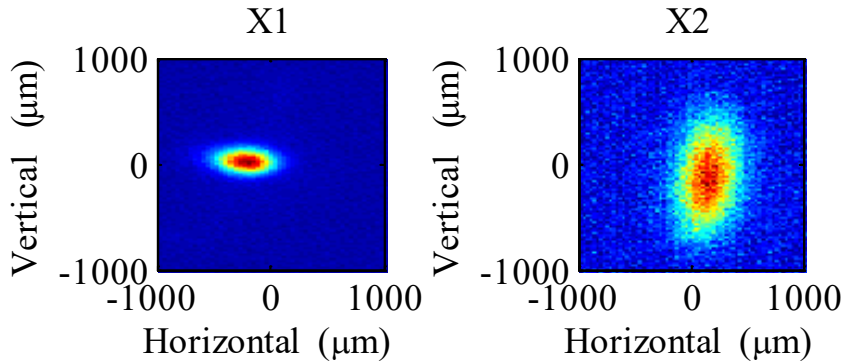
Test Stand e Beam Study



Electron Beam

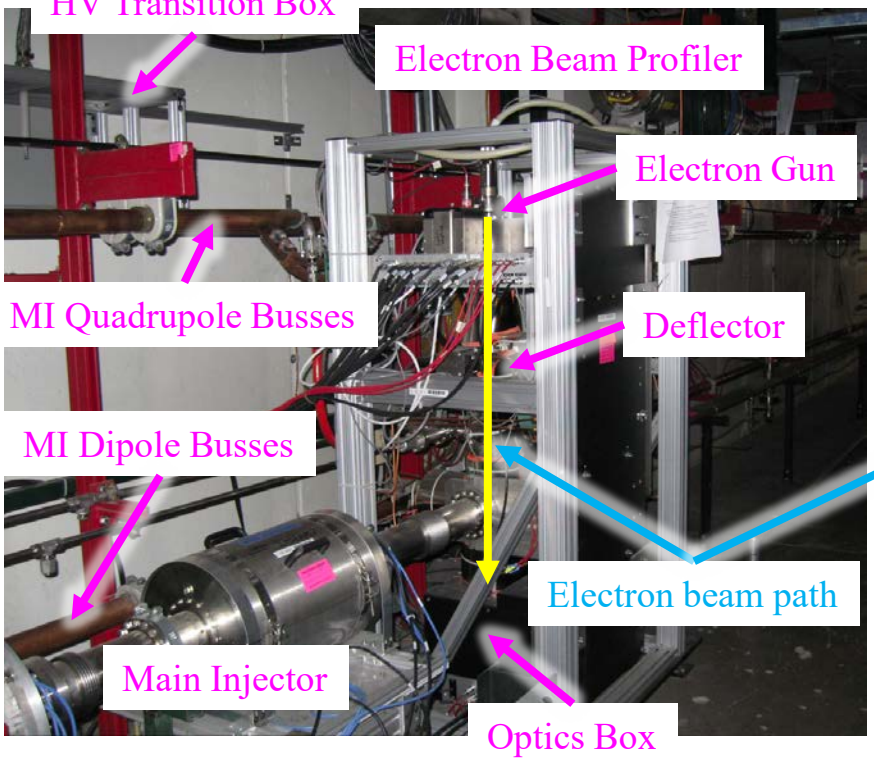
- 50 keV
- 1 mA

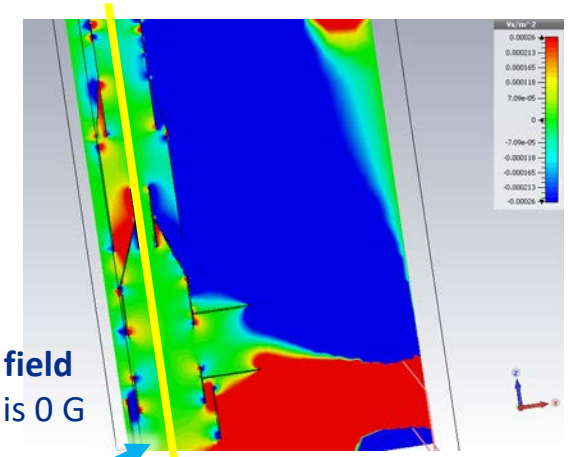




Installation

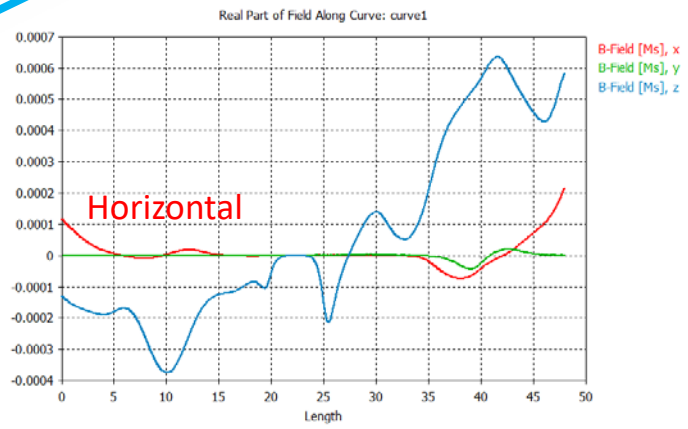
- Magnet ramp produces from 0 to ~7 gauss along electron beamline
- Wrapped in 3 layers of mumetal





