Progress on an Electron Beam Profile Monitor at the Fermilab Main Injector*

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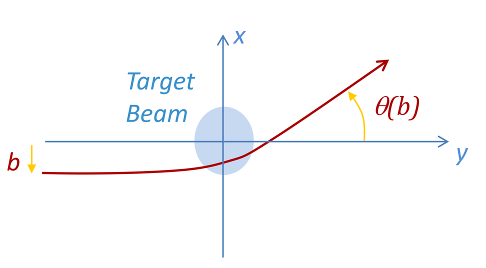
Abstract
The current program at Fermilab involves the construction of a new superconducting linear accelerator (LINAC) to replace the existing warm version. The new LINAC, together with other planned improvements, is in support of proton beam intensities in the Main Injector (MI) that will exceed 2 MW. Measuring the transverse profiles of these high intensity beams in a ring requires non-invasive techniques. The MI uses ionization profile monitors as its only profile system. An alternative technique involves measuring the deflection of a probe beam of electrons with a trajectory perpendicular to the proton beam. This type of device was installed in MI and initial studies of it have been previously presented. This paper will present the status and recent studies of the device utilizing different techniques.

Introduction

Historically, thin wires were rapidly swept through the beam and downstream losses recorded as a function of the position of the wire to construct the profile. These were called flying wires [1]. In the Main Injector (MI) at Fermilab, they were removed around 2012 due to wire breakage which was not understood.

The concept of a probe beam of charged particles to determine a charge distribution has been around since at least the early 1970's [2-4]. Several conceptual and experimental devices have been associated with accelerators around the world [5-9]. An operational device is presently in the accumulator ring at the Spallation Neutron Source at Oak Ridge National Lab [10]. The EBP was constructed and installed in the Main Injector (MI) in 2014 and initial results have been presented previously [11].

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 $\theta \approx \frac{|\Delta\vec{p}|}{|\vec{p}|}$

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

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

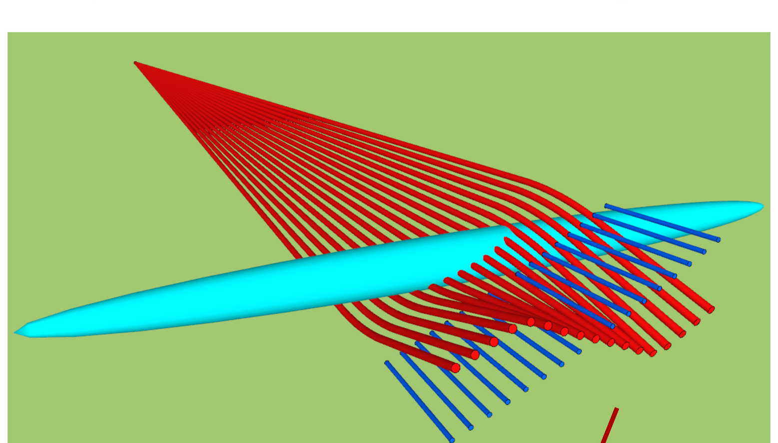
$$\theta(b) = \mathrm{erf}(b)$$

Experimental Technique

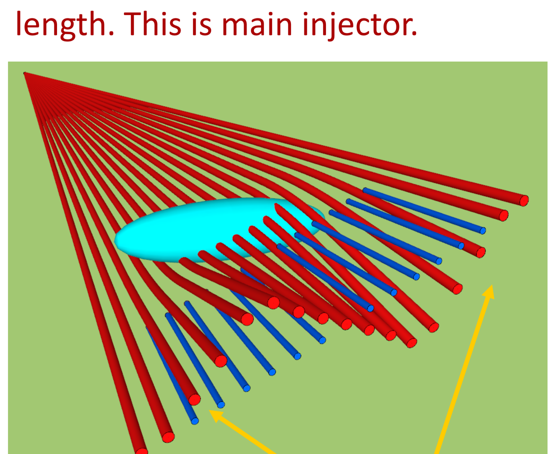
Measure the deflection for a range of impact parameters. There are various approaches to accomplishing this.

Fast sweeps diagonally through bunch

Sweep time much shorter than bunch length



Sweep time longer than bunch length. This is main injector.



