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.

INTRODUCTION

Traditional techniques for measuring the transverse profile of proton beams typically involve the insertion of a physical object into the path of the proton beam. Flying wires for instance in the case of circulating beams, or secondary emission devices for single pass beamlines. With increasing intensities, these techniques become difficult, if not impossible. A number of alternatives exist including ionization profile monitors, gas fluorescence monitors, and the subject of this paper, electron beam profile monitors.

The use of a probe beam of charged particles to determine a charge distribution has been around since at least the early 1970's [1-3]. In those examples, the charge distribution was a plasma, and the probe beam was electrons. Later, the concept was applied to ion beams at a number of facilities [4-6]. At CERN a version using a probe beam of ions was used to average over the bunch structure of the proton beam in the SPS [7]. A variation on the technique was the use of an electron probe beam to measure the longitudinal charge distribution in an electron injector at BINP [8]. The most recent incarnation of this technique is a profile monitor in the accumulator ring at SNS [9,10].

An Electron Beam Profiler (EBP) has been constructed at Fermilab and will be installed shortly in the Main Injector. The Main Injector is a proton synchrotron that can accelerate protons from 8 GeV to 120 GeV for use by a number of neutrino experiments, and eventually several muon-based experiments. The protons are bunched at 53 MHz for a typical rms bunch length of 1-2 ns. In this paper we discuss the design of the EBP and present some studies of the electron beam.

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THEORY

The principle behind the EBP is just electromagnetic deflection of the probe beam by the target beam under study (Fig. 1).

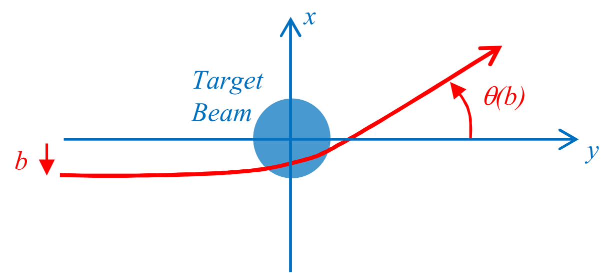

Figure 1: Probe beam deflection (red) for some impact parameter b.

If one assumes a target beam with $\gamma \gg 1$, no magnetic field, and $\rho \neq f(z)$, then the force on a probe particle is

$$\vec{F}(\vec{r}) \propto \int d^2\vec{r}'\rho(\vec{r}')\frac{(\vec{r}-\vec{r}')}{|\vec{r}-\vec{r}'|^2}$$

and the change in momentum is

$$\Delta\vec{p} = \int_{-\infty}^{\infty} dt\ \vec{F}\big(\vec{r}(t)\big)$$

For small deflections, $\vec{r} \approx \{b, vt\}$, and the change in momentum is

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

where $\{\}$ indicates a vector. For small deflections, $\vec{p} \approx \{0,p\}$ and $\theta \approx \frac{|\Delta\vec{p}|}{|\vec{p}|}$. The integral over time can be written as $\mathrm{sgn}(b - x')$ leading to an equation for the deflection

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

If one takes the derivative of $\theta(b)$ with respect to b, the sgn function becomes $\delta(b-x')$ leading to

$$\frac{d\theta(b)}{db} \propto \int_{-\infty}^{\infty} dy'\,\rho(b,y')$$

which is the profile of the charge distribution of the beam. Thus for a Gaussian beam, this would be a Gaussian distribution and the original deflection angle would be the error function, $\mathrm{erf}(b)$. This of course is true only to the extent that the above assumptions are valid.

EXPERIMENTAL PROCEDURE

There are a number of techniques for obtaining $\theta(b)$. A fast scan of the electron beam diagonally through the proton bunch (Fig. 2) can in principle achieve a measurement in one pass of the bunch. This requires a deflection of the electron beam in a period that is much shorter than the proton bunch. For the Main Injector, this would be sub-nanosecond and may be difficult to achieve.