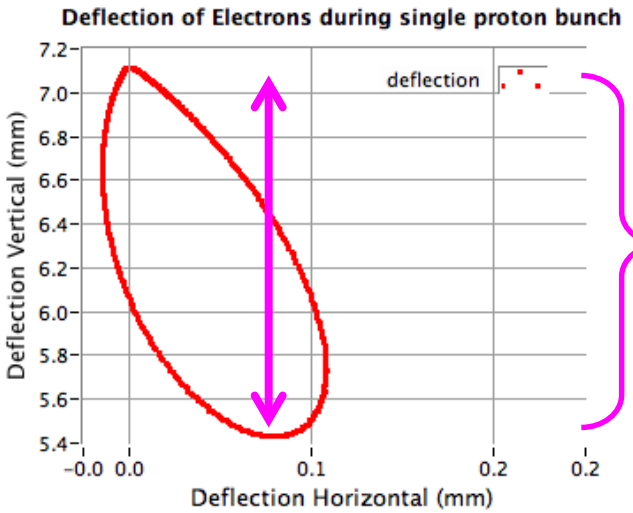
Horizontal B field
Green is 0 G

1 gauss / div

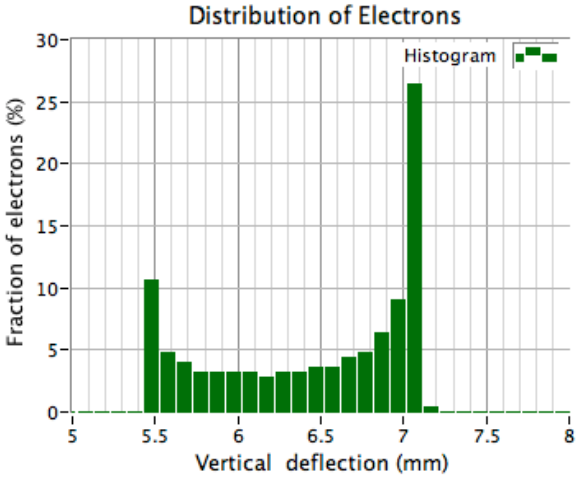


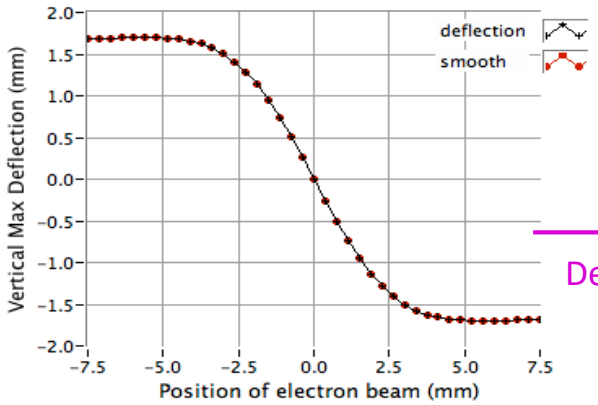
Stationary Electron Beam

- Position the electron beam at some impact parameter
- Record the deflection of the beam
- Move the electron beam and repeat the measurement

