Electron Beam Profiler for the Fermilab Main Injector*

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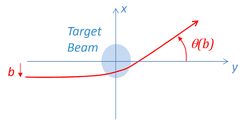
Abstract
The long range plan for Fermilab calls for large proton beam intensities in excess of 2 MW for use in the neutrino program. Measuring the transverse profiles of these high intensity beams is challenging and generally relies on non-invasive techniques. One such technique involves measuring the deflection of a beam of electrons with a trajectory perpendicular to the proton beam. A device such as this is already in use at the Spallation Neutron Source at ORNL and a similar device will be installed shortly in the Fermilab Main Injector. The Main Injector device is discussed in detail and some test results and simulations are shown

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 $\vec{r} \approx \{b, vt\}$

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

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

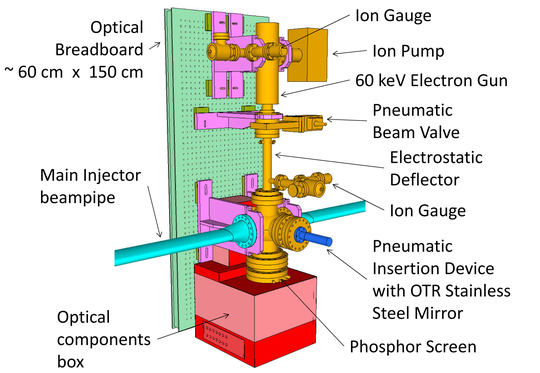
Assume again that deflection is very small such that $\vec{p} \approx \{0,p\}$ and $\theta \approx \frac{|\Delta\vec{p}|}{|\vec{p}|}$

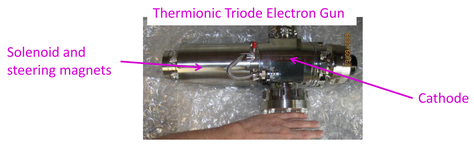
$$\theta(b) \propto \int_{-\infty}^{\infty}dx' \int_{-\infty}^{\infty}dy'\ \rho(x',y')\,\mathrm{sgn}(b-x') \rightarrow \frac{d}{db}\mathrm{sgn}(b-x') \propto \delta(b-x')$$

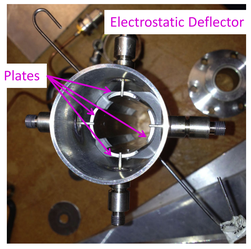
$$\frac{d\theta(b)}{db} \propto \int_{-\infty}^{\infty}dy'\ \rho(b,y') \leftarrow \text{x profile} \xleftarrow{\rho=2D\ gaussian} \frac{d\theta(b)}{db} = Gaussian(b)$$

