THE FEASIBILITY OF OTR IMAGING OF HIGH-INTENSITY PROTON BEAMS AT FNAL*

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Abstract

The Fermi National Accelerator Laboratory (FNAL) is currently pursuing a number of projects where either beam luminosity for the Tevatron collider (Run II) or proton intensity for neutrino experiments requires careful tracking of beam properties throughout the facility or before a target. The feasibility of using optical transition radiation (OTR) imaging for the proton (or antiproton) beam sizes in transport lines between the rings of the facility has recently been evaluated. Based on comparisons to electron beam results at the Advanced Photon Source (APS) linac and proton results at CERN, the potential of OTR imaging at FNAL looks very encouraging.

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). The preponderance of these measurements has been on electron accelerators where the beams have $\gamma > 10$ and adequate charge ($\sim 10^9$ e^-) within a 30-ms video camera frame time to produce useable images. The potential for online imaging of proton beams with $\gamma > 10$ at the accelerators at Fermi National Accelerator Laboratory (FNAL) has recently been reviewed. The accelerators at FNAL involve a number of projects where proton beam intensity for the Tevatron collider (currently in Run II) or proton intensity for neutrino experiments requires careful tracking of beam properties throughout the facility or before a target [1]. The feasibility of using OTR imaging for the intense proton beams is evaluated in comparison to electron-beam results at the Advanced Photon Source (APS) linac [2] and proton-beam results at CERN [3]. The scalings on γ and the charge intensity indicate significant levels of OTR will be generated by the generally lower γ, but higher-intensity (5×10^{12} p) proton beams. The signal levels are compatible with standard CCD or CID camera technology. In addition, by using a thin metal screen as the converter foil, a minimally intercepting beam profile capability would be attained.

BACKGROUND

FNAL Complex

The FNAL accelerator complex has evolved during the last decades. Major upgrades have included the construction of the Tevatron with its superconducting magnet upgrade and the addition of the new Main Injector (MI) ring. The protons from the linac are stacked and ramped to 8 GeV in the booster. A transport line, MI-8, brings the protons to the new MI, which ramps the beam energy to 120 GeV. As can be seen in Fig. 1, the protons are extracted through the P1 line to F0 where they are either switched into the Tevatron or else continue along the P2 line to F17. At F17 the protons are switched to the AP-1 line and directed to the antiproton target. The prototype experiment with OTR is to be done in the AP-1 proton line just upstream of the target. During normal antiproton production, protons are sent to the target in a single 1.6-μs-long pulse train every 2 to 3 seconds.

OTR Background

Optical transition radiation is generated when a charged-particle beam transits the interface of two media with different dielectric constants (e.g., vacuum to metal or vice versa) [3-6]. The effect is a surface phenomenon that might be simply understood as the collapsing of the electric dipole formed by the approaching beam charge and its image charge in the metal at the surface. As the fields readjust, a burst of radiation is emitted. The expression for the single-particle spectral angular distribution of the number of photons, N_1, per unit frequency (ω) and solid angle ($d\Omega$) is given by [6,7],

$$\frac{d^2 N_1}{d\omega d\Omega} \approx \left| r_{\perp,\parallel} \right|^2 \frac{e^2}{\hbar c \pi^2 \omega} \frac{\left(\theta_x{}^2 + \theta_y{}^2\right)}{\left(\gamma^{-2} + \theta_x{}^2 + \theta_y{}^2\right)^2}, \quad (1)$$

where e is the electron charge, $\hbar$ is Planck's constant divided by 2π, c is the speed of light, γ is the Lorentz factor, and θ_x and θ_y are angles relative to the beam direction. The reflectivity of the surface for perpendicular and parallel polarized light is $\left| r_{\perp,\parallel} \right|^2$. In this paper we are only dealing with a single-foil, single-particle expression and its product with N_p, the number of particles.

Since it is a surface phenomenon, thin foils are often used as the converter screen to reduce beam scattering and to minimize heat deposition. The latter feature is of particular importance for proton beams due to their higher *dE/dx* than that of electrons. The radiation is emitted around the angle of specular reflection for backward (vacuum to metal) OTR so that if the foil is at 45° to the beam direction, the radiation is at 90° to the beam direction. This is schematically illustrated in Fig. 2.