Variation

Deflection shape is function of bunch length

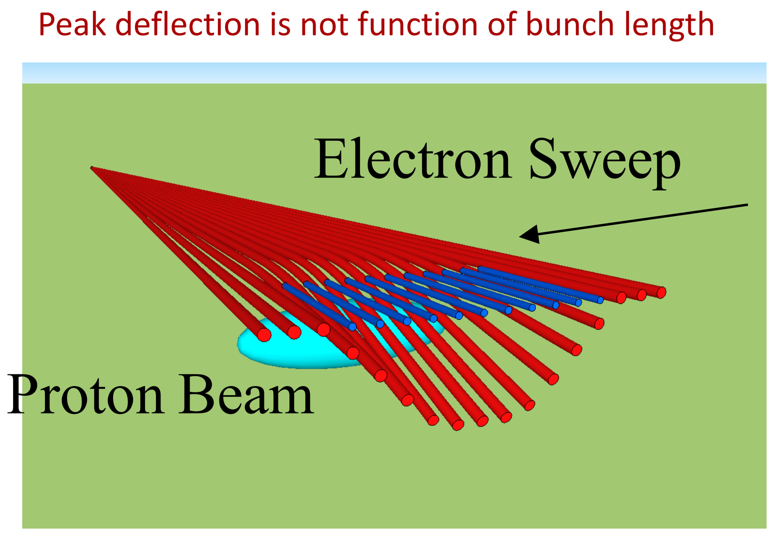
Solutions?

Slow sweep diagonally through many bunches

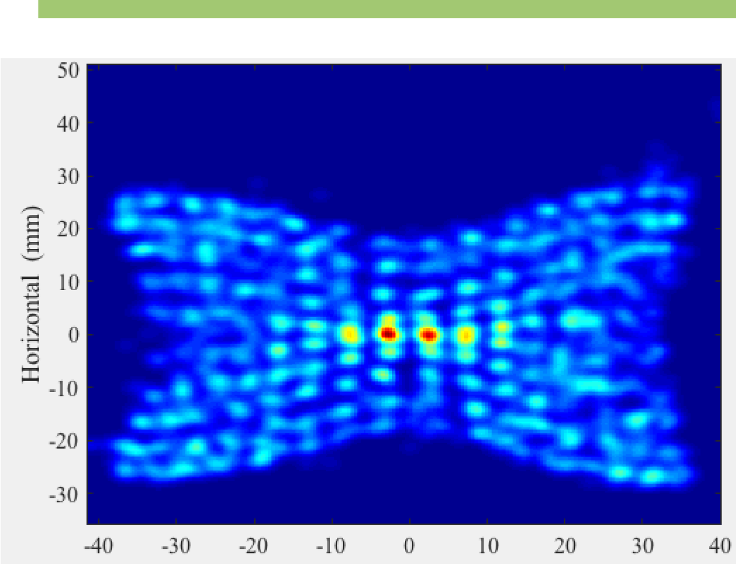
Similar to above, but instead of a long bunch, it is a train of short bunches, so the gap between the deflected and non-deflected fills in.