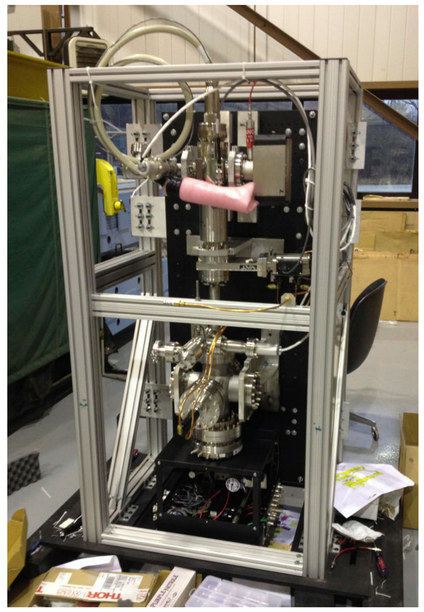
$$\theta(b) = \mathrm{erf}(b)$$

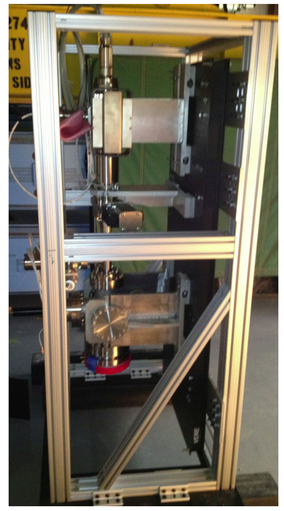
Device



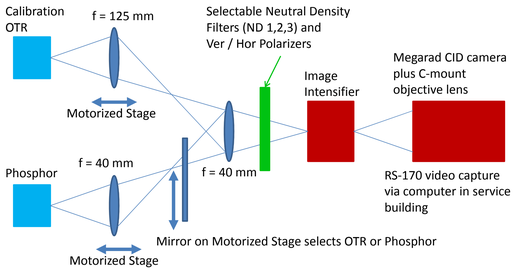


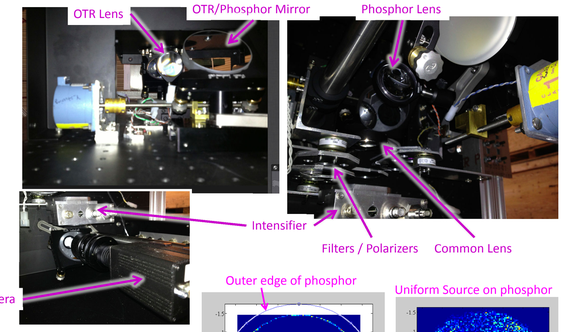


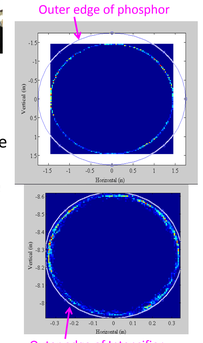


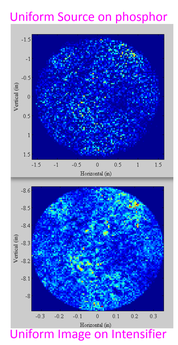


Optics







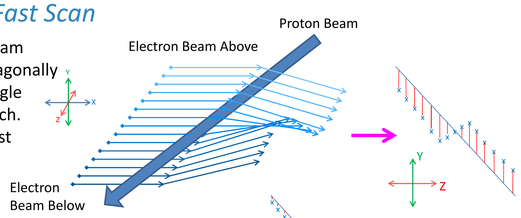


Ray tracing from source (top) to image planes (bottom) to determine aperture (left) and uniformity (right).

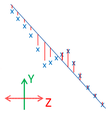
Experimental Techniques

Fast Scan

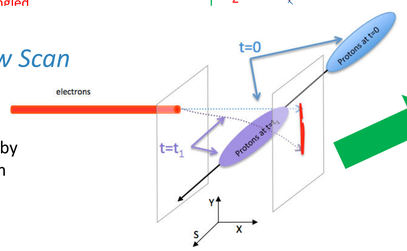
Electron beam scanned diagonally through single proton bunch. Requires fast deflector.



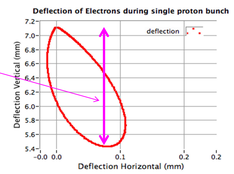
If scan time is too slow longitudinal and transverse charge distributions become entangled



Slow Scan



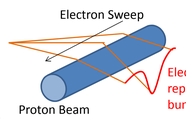
Trajectory followed by a stationary electron beam as the proton bunch passes by. There is some deflection along the proton beam direction due to the magnetic field of the proton beam, but it is much smaller than the deflection transverse to the proton beam.



Deflection

Fast and Slow

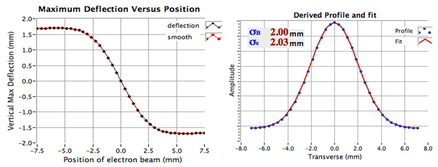
Electron beam scanned along single proton bunch. Repeated at different impact parameters.



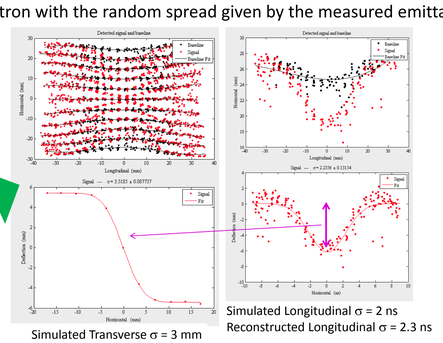
Electron deflection replicates longitudinal bunch structure

Simulations

Deflection plot of electron beam using slow scan method, and the derivative of it, showing agreement to better than 2%.



