INITIAL CHARACTERIZATION OF A COMMERCIAL ELECTRON GUN FOR PROFILING HIGH INTENSITY PROTON BEAMS IN PROJECT X*

R. Thurman-Keup#, A. S. Johnson, A. H. Lumpkin, J. C. T. Thangaraj, D. Zhang†,
FNAL, Batavia, IL 60510, U.S.A.
W. Blokland, ORNL, Oak Ridge, TN 37831, U.S.A.

Abstract

Measuring the profile of a high-intensity proton beam is problematic in that traditional invasive techniques such as flying wires don't survive the encounter with the beam. One alternative is the use of an electron beam as a probe of the charge distribution in the proton beam as was done at the Spallation Neutron Source at ORNL. Here we present an initial characterization of the beam from a commercial electron gun from Kimball Physics, intended for use in the Fermilab Main Injector for Project X.

MOTIVATION

Traditional proton-beam transverse profile measurements such as flying wires or secondary emission devices involve intercepting the beam in some fashion. As beam intensities increase, the survivability of such instruments is greatly reduced. Alternatives to these invasive types include ionization based devices, which collect the ionization remnants of the residual beamline gas, and exotic devices like gas or liquid jets or sheets which act like invasive devices, but avoid the resulting destructive failure associated with solid devices. This paper is concerned with another alternative, the use an electron beam as a probe beam for determining the transverse charge profile. This type of measurement has been around since the 1970's in the context of plasma measurements [1]. CERN experimented with ion beams instead of electron beams [2]. More recently, the Spallation Neutron Source (SNS) at Oak Ridge National Lab in collaboration with the Budker Institute of Nuclear Physics installed an electron beam profiling device in the SNS proton ring [3-6]. The long range plan for Fermilab involves a high intensity proton source called Project X. The design power for Project X is greater than 1 MW and as such requires more exotic profile measurement devices. This paper presents some initial studies of a commercial electron gun from Kimball Physics with an eye toward creating an proton beam profiling device for the Project X era Main Injector at Fermilab.

THEORY

When the trajectory of a charged particle brings it in close proximity to a charge distribution, e.g. a particle beam, the particle is deflected by the electromagnetic fields of the beam. The deflection of the particle is determined by the exact spatial distribution and motion of the charges, and as such, if one measures the deflection of a probe beam as it traverses a target beam, one should be able to derive information about the charge distribution of the target beam. In the context of Project X, the probe beam is an electron beam from a thermionic gun and the target beam would be a proton beam.

Figure 1 shows a possible layout for an electron beam diagnostic for the circulating proton beam in the Main Injector at Fermilab.

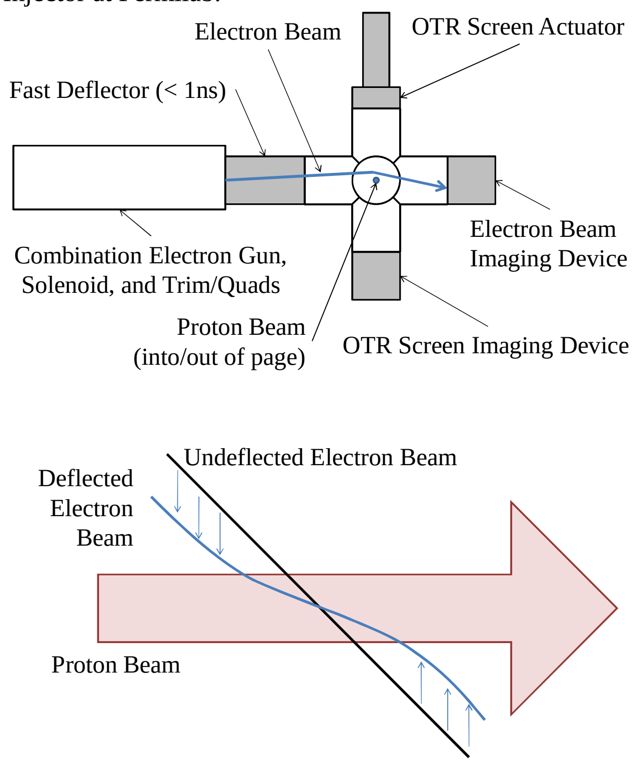

Figure 1: The upper diagram shows a possible electron beam based profile measurement device for a high intensity proton beam with several nanosecond bunch lengths. The fast deflector is designed to sweep the electron beam through the proton beam during the peak of a single bunch. The lower diagram demonstrates the fast sweep of the electron beam within the center of a proton bunch.

The beam in the Main Injector circulates once every 11 μs and is bunched by a 53 MHz rf system. To measure a single rf bucket of beam, the electrons must be swept through the beam at the peak of the bunch intensity. The electrons are swept both transversely through the beam and simultaneously along it to allow the deflection to be imaged. If the electrons were only swept perpendicular to the beam, then the deflection would overlap the path of the sweep and be unmeasureable.