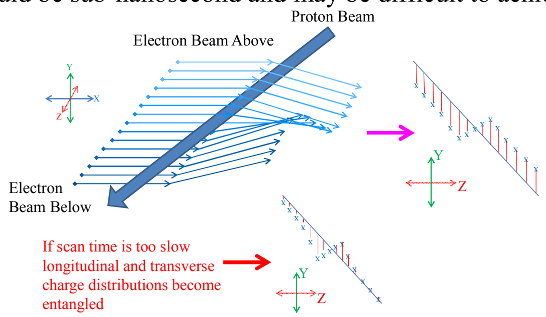

Figure 2: Fast scan of the electron beam though the proton beam. One can see the erf-like deflection from the baseline.

A second method involves slowly stepping the electron beam through the proton beam and recording a deflection value on each turn of the proton bunch (Fig. 3). In this method the electron beam is stationary each time the proton bunch passes, and then is moved to the next impact parameter.

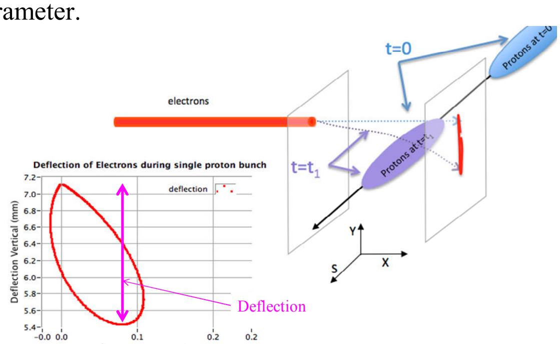

Figure 3: Trajectory followed by a stationary electron beam as the proton bunch passes by. There is some deflection along the proton beam direction due to the magnetic field of the proton beam, but it is much smaller than the deflection transverse to the proton beam.

A variation on the slow scan is to scan quickly along the proton beam direction and slowly transverse to the beam (Fig. 4). This provides a measurement of the longitudinal profile at each step as well as the transverse profile.

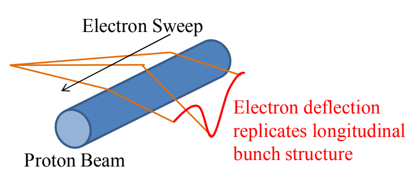

Figure 4: Deflection when the electron beam is scanned along the direction of the proton bunch with a duration equalling the bunch structure.

APPARATUS

The device (Fig. 5 and Fig. 6) that was constructed for the Main Injector consists of the EGH-6210 electron gun from Kimball Physics, followed by a cylindrical, parallel-plate electrostatic deflector, and terminating in a phosphor screen.

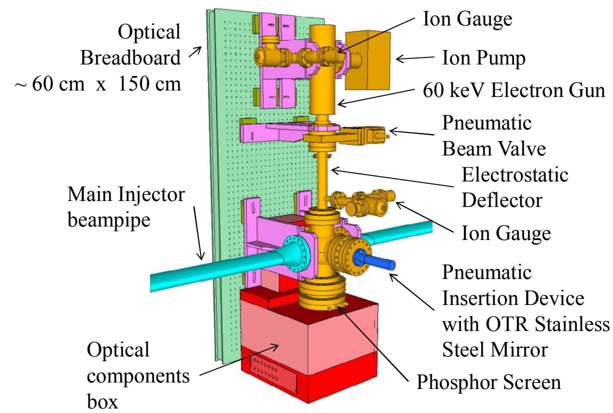

Figure 5: Model of the EBP showing the main components.

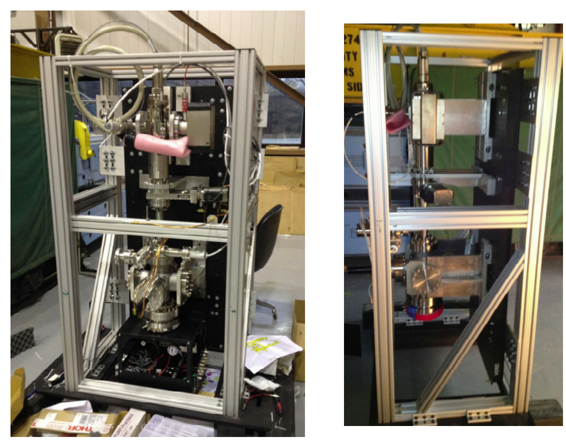

Figure 6: Assembled device front and side views.