Simulated deflection data for varying impact parameters using the fast and slow method. The black points are baseline deflections with no beam. They result from the non-uniform deflector field. Each point represents a single electron with the random spread given by the measured emittance.

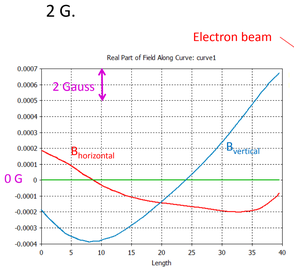


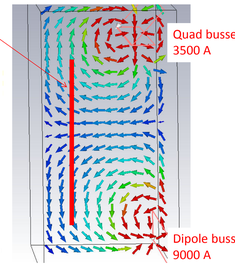
Simulated Transverse σ = 3 mm
Reconstructed Transverse σ = 3.5 mm

Simulated Longitudinal σ = 2 ns
Reconstructed Longitudinal σ = 2.3 ns

External Magnetic Fields

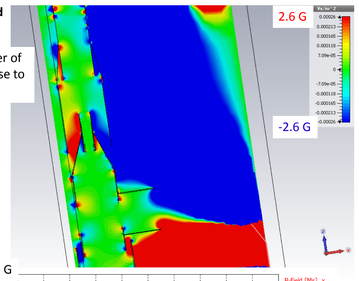
CST simulation of magnetic field from magnet busses along the line of the electron beam. The horizontal component is most important as the electron beam is vertical. The maximum horizontal field is 2 G.



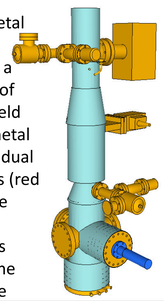


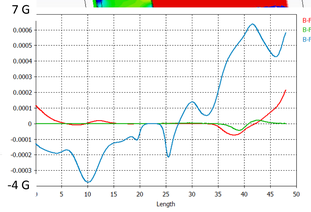
Horizontal B field
Green is 0 G

Slice through center of Mu metal transverse to proton beam



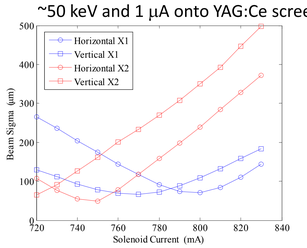
Model of mumetal wrap. The far intensity plot is a CST simulation of the magnetic field inside the mumetal shield. The residual horizontal fields (red and green in the lower plot) are significantly less than 1 G with the exception of the ends.



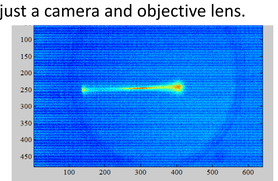


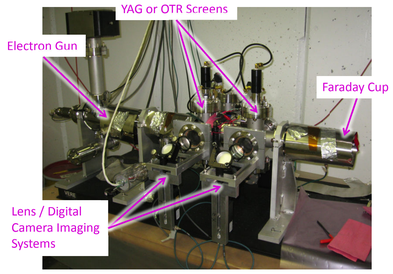
Test Stand

Horizontal and vertical rms beam sizes at the first (blue) and second (red) crosses in the test stand. The electron beam was ~50 keV and 1 μA onto YAG:Ce screens.

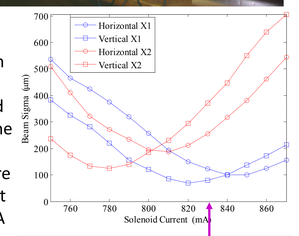


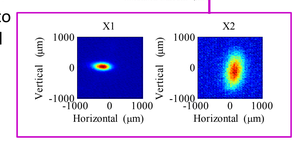
Trace of the electron beam on the phosphor screen for a deflecting voltage of ~±150 V. This image was taken with just a camera and objective lens.





Horizontal and vertical rms beam sizes at the first (blue) and second (red) crosses in the test stand. The measurements are from OTR taken at ~50 keV and 1 mA beam current onto the stainless steel mirrors.





* Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy.
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