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Initial OTR Measurements of 150 GeV Protons in the Tevatron at FNAL

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Abstract. Fermilab has developed standard optical transition radiation (OTR) detectors as part of its Run II upgrade program for measuring intense proton and antiproton beams. These detectors utilize radiation-hardened CID cameras to image the OTR and produce high-resolution two-dimensional beam profiles. One of these detectors has been installed in the Tevatron next to the new ionization profile monitor (IPM). Initial OTR measurements are presented for 150 GeV injected coalesced and uncoalesced proton bunches. OTR images are taken for one-turn and two-turn injections over an intensity range of 1.5e11 to 3.5e11 protons. Preliminary profile measurements give uncoalesced beam size sigmas of 1.0 mm horizontally by 0.7 mm vertically and coalesced beam size sigmas of 1.8 mm horizontally by 0.70 mm vertically. OTR images are also presented for changes in the Tevatron skew quadrupole magnet currents, which produce a rotation to the OTR image, and for changes to the Tevatron RF, which can be used to measure single-turn dispersion. Operational aspects of this detector for beam studies and Tevatron tune-up are also discussed.

Keywords: Optical Transition Radiation, Beam Profile Measurements.
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INTRODUCTION

Particle-beam diagnostic techniques based on optical transition radiation (OTR) have been demonstrated at a number of facilities over a wide range of beam energy (or Lorentz factor, γ) [1] - [3]. OTR is generated when a charged particle transits the interface between two media with different dielectric constants [2]. The OTR extends over the visible region and allows the use of standard commercial off-the-shelf camera and optics for acquisition. In addition, OTR is a surface phenomenon so that thin foils can be used to minimize their effect on the beam.

Previous measurements with a prototype OTR detector demonstrated the feasibility of using OTR as a beam profile monitor for protons [4]. As part of its Run II upgrade program, Fermilab has developed a standard OTR detector design for use in various proton beamlines [5]. The standard OTR detector consists of a pair of aluminized mylar foils, in vacuum, that can be rotated into the beam path and allow measurements of OTR for beams in either direction. The OTR detector also utilizes a radiation-hardened CID camera and neutral density filters to allow operation over a range of beam intensities and under various radiation environments.

One of these detectors has been installed in the Tevatron next to the new ionization profile monitor (IPM) [6] to allow cross calibration of the beam profiles. Figure 1 shows the OTR detector installed in the Tevatron. Since this OTR detector has been installed in a storage ring collider, it can only be used for injection studies that remove the beam after a few turns in the Tevatron. However, the two-foil design allows the OTR detector to measure both proton and antiproton injections. Additionally, this detector is the only device that gives a two-dimensional transverse profile of the beam at injection.