The gun (Fig. 7) is a 60 keV, 6 mA, thermionic gun with a LaB_6 cathode, that can be gated from 2 µs to DC at a 1 kHz rate. The gun contains a focusing solenoid and four independent magnet poles for steering/focusing. The minimum working spot size is <100 µm. The electrostatic deflector (Fig. 7) contains 4 cylindrical plates that are 15 cm long and separated by ~2.5 cm.Following the electrostatic deflector is the intersection with the proton beamline. There is a pneumatic actuator at this point with a stainless steel mirror for generating optical transition radiation (OTR) to be used in calibrating the electron beam. After the proton beam intersection there is a phosphor screen from Beam Imaging Systems (Fig. 7). It is composed of P47 (Y_2SiO_5:Ce3+) with an emission wavelength of 400 nm, a decay time of ~60 ns and a quantum yield of 0.055 photons/eV/electron. The phosphor screen has a thin conductive coating with a drain wire attached.

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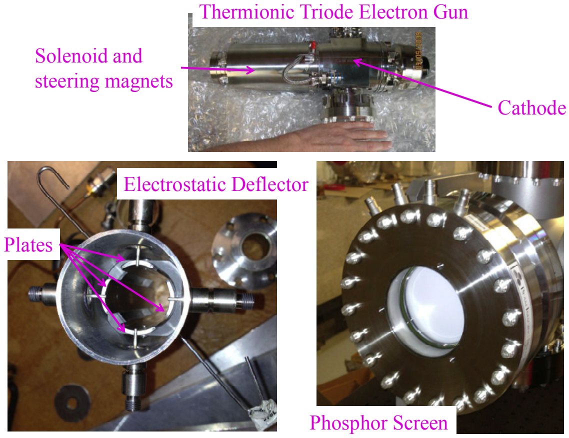

Figure 7: Left) Inside view of the electrostatic deflector showing the cylindrical parallel plates. Right) Phosphor screen mounted in an 8 in Conflat flange. A drain wire is attached between the screen and one of the SHV connectors.

Both the OTR and the phosphor screen are imaged by a single intensified camera system (Figs. 8 and 9). The source is chosen by a mirror on a moving stage. Each source traverses a two-lens system plus optional neutral density filters or polarizers before entering the image intensifier (Hamamatsu V6887U-02). The output of the intensifier is imaged by a Megarad CID camera from Thermo-electron with a C-mount lens.

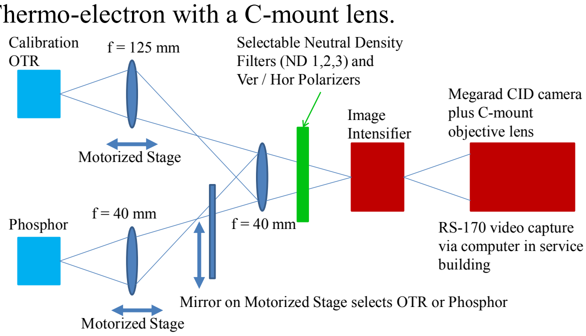

Figure 8: Optical paths followed by the OTR light and the phosphor screen light. Of the two lenses in each path, one is shared.

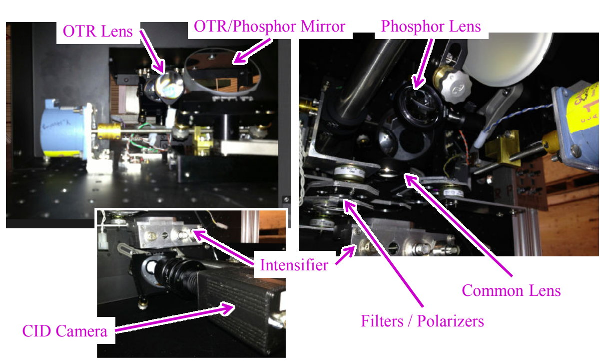

Figure 9: Optical components mounted inside box. The top left picture is looking vertically along the OTR line. The top right picture shows the phosphor path.