Multiple fast sweeps along bunch

Peak deflection is not function of bunch length

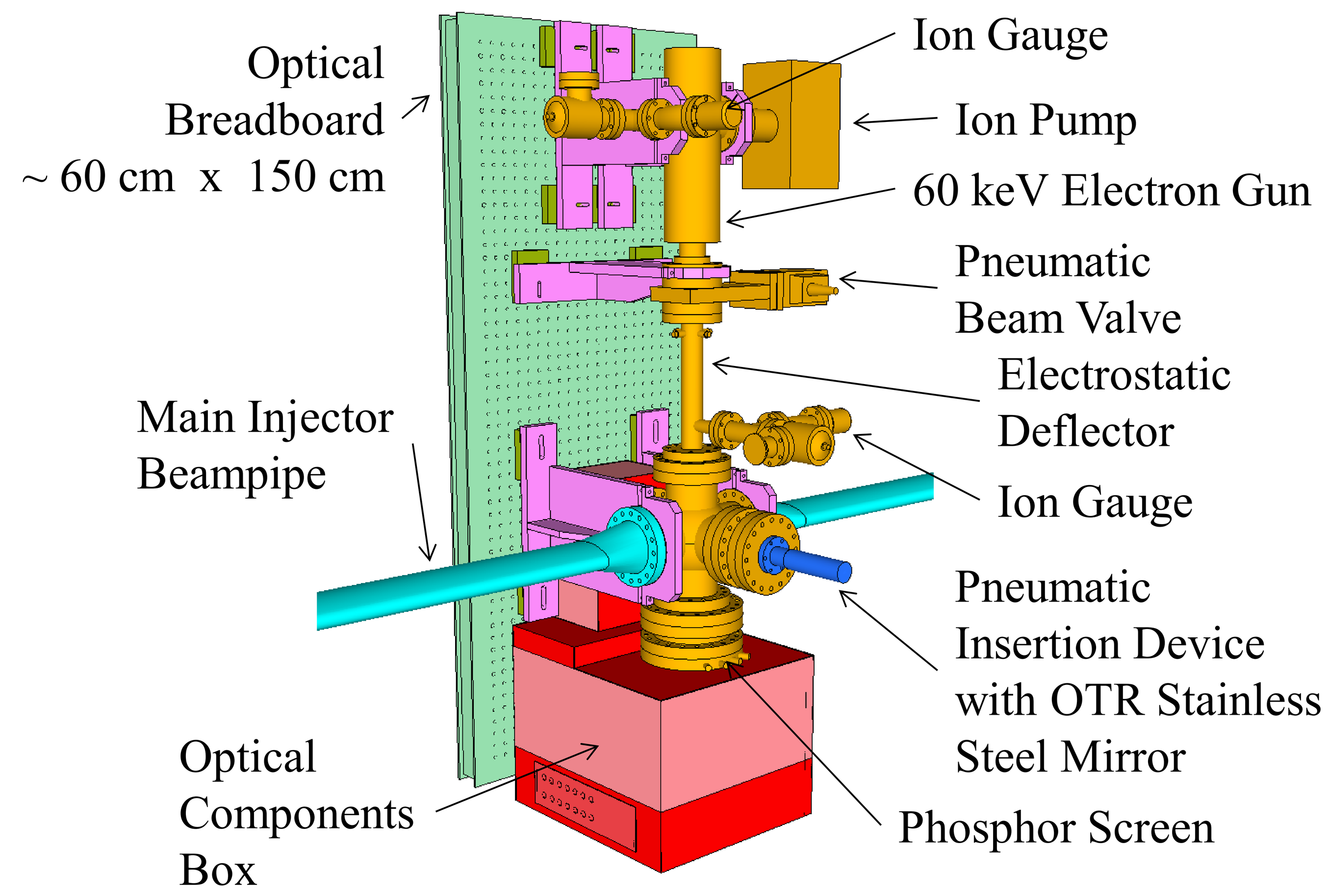


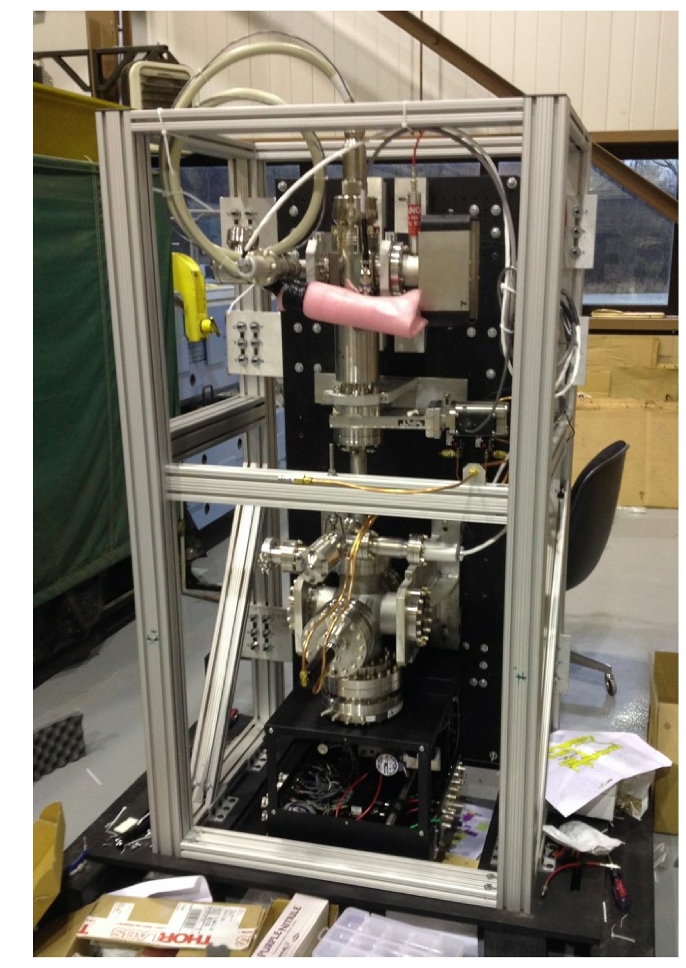
Electron deflection replicates the longitudinal bunch structure. Might be possible to measure transverse size vs. longitudinal position.