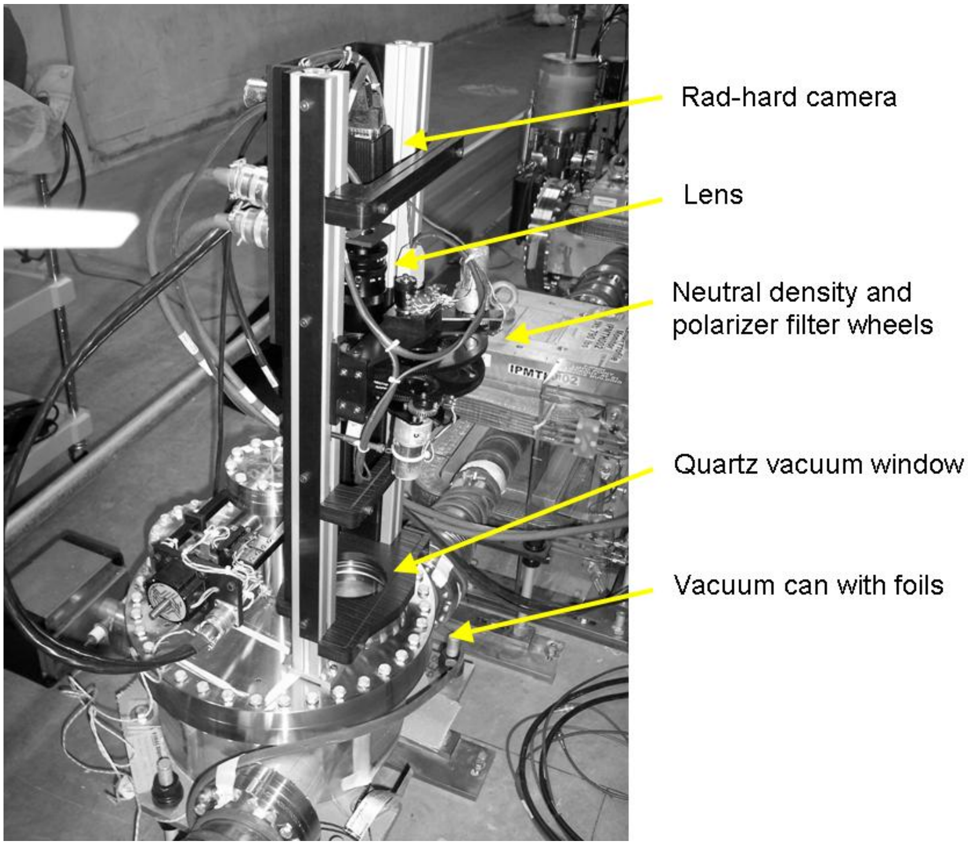

FIGURE 1. OTR detector installed at location E0 in the Tevatron next to the IPM detector.

MEASUREMENTS

Initial Tevatron OTR measurements were taken during special machine studies before the 2006 shutdown. Measurements were made of coalesced and uncoalesced 150 GeV proton bunches at injection from the Main Injector into the Tevatron. Beam intensities ranged from ~1.5e11 to 3.5e11 protons. Injections were aborted after one or two turns in the Tevatron, where one turn is 21 μs.

All OTR images are corrected for perspective and rotated into the transverse plane of the beam. Fiducial calibrations have also been applied to translate from image pixel space into real space. In addition, a structured image background from an unknown source has contaminated all images. For large OTR signals, this background is not significant and is reduced further by applying an averaging filter.

Uncoalesced Proton Beam Measurements

An uncoalesced proton beam consists of ~30 consecutive 53 MHz RF bunches. This bunch format is maintained from the Booster through the Main Injector into the Tevatron and is nominally used for tuning the Tevatron for collider operations. The CID camera integrates the OTR of these bunches into one image.

Single-Turn Injection Measurements

A number of single-turn uncoalesced proton injections were measured. Figure 2a shows an OTR image from a single-turn injection of 3e11 protons. Figures 2b and 2c show x and y beam profiles of the OTR image along with Gaussian fits. The fits show that the uncoalesced beam appears Gaussian with average beam sizes of 1.0 mm by 0.7 mm in x and y, respectively.