TEST STAND RESULTS

Electron Gun

The initial test stand was setup to test characteristics of the electron gun. It consisted of a pair of YAG:Ce screens used to measure the spot size and divergence to verify the manufacturer's specifications and for use in the simulation (Fig. 10).

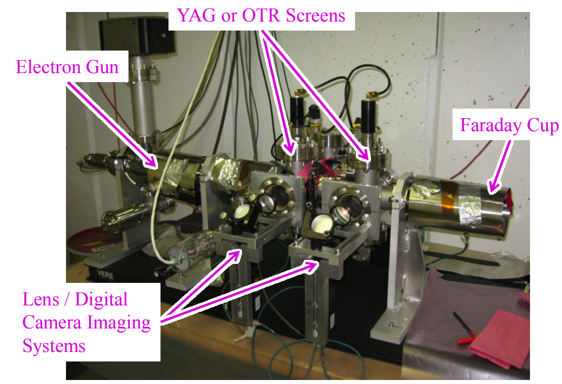

Figure 10: Initial test stand for measuring beam parameters.

The beam measurements were carried out using the solenoidal magnet in the gun to focus the beam at the first screen (Fig. 11), allowing a measurement of the emittance of the electron beam.

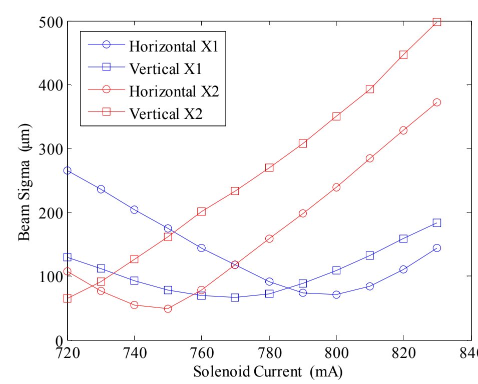

Figure 11: Horizontal and vertical rms beam sizes at the first (blue) and second (red) crosses in the test stand. The electron beam was ~50 keV and 1 μA onto YAG:Ce screens.

Following the intial measurements, the YAG:Ce screens were replaced with stainless steel mirrors to enable running at 1 mA beam currents. Measurements from these currents are shown in (Fig. 12) and are larger as might be expected.

Electrostatic Deflector

The electrostatic deflector was designed to deflect the electron beam from one side of the phosphor screen to the other. One would like to minimize the voltage required for the deflector while also minimizing the length of the deflector. Unfortunately, physics doesn't work that way. A reasonable compromise is the 15 cm-long plates, for

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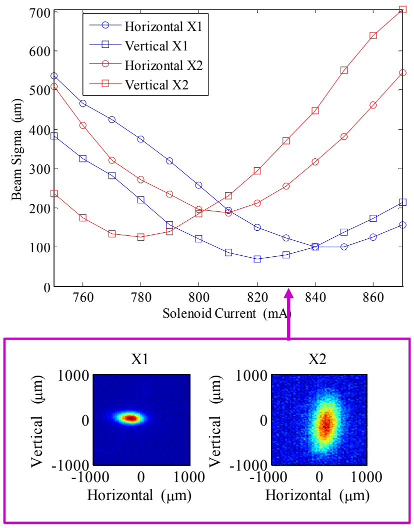

Figure 12: Horizontal and vertical rms beam sizes at the first (blue) and second (red) crosses in the test stand. The measurements are from OTR taken at ~50 keV and 1 mA beam current onto the stainless steel mirrors.

which ±400 V on each plate is more than sufficient to deflect a 15 keV beam. The deflector was tested with ~150 V with a sweep time of 80 ns. The result on the phosphor screen is shown in (Fig. 13). There appear to be focusing effects during the sweep, but the magnitude of the sweep is roughly correct.