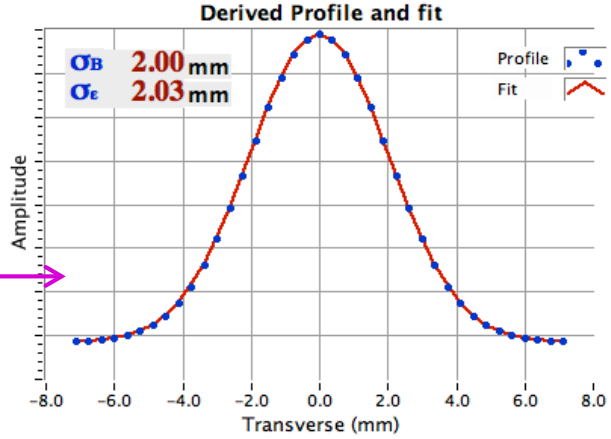


Projection





Derivative

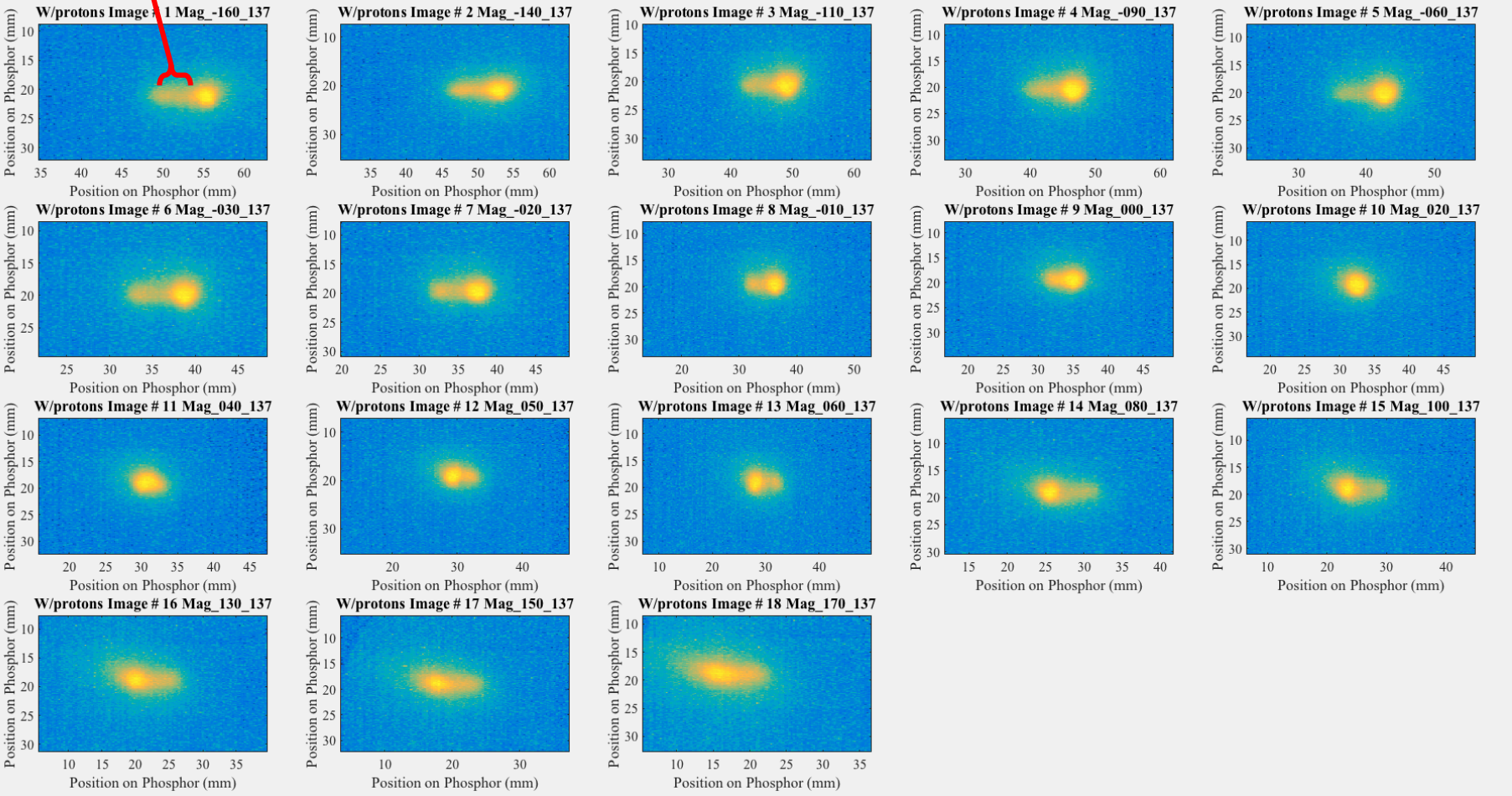


Plots courtesy of Wim Blokland

Stationary Electron Beam at Injection to MI