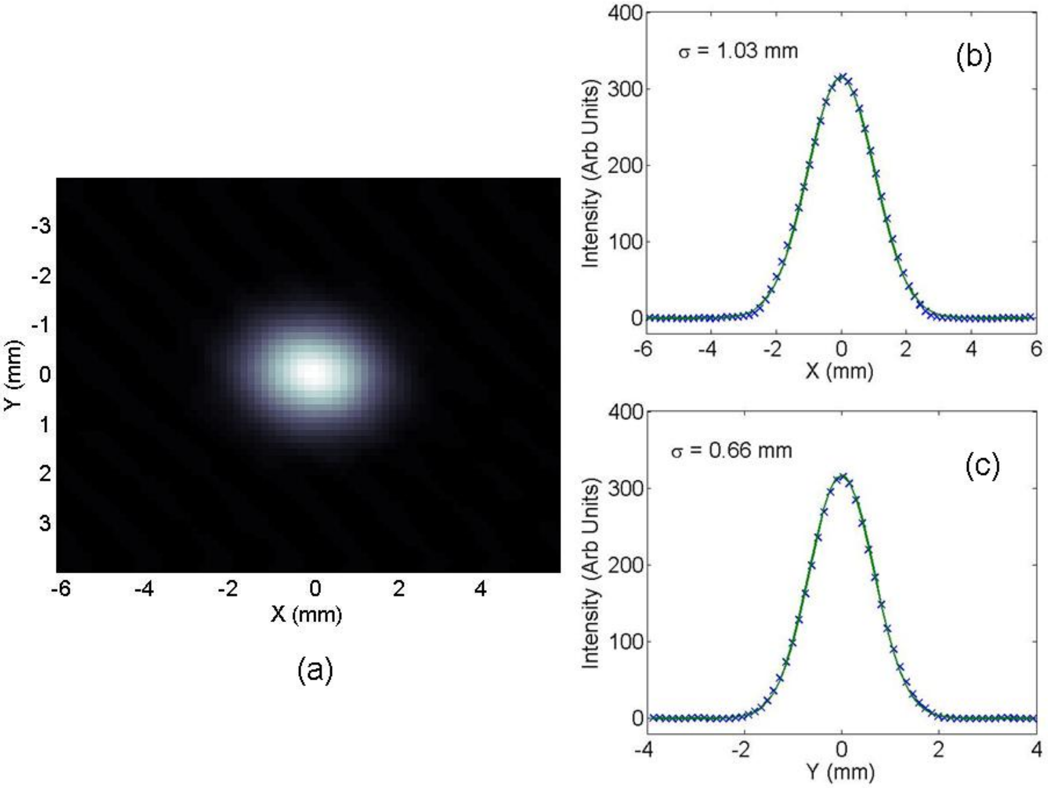

FIGURE 2. (a) Single-turn OTR image of 3e11 uncoalesced protons. (b) and (c) are X and Y beam profile data with fits, respectively.

Measurements were also taken of injected uncoalesced protons with changes to the Main Injector-Tevatron RF. Figure 3 shows three images of OTR with RF changes of +/- 40 Hz. The OTR images clearly show the change in radial (x) position of the beam. Measurements of beam position for different RF settings can be used to determine single-turn dispersion at the location of the OTR detector.

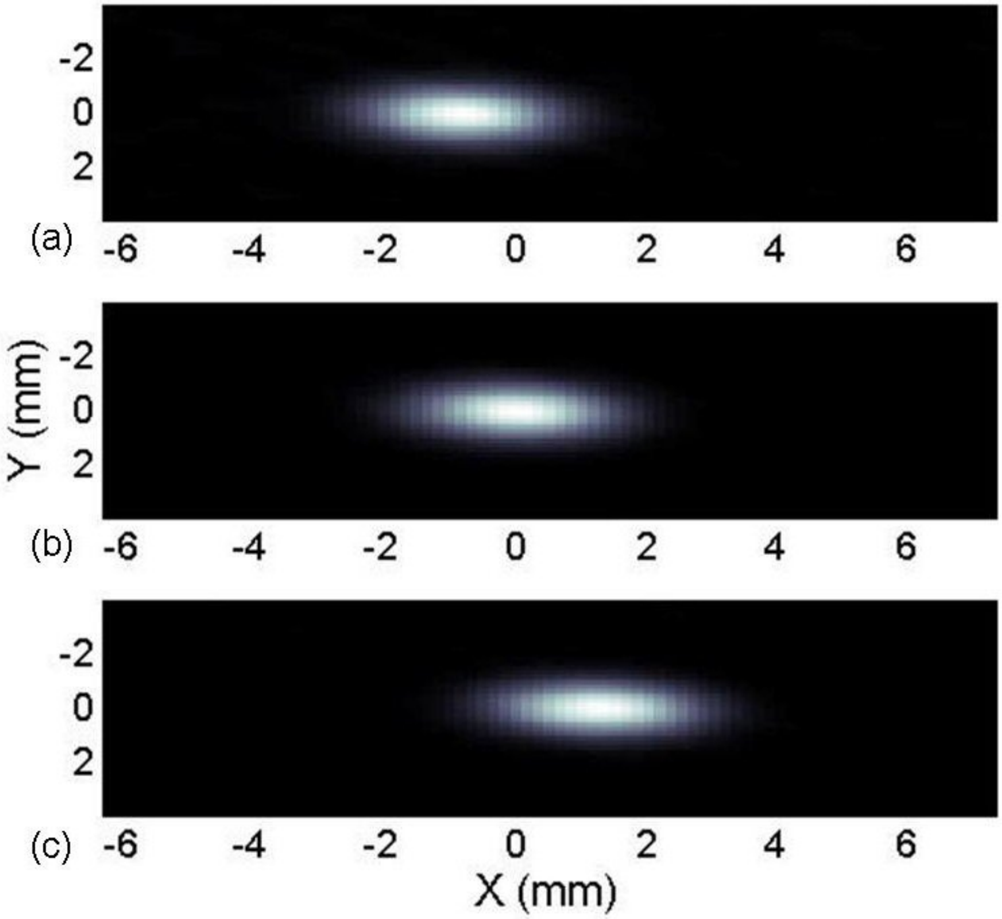

FIGURE 3. Single-turn OTR image of 3e11 uncoalesced protons for (a) RF increase of 40 Hz from nominal, (b) no change in nominal RF and (c) RF decrease of 40 Hz from nominal.