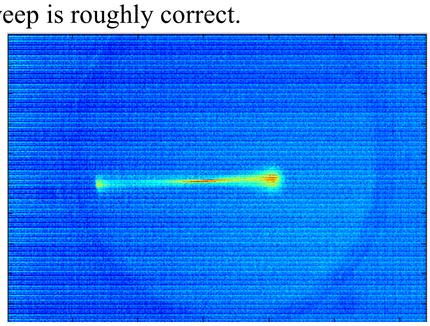

Figure 13: Trace of the electron beam on the phosphor screen for a deflecting voltage of ~150 V. This image was not taken with the design optics. It was taken with just a camera and objective lens. The beam started off the screen on the left side and was then swept to the right.

SIMULATIONS

Electron Beam

Simulations of the electron beam were developed both at SNS and Fermilab. The SNS calculations (as seen in Fig. 3 and Fig. 14) showed that the measured profile was within 2% of the actual profile. This simulation was based on the slow stepping method.

At Fermilab, an electron beam simulation was developed in MATLAB to track electrons through the deflector and proton beam to the phosphor screen. The simulation starts with the measured emittance of the electron gun and propagates the beam through the deflector electric field, calculated via POISSON, and

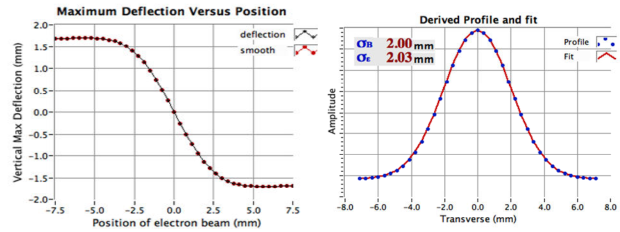

Figure 14: Deflection plot of electron beam, and the derivative of it, showing agreement to better than 2%.

through the electric and magnetic fields of a proton bunch. Presently, the electric fields of the deflector have no edge effects since POISSON is a 2-D calculation. The time dependence of the deflector field is handled by a linear scaling of the POISSON fields. The time dependence of the proton bunch position however, is fully accounted for in evaluating the fields at a given point in time. This simulation was focused on the third method, using fast sweeps along the proton direction while slowly stepping through the proton beam. Some results of this simulation are shown in (Fig. 15).

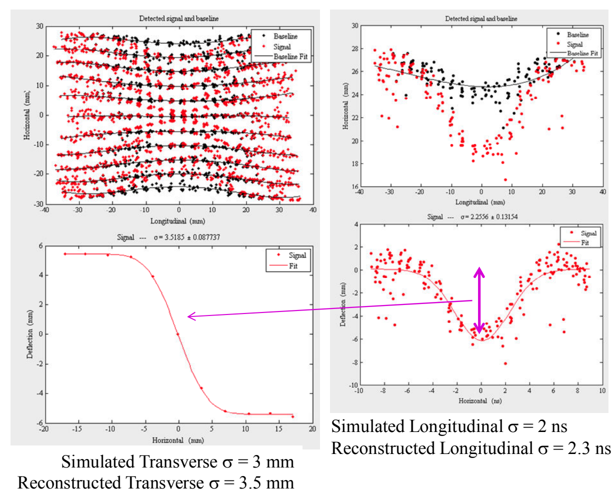

Figure 15: Simulated deflection data for varying impact parameters. The black points are baseline deflections with no beam. They result from the non-uniform deflector field. Each point represents a single electron with the random spread given by the measured emittance.

Optics

Since the imaging optics contain relatively fast lenses, and the source size is large, ray tracing was used to determine the optical acceptance of the phosphor screen at the input to the image intensifier. The face of the phosphor screen was randomly populated with light rays heading in random directions. These rays were traced through the optics to the image intensifier to produce an acceptance map. One can see from (Fig. 16) that the acceptance is quite uniform over most of the phosphor screen.