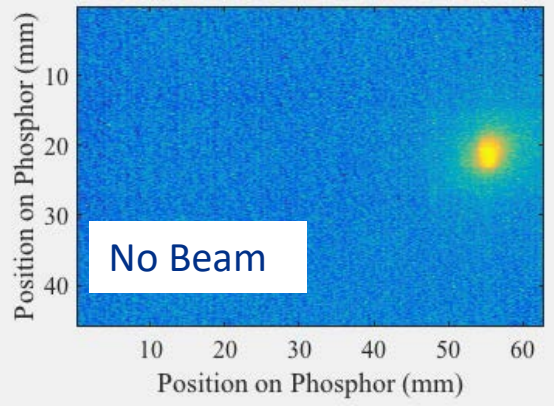
Deflection

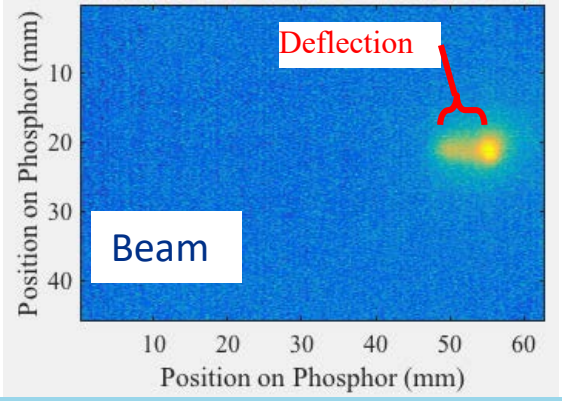
Impact parameter →

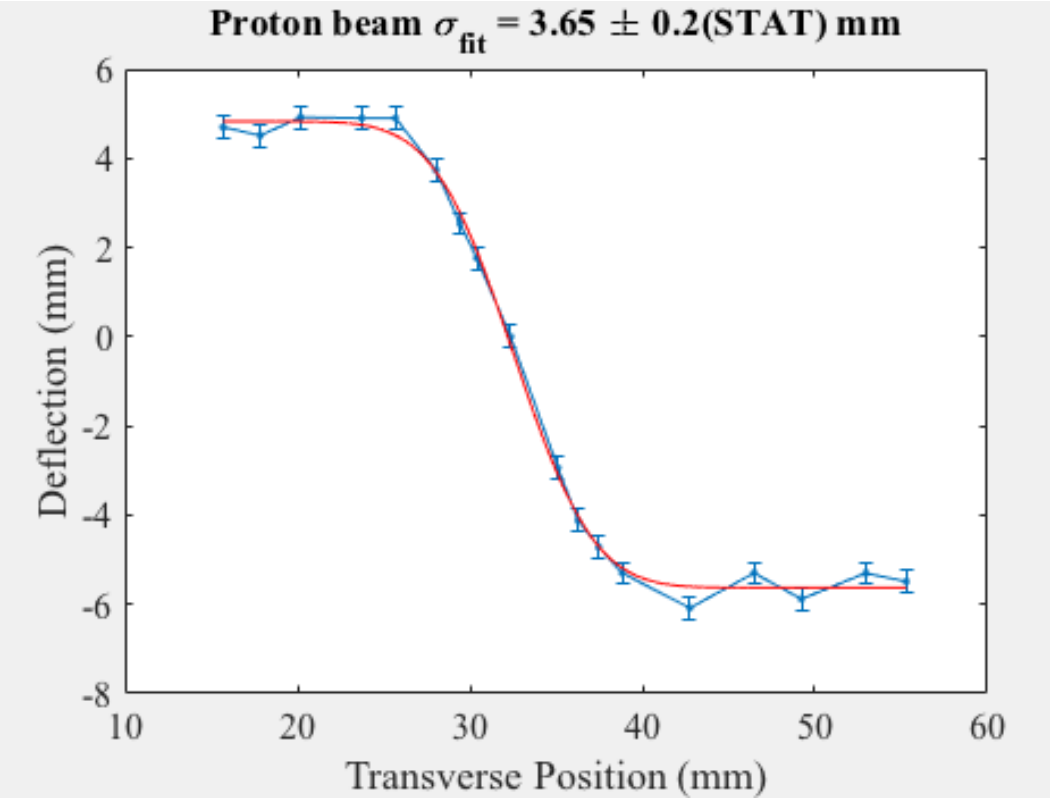


Measurement at Injection to MI

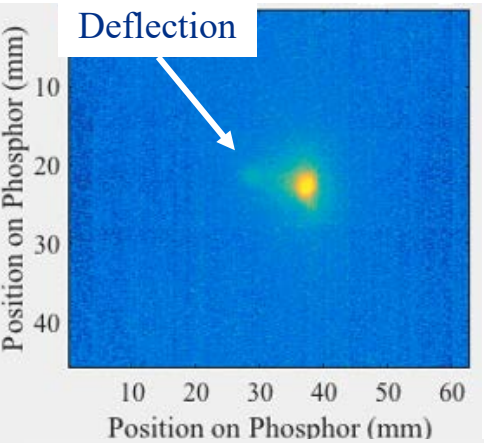
- MI Beam at injection is expected to be
  - ~3 mm horizontal rms
  - Several nanoseconds longitudinal rms