Multiple-Turn Injection Measurements

Since our camera integrates for 33 ms, OTR from a multiple-turn measurement appears in a single image. Under normal operating conditions, injections from the Main Injector are well matched to the Tevatron closed orbit to minimize betatron oscillations. OTR measurements were taken for various levels of injection mismatch to produce betatron oscillations. Since the Tevatron tune is ~0.58, consecutive turns produce OTR at different regions of the camera sensor. Figures 4a, 4b and 4c show OTR images for two-turn injections for increasing levels of vertical injection mismatch. Also shown are double Gaussian fits to the vertical profiles for each image. Differences in measured intensity for Figs. 4b and 4c from turn 1 to turn 2 are not well understood and are discussed below.

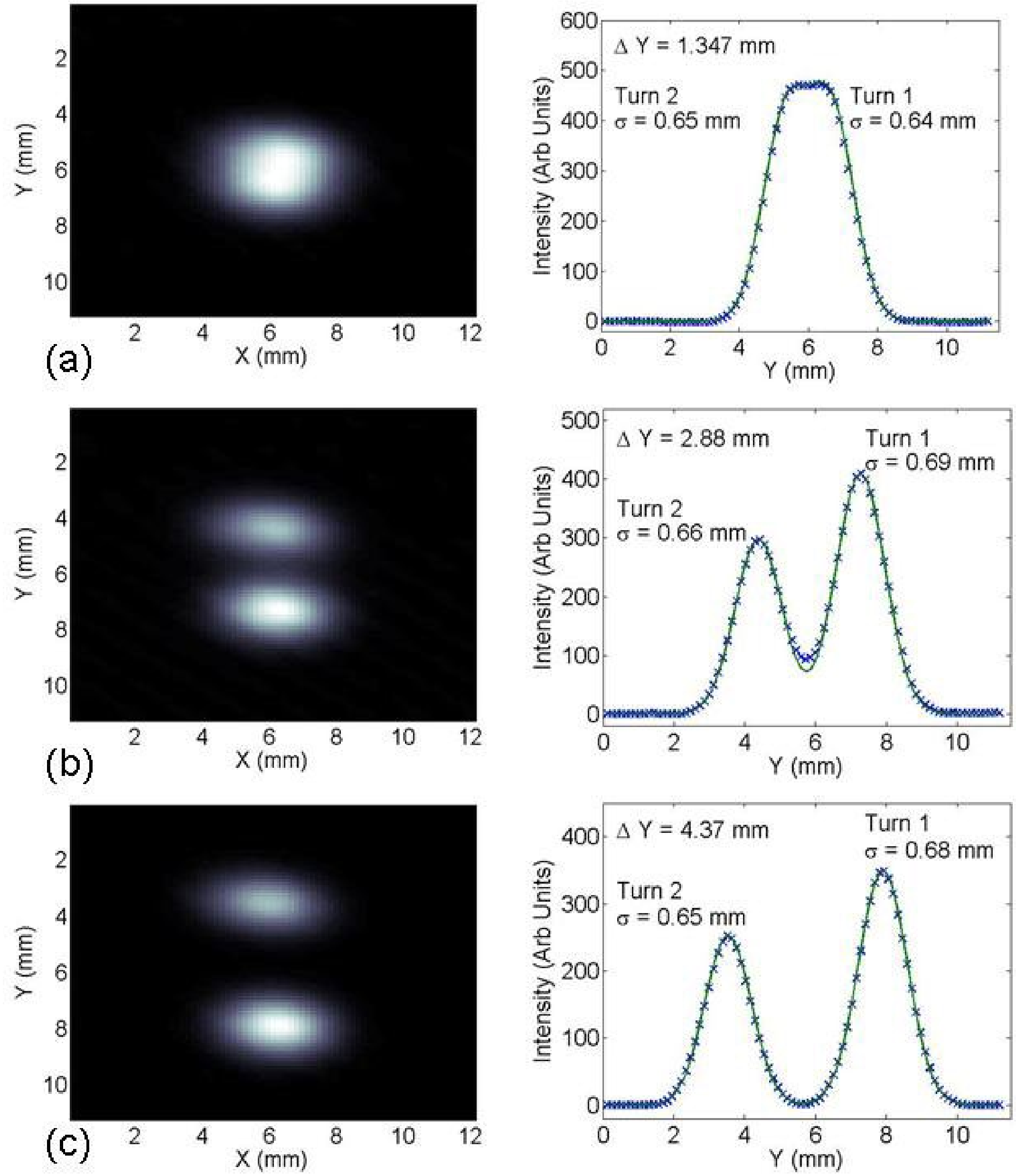

FIGURE 4. (a) Two-turn OTR image of 3e11 uncoalesced protons with double Gaussian fit of vertical profile. (b) and (c) Same as (a) but with increased vertical injection mismatch from the Main Injector into the Tevatron.

Coalesced Proton Beam Measurements

A coalesced proton beam consists of a single 53 MHz RF bunch injected into the Tevatron. This bunch is coalesced in the Main Injector from ~7 consecutive 53 MHz bunches. This is the normal bunch structure used for Tevatron collider operations.

Figure 5a shows a corrected and calibrated OTR image from a single-turn injection of 2.7e11 coalesced protons. Structured image background is noticeable in this image even after filtering. Figures 5b and 5c show x and y profiles, respectively, of the OTR image along with Gaussian fits. The fits show that coalesced beam has an average beam size of 1.8 mm by 0.7 mm in x and y, respectively. The increased size in x, compared to uncoalesced beam, is due to the larger momentum spread from coalescing. Figure 5c shows that the x profile is not as good a fit to a Gaussian compared to the y profile or to uncoalesced beam.