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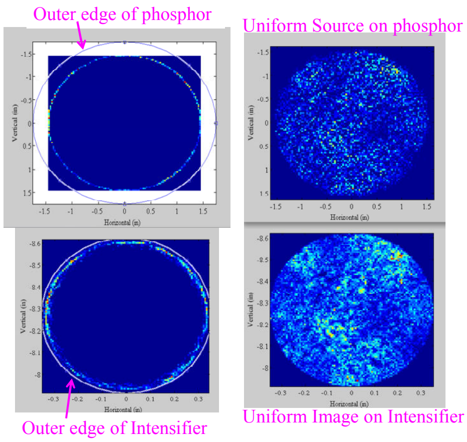

Figure 16: Ray tracing from source (top) to image planes (bottom) to determine aperture (left) and uniformity (right).

External Magnetic Fields

External magnetic fields are a serious problem for low energy electron beams. From calculations, a 2 G transverse field will deflect the 15 keV electron beam by 100 mm from gun to phosphor screen. This makes the device inoperable. Figure 17 shows the magnetic fields from the Main Injector magnet busses which are located ~50 cm from the electron beam. The busses run in pairs to mostly cancel the magnetic fields, but there are still low levels remaining.

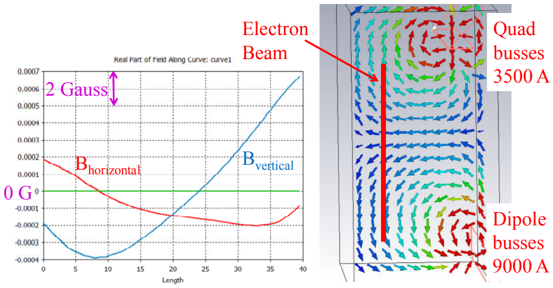

Figure 17: CST simulation of magnetic field from magnet busses along the line of the electron beam. The horizontal component is most important as the electron beam is vertical. The maximum horizontal field is 2 G.

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One solution that will be tried is to surround the electron beam with mumetal shielding. Bench tests seem to indicate that 3 layers of mumetal should be sufficient to eliminate problems from the magnetic field. In addition, calculations with CST (Fig. 18) show the mumetal as being effective. However, a previous attempt to shield an electron cloud measurement from the same bus fields was not very successful. If the mumetal does not work, further shielding of the busses may be required. The device at SNS has a low-μ shield as well as a high-μ shield.

SUMMARY

An electron beam profiler has been built for the Main Injector at Fermilab and will be installed during the current multi-week shutdown. It will measure the horizontal profile of the Main Injector proton beam during normal operations and provide a secondary profile measurement to the Ionization Profile Monitor.

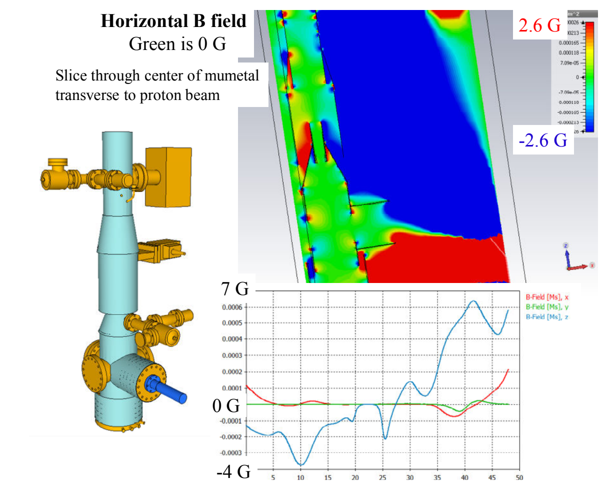

Figure 18: Model of mumetal wrap. The intensity plot is a CST simulation of the magnetic field inside the mumetal shield. The residual horizontal fields (red and green in the lower plot) are significantly less than 1 G with the exception of the ends.

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