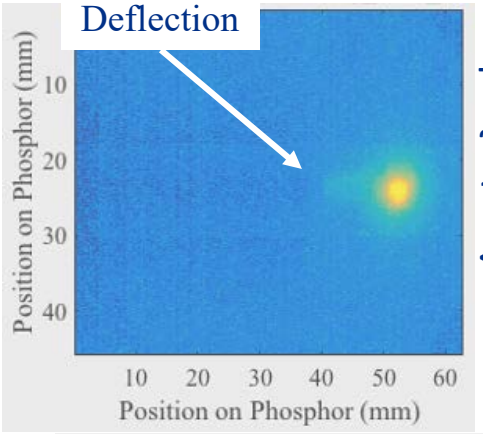




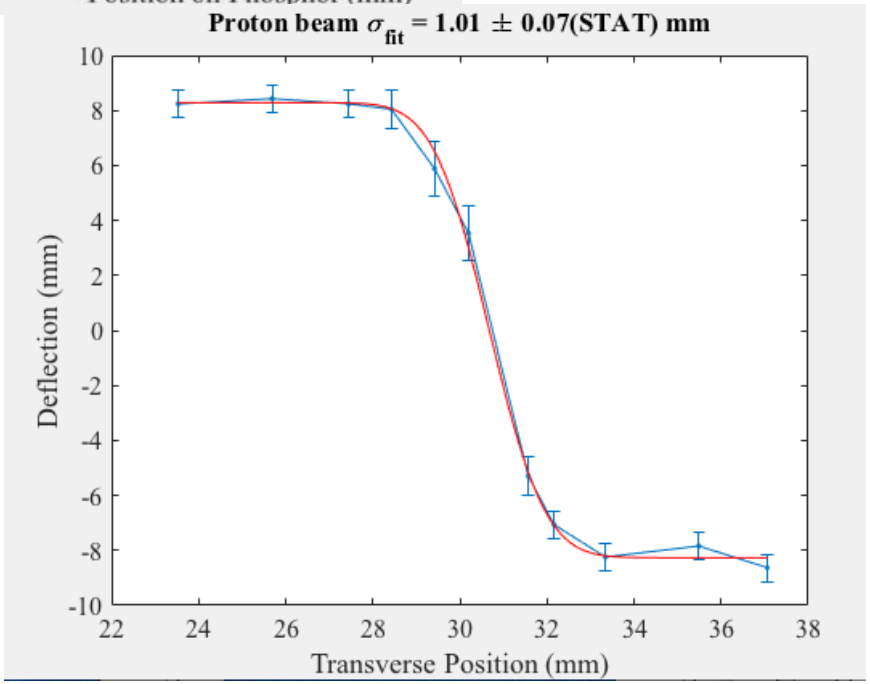
MI Extraction and Transition Crossing

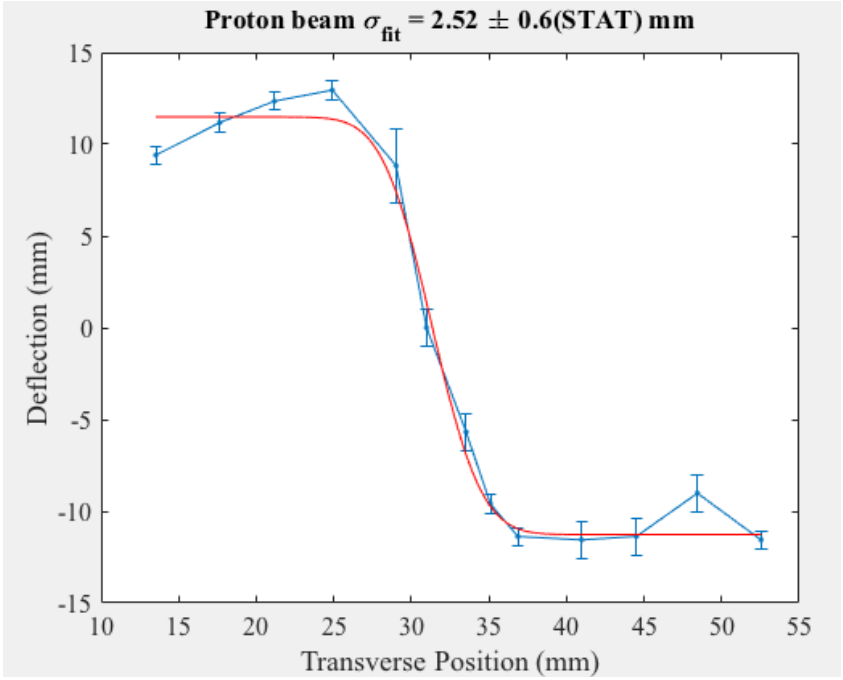


Extraction from MI
120 GeV
~1 mm horizontal rms
~1 ns longitudinal rms



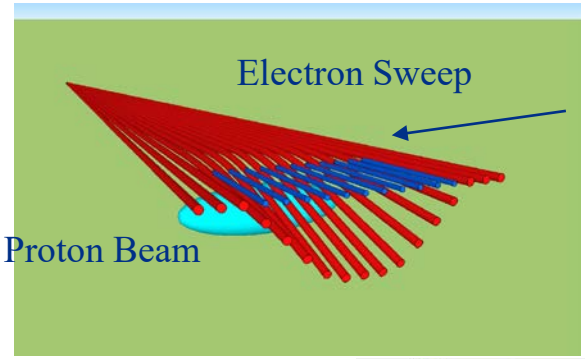
Transition Crossing
~20 GeV
? mm horizontal rms
<1 ns longitudinal rms