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#keup@fnal.gov
†Now at SLAC

If the requirements on a fast deflector prove to be too difficult to meet, a slow sweep method might work, whereby the electron beam is positioned and then the maximum deflection is recorded. The electron beam is then stepped and the deflection recorded again.

EXPERIMENTAL SETUP

A test beamline is in operation in a previously unused interlocked concrete enclosure in one of the service buildings at Fermilab (Fig. 2).

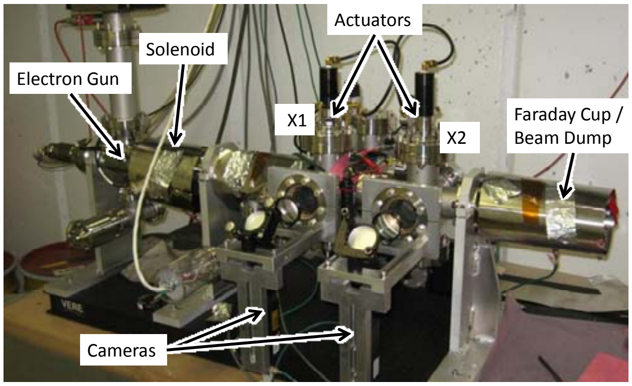

Figure 2: Electron gun beamline showing the various diagnostic elements.

It consists of an electron gun and a short beamline with diagnostics. The gun is an EGH-6210 from Kimball Physics, and has a 300 µm diameter LaB_6 cathode. The advertised spot size is a minimum of 50 µm which is important since the Main Injector proton beam has a typical transverse rms size of ~1mm. It has an energy range of 1 keV to 60 keV and a beam current range of 10 µA to 6 mA. The gun can be gated from 2 µs up to dc, with a maximum repetition rate of 5 kHz. The gun is also equipped with a focusing solenoid and steering / focusing magnets.

The beamline used for these measurements consists of 2 crosses (X1 and X2) with linear actuators containing either Ce:YAG powder scintillators, or 1 mm thick polished stainless steel plates for OTR. The stainless steel plates were hand polished to a reasonable though not optics grade quality. The scintillators, which are used for low current measurements are oriented 45º to the beam, while the stainless steel plates, used for high current measurements, are oriented between 15º and 20º to the beam direction to capture one lobe of the wide OTR distribution. The beam images are captured by Firewire-based cameras which are read by a LabVIEW program that also controls the electron gun. These camera systems consist of a light collecting field lens ~175 mm from the screen, followed by a flat mirror that redirects the light to the camera with a 75 mm f8 objective lens. The system was calibrated on a bench with a target resulting in a scale of 10 µm / pixel and an object resolution of ~25 µm. At the end of the beamline there is a Faraday cup / beam dump for measuring the beam current.

BEAM MEASUREMENTS

Measurements of the beam were taken at an energy of 60 keV and at 2 different beam currents. At a current of 1 µA, the Ce:YAG powder screens were used to image the beam at the two crosses for a range of focusing solenoid currents. A similar scan was done for a beam current of 1 mA on the stainless steel OTR screens. Figure 3 shows one image from each of the high and low currents. The images represent the minimum beam size observed. The cause of the large horizontal size of the 1 mA image is unknown at this time and will be investigated.

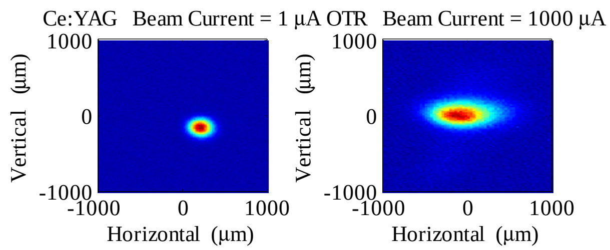

Figure 3: Images taken at two beam currents. The left image is from the scintillator and the right is the OTR image from the high current beam.

Figure 4 summarizes the results of the solenoid scan for the 1 µA beam. It is not clear why the spot size at cross X2 which is further from the solenoid should have a smaller minimum value than X1. Using this data, the beam emittances can be calculated and are listed in Table 1.