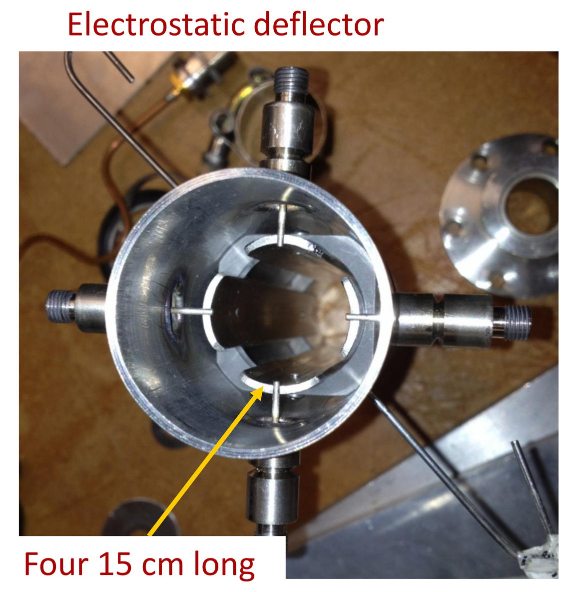
Simulations of the deflections in this approach. Successive sweeps along the proton direction at different impact parameters are displayed in the same image. One can see that the central deflections may overlap each other and need to be separated, perhaps in different camera frames.