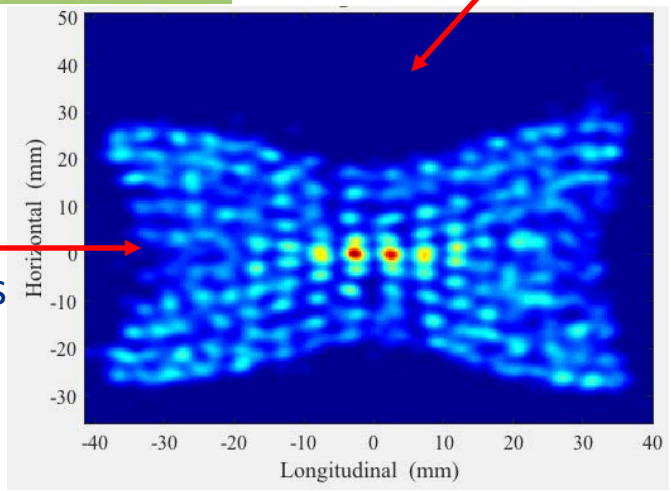




Raster Scan

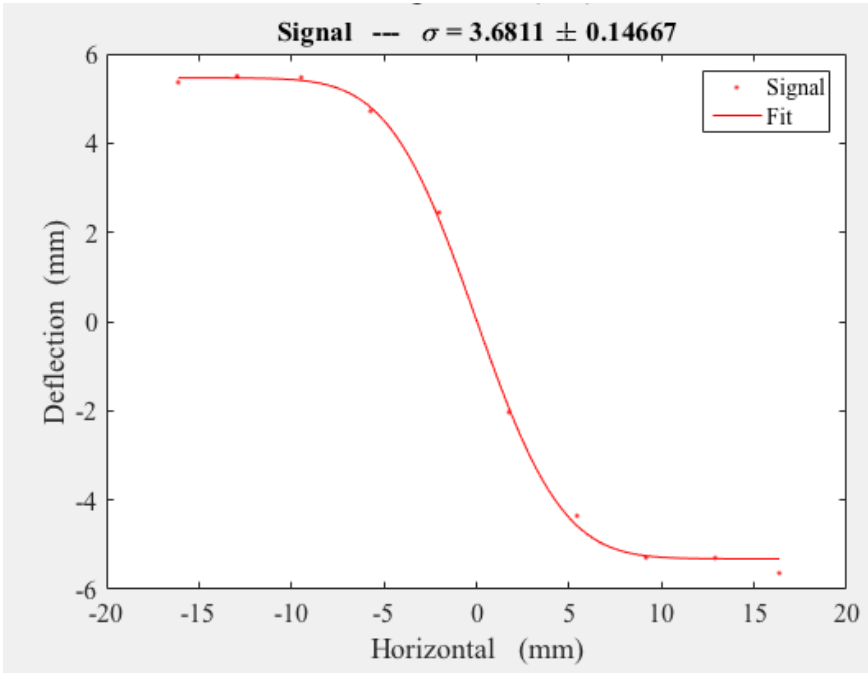
- Simulate a series of fast longitudinal sweeps each at a different impact parameter
- All sweeps appear within a single camera image