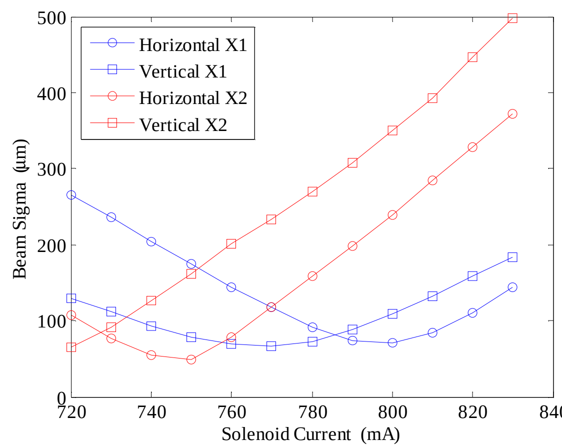

Figure 4: The results of a scan of the focusing solenoid current. Cross X1 is the first and represents the position that the proton beam would be. X2 represents the location of the deflection imaging setup. The beam size at X2 is important since it determines how well one can see the deflection.

In the case of OTR, some studies were required to verify that we were indeed observing OTR from the screens given the very low energy of the electron beam. After installation, the beam image was observed on the plates, however, when a polarizer was placed in front of the camera, there was no polarization effect observed. After further studies, it was concluded that the beam was heating the plate and producing visible blackbody radiation. In support of this theory, Figure 5 shows the increase in light yield over the course of a 2 ms electron pulse despite the fact that the beam current was constant. It was also observed that if the beam was defocused slightly that the increase in light vanished and the light exhibited the expected OTR polarization. To counter the heating problem, the pulse duration was decreased and a train of pulses was introduced. The correct OTR polarization was then observed, as was a constant light yield over the train of pulses.

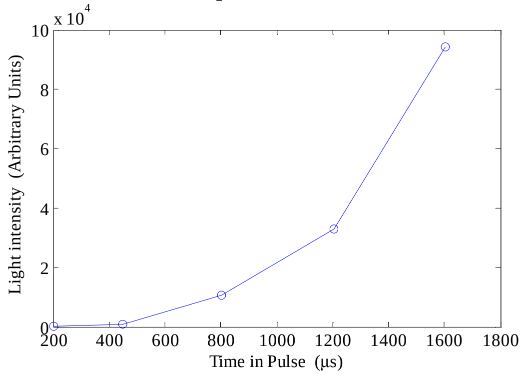

Figure 5: The increase in light yield over the course of a 2 ms electron pulse striking the stainless steel mirrored plate. The increase is speculated to be blackbody radiation from heating of the plate.

Figure 6 is the result of the solenoid scan for the 1 mA beam. The horizontal emittance is much larger than the vertical emittance, due to the large spot size. Since the screen is at a very large angle relative to the camera, it is possible that due to the depth of focus, the spot was not at the design focal point, although this should have impacted the vertical as well. The emittances calculated from these measurements are listed in Table 1.

An attempt was also made to measure the energy spread using a small dipole magnet at low beam current. Introducing a dispersion of ~24 mm led to no increase in the minimum spot size. In fact, the minimum spot size decreased some presumably due to edge focusing effects in the small dipole magnet. With the indicated dispersion, an energy spread of 0.4% could have been observed. This however is several orders of magnitude larger than the expected thermal energy spread.

Table 1: Emittances at low and high currents. The source of the large horizontal emittance for the 1 mA beam is unknown and must be investigated.

Beam Current	Horizontal Emittance	Vertical Emittance
1 µA	0.078 mm mr	0.071 mm mr
1 mA	0.27 mm mr	0.16 mm mr

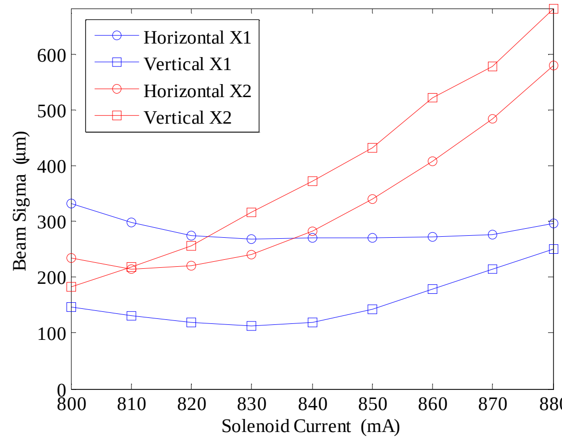

Figure 6: Results of the solenoid scan with the 1 mA beam and the OTR screens. The rather large horizontal beam size is unexpected and requires further investigation. The plot appears to have a flat minimum which may indicate an unaccounted for resolution term.

CONCLUSIONS

Despite the fact that the horizontal spot size is abnormally large in the high current measurement, the spot size at the downstream cross X2 is reasonable in the context of measuring the deflection. A thin foil OTR would help with the beam heating and should be tried.

The next phase of this experiment is to simulate the proton beam with a pair of current carrying wires and to design and construct a fast deflector. Some of the remaining issues to be considered include determining the minimum beam current needed to observe the deflected beam for a given sweep time and the impact of longitudinal variations in the charge density of the bunch.

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