Experimental Device

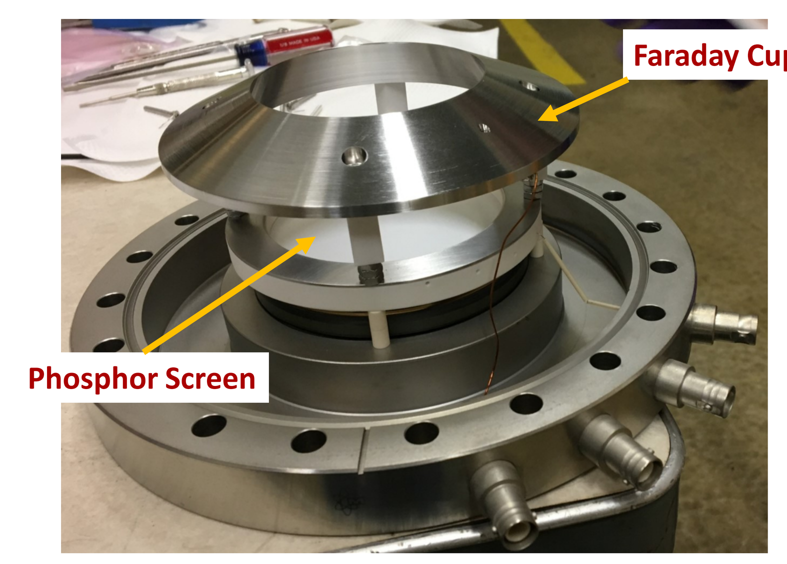


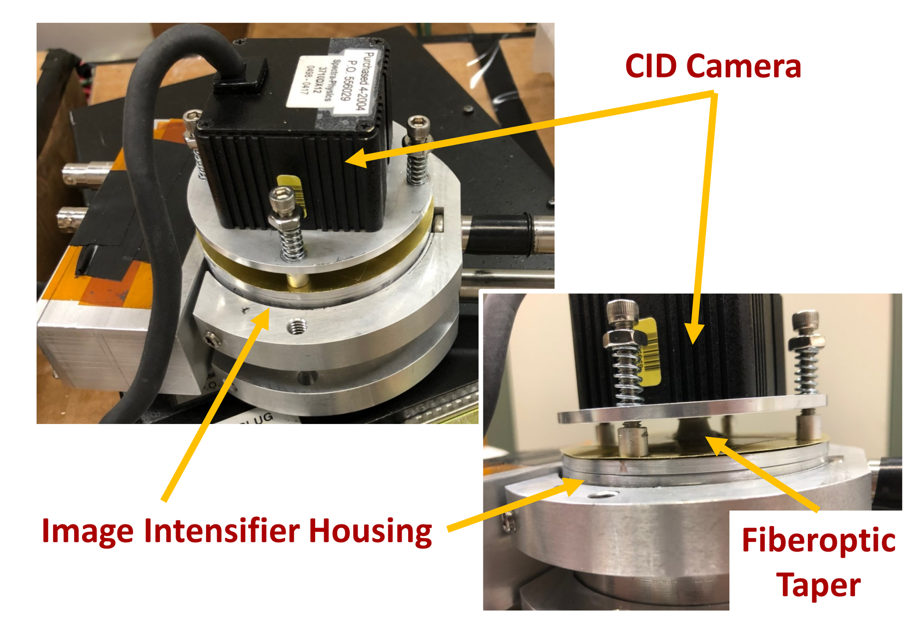


Electrostatic deflector



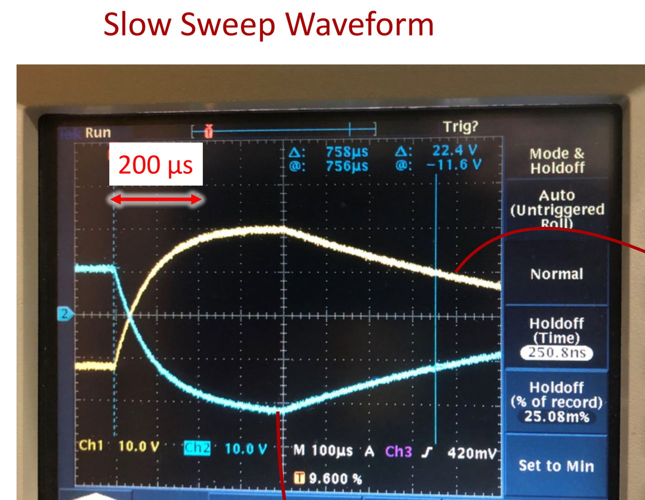
Four 15 cm long curved plates





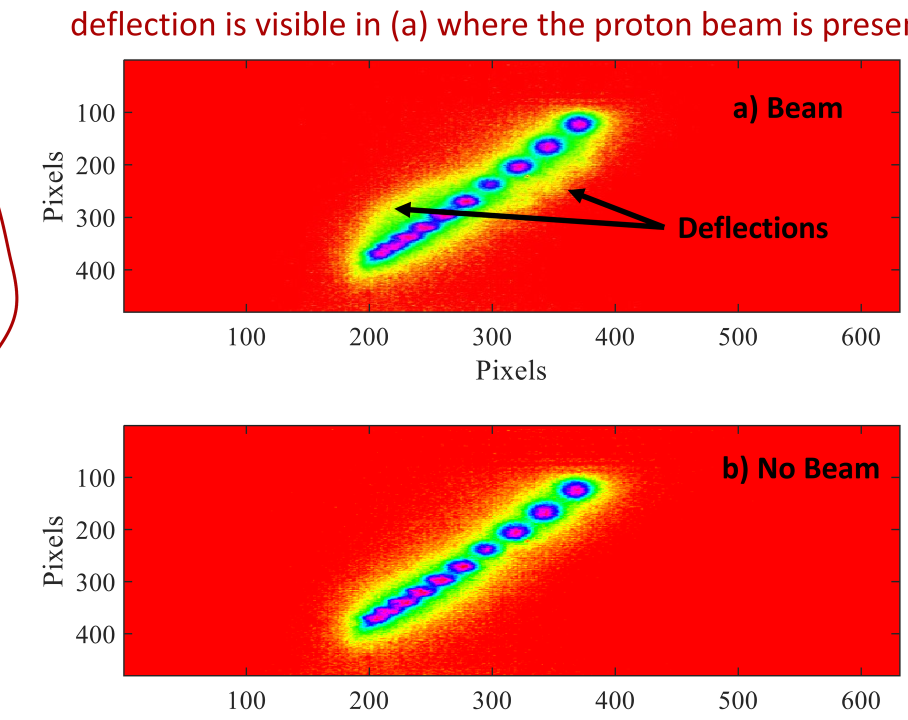
Slow Sweep

Slow Sweep Waveform



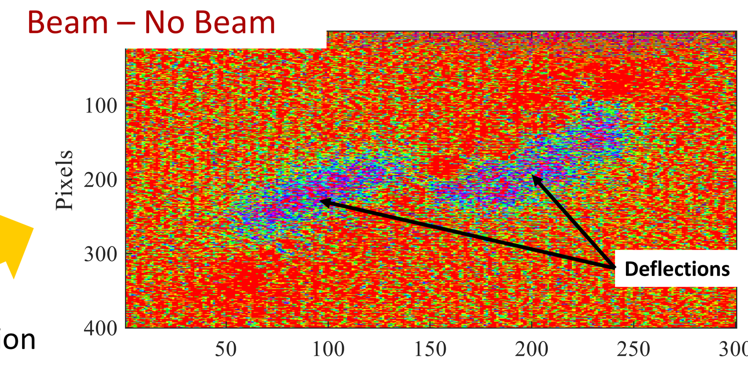
One trace to adjacent pairs of deflecting plates

Slow sweep of electron beam. The individual spots are image intensifier gates. A slight enhancement from the electron deflection is visible in (a) where the proton beam is present.