Problem with overlapping traces

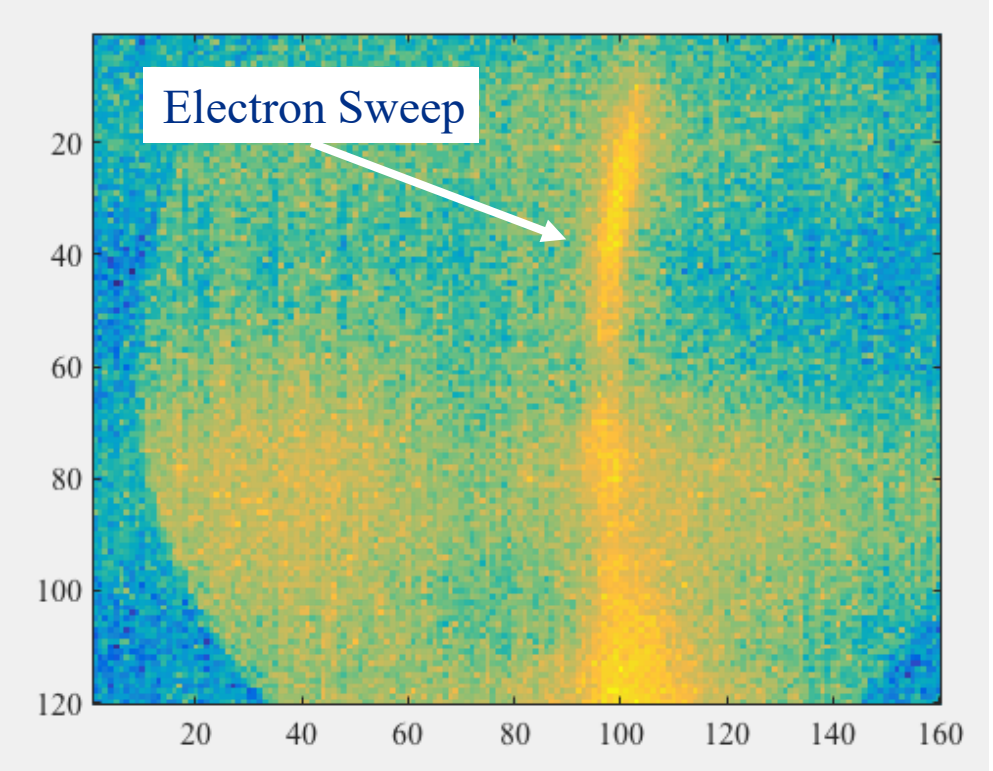
Generated at 3 mm



Fast Deflection

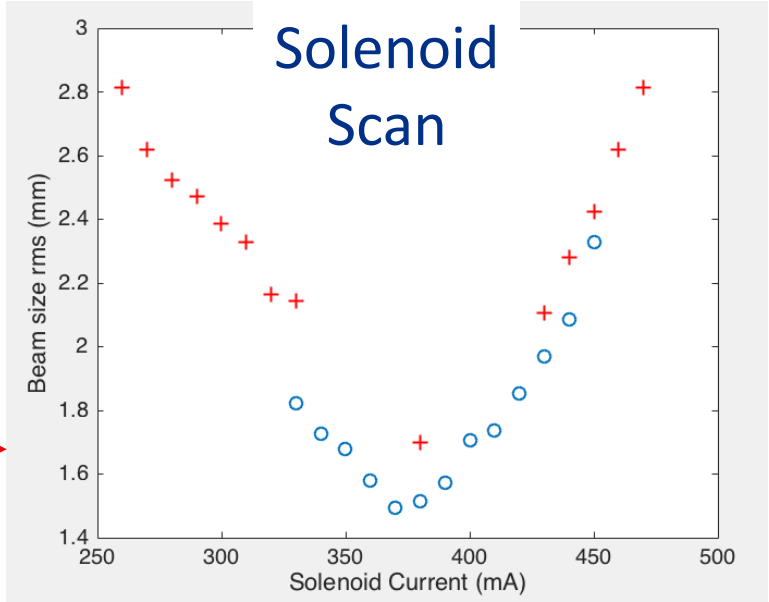
- Reused a fast pulser from Tevatron
  - Multi-FET based; positive and negative channels
  - Use rise of pulse as sweeping voltage
  - Rise time is < 20 ns on bench
    - Need to measure actual including cable
  - Need up to 500 V pulse

Sweep contains both initial deflection and return deflection
→ ~5 times brighter than just initial



Issues and Improvements

- CCD camera radiation sensitive and presents large 4 MHz noise
  - Noise downconverted from 53 MHz (MI bunch frequency)
  - Used for better sensitivity compared to CID camera
  - Replace with CID fiber-optically coupled to image intensifier
    - Better light collection to overcome sensitivity issue
- Replace phosphor screen which was damaged in initial startup (caused by poor CID sensitivity)
- Electron beam spot is not as small as expected from test stand results
  - Should have been much less than 1 mm rms
  - Measured spots on phosphor are > 1 mm rms



Summary

- Electron Beam Profiler has been installed in the Main Injector at Fermilab
- Initial testing has been done and a number of issues have been uncovered
  - Damaged phosphor screen
  - Optical sensitivity
- Measurements have been made using the stationary electron beam approach
  - Values and features are consistent with what is expected
- More commissioning will continue with the fast deflector setup
- Acknowledgements
  - Carl Lundberg, Peter Prieto, Matthew Alvarez, James Zagel, Jim Fitzgerald – FNAL
  - Willem Blokland – ORNL / SNS