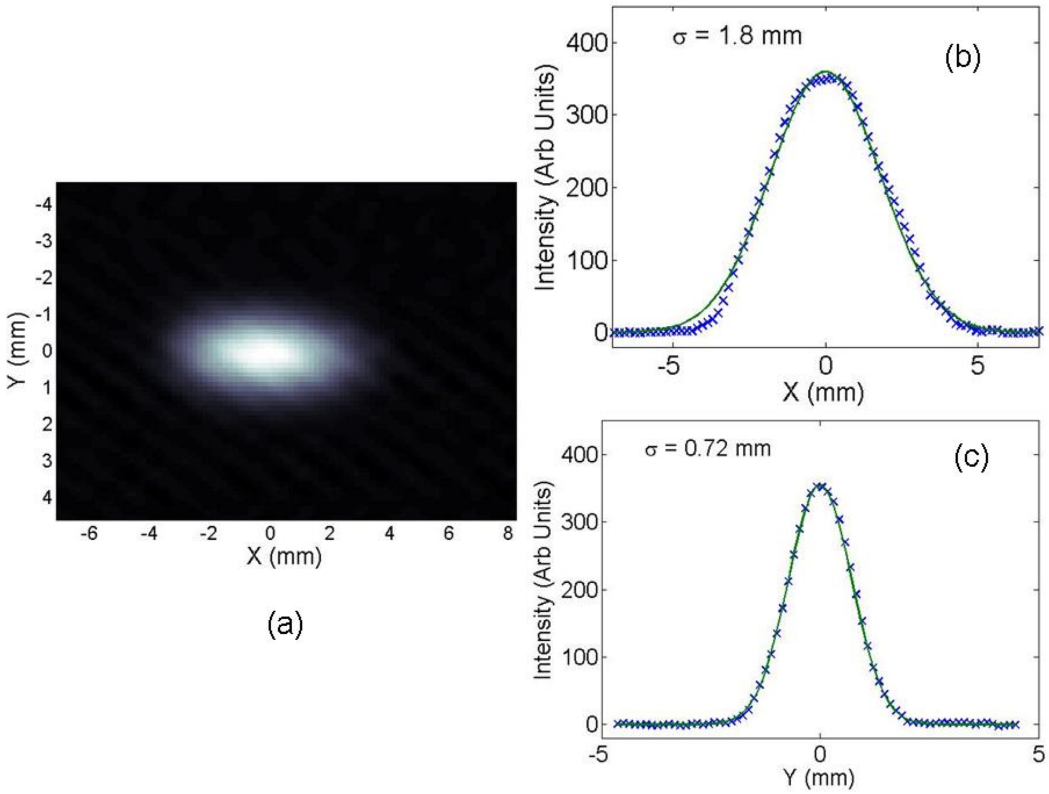

FIGURE 5. (a) Single-turn OTR image of 2.7e11 coalesced protons. (b) and (c) are X profile and Y profile data with fits, respectively.

One of the key advantages of an OTR detector over wire profile monitors is the ability to make two-dimensional measurements of a beam profile. This allows an OTR detector to measure the ellipticity and tilt of the beam profile. The advantage of a two-dimensional profile is evident in Figs. 6a and 6b which show OTR images of coalesced protons for changes to the Tevatron skew quadrupole magnet strengths.

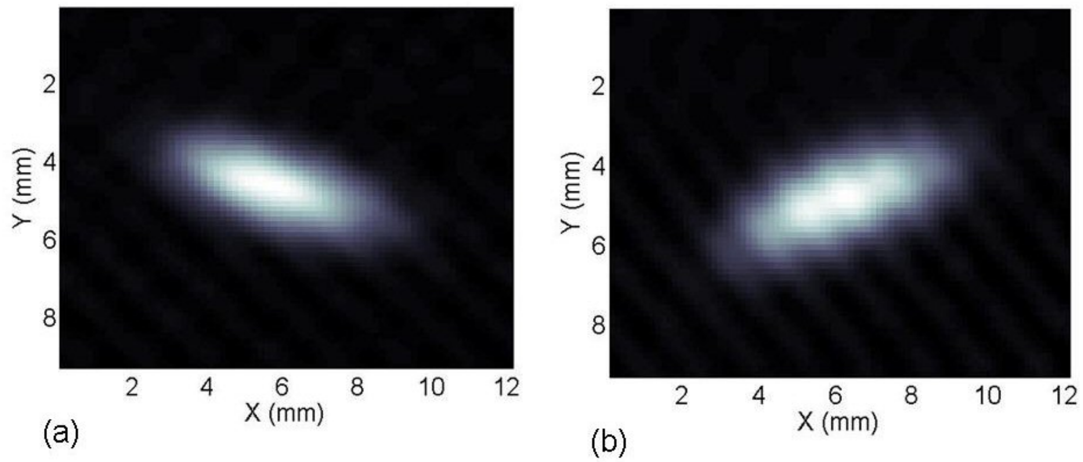

FIGURE 6. (a) Single-turn OTR image of 2.7e11 coalesced protons with Tevatron skew quadrupole magnets increased by 20 amps and (b) decreased by 20 amps from nominal operating value.

OTR ISSUES

Previous measurements of OTR with proton beams at Fermilab [4] indicate that the OTR generated for the Tevatron beam size, energy and intensity is from 20 to 50 times less than expected. Also, there appears to be a change in the measured OTR as a function of transverse position, as shown in Fig. 3. Small errors in geometric alignment and OTR optical acceptance can produce a change in intensity across the field of view, but cannot explain the order of magnitude reduction in measured OTR.

In the Introduction it is stated that OTR is a surface phenomenon. However, Jackson [7] gives a formation depth for the generation of smooth intensity OTR. Equation (1) gives this formation depth, where γ is the Lorentz factor of the charged particle, c is the speed of light and ω_p is the plasma frequency of the foil.

$$D = \frac{\gamma c}{\omega_p} \tag{1}$$

For 150 GeV protons and aluminum foils, D is of the order 1 μm. The present OTR detector foils have ~0.12 μm aluminum on 5 μm mylar. This would seem to indicate that the present aluminum thickness is too small and might explain the large reduction in OTR.

CONCLUSION

The Tevatron OTR detector provides a new beam diagnostic tool that will allow machine operators to tuneup the Tevatron for collider operations. In addition, the OTR detector will provide a crosscheck for the newly installed IPM detector. Initial operation of the Tevatron OTR detector shows that it can measure two-dimensional uncoalesced and coalesced proton beam profiles at injection.

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