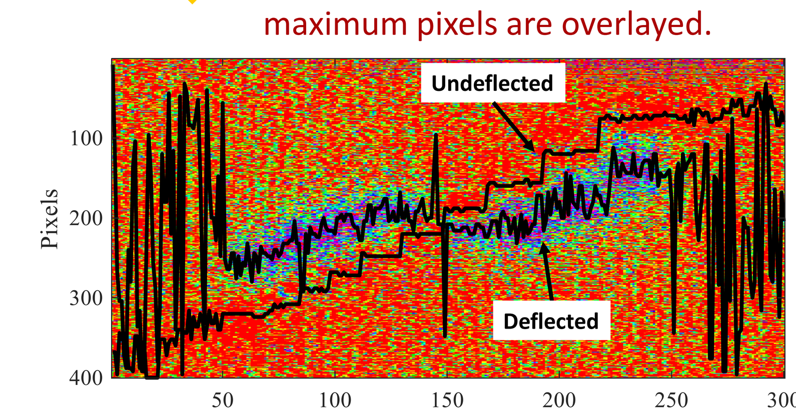


Deflection Direction

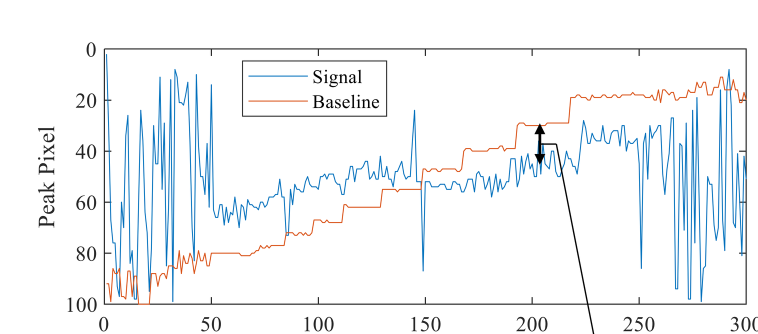
Beam – No Beam

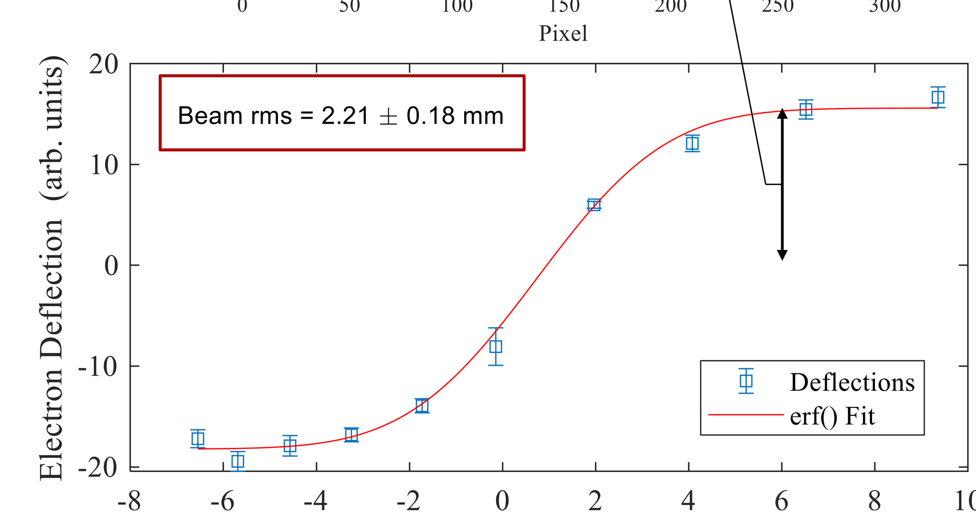


Now find the maximum pixel value in each column as well as the maximum pixel in each column of the no-beam image. Here these two curves of maximum pixels are overlayed.



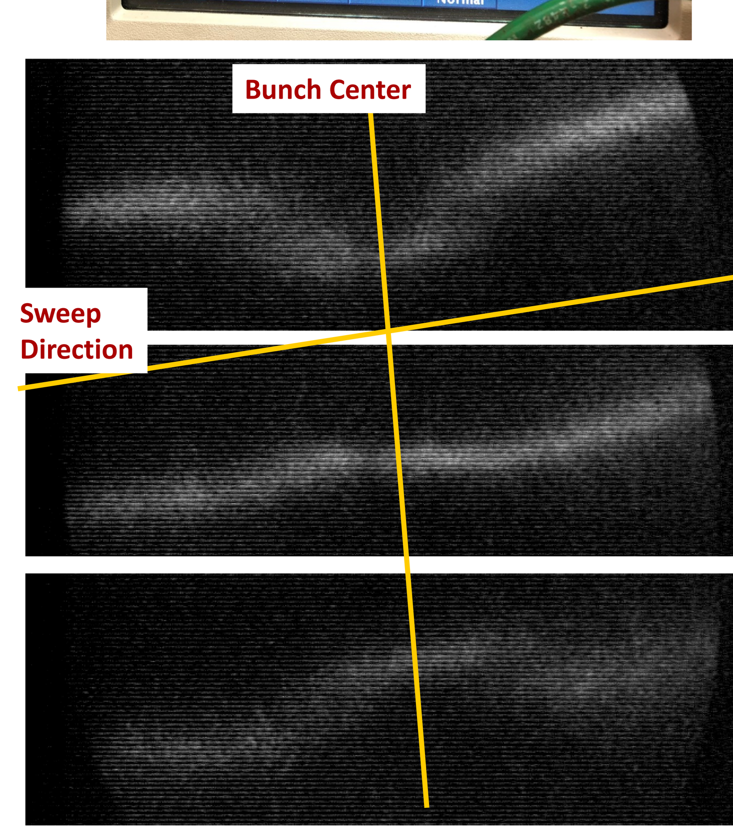
The undeflected curve shows the step structure of the discrete spots in the original no-beam image . The difference between these two curves is the deflection distance. We evaluate the average deflection distance for each step region, together with the impact parameter for each step to produce the $\theta(b) = \mathrm{erf}(b)$ curve below. For reference, the ionization profile monitor measured 1.71 mm.





Fast Sweep Test

Fast deflection waveforms.



Deflected Down

Not Deflected

Deflected Up

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