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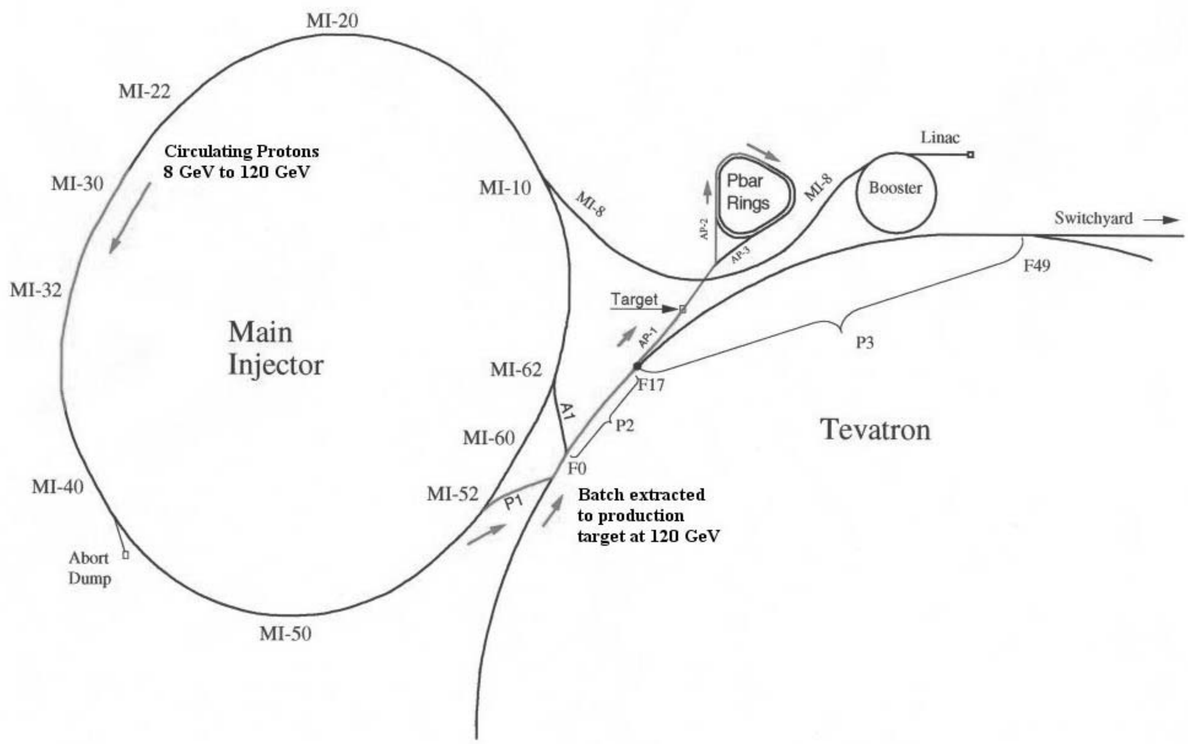

Figure 1: A schematic of the FNAL complex showing the linac, booster, Main Injector, Tevatron, and the transport lines between them.

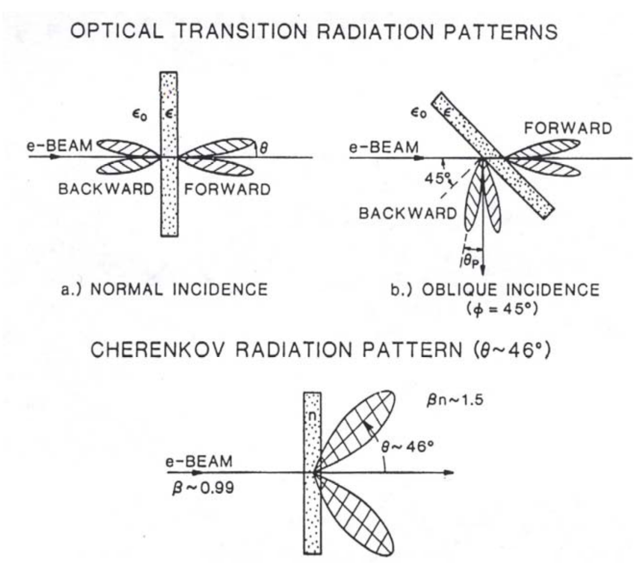

Figure 2: A schematic of the OTR radiation cases for normal incidence and for the foil at 45° to the beam direction. Backward and forward OTR are emitted at the two interfaces. The Cherenkov radiation pattern is shown for comparison.

The basic strategy is to convert the particle-beam information to optical radiation and then to take advantage of imaging technology such as cameras, video digitizers, and image processing programs. These techniques can provide information on transverse position, transverse profile, divergence, beam angle, emittance, intensity, energy, and bunch length. In the case of the proton beam applications, beam position and transverse profile are the two parameters of interest, particularly the latter. As mentioned, the possibility that beam scattering effects are negligible compared to intrinsic beam properties would make this a minimally intercepting technique (potentially online at all times subject to foil survivability).

OTR FEASIBILITY CONSIDERATIONS

Electron Beams

The feasibility of using the OTR techniques for the FNAL proton beams was assessed in part by considering recent experiments at the APS linac. We have performed experiments with electron beam energies from 50 to 600 MeV. The 0.3-nC micropulse from an rf photocathode gun or the 1-nC macropulse from the rf thermionic gun was accelerated and sampled at several beamline stations. Beam imaging was successful for such charges, and beam sizes of about 0.2 mm (σ) were measured [2].

Proton Beams

Since the original work by Jelley with intense proton beams in the 1950s [5], a significant amount of work has been done at CERN beginning with collaborations with L. Wartski in 1984 [3]. The CERN results indicate imaging screens of aluminized mylar or thin Ti foils can survive proton beams of 10^{12} particles and with beam focus sizes of a few mm [8].

Potential FNAL Proton Beam Case

Although several cases have been considered at FNAL, we have recently directed our attention towards a measurement of the 120-GeV proton beams in the AP-1 transport line upstream of the antiproton production target. At this location there was an air gap in the transport line as part of a vacuum isolation of the downstream Be vacuum window and the rest of the beamline. At the air-gap z location the beam is not tightly focused, and the two Ti foil vacuum windows on either end of the gap establish the survivability of foils at this location. A Ti foil in the air gap at 45° to the beam would serve as the OTR converter screen. A mirror and lens system will transport the OTR to the in-tunnel CID camera.

The expected beam properties for the protons are compared to the known electron beam case at APS in Table 1. For comparable γ between the beams, the key particle number of 5×10^{12} for the protons indicates about 10^3 times more light than the electron cases. The camera will be integrating the signal over the 84 bunches of protons in the 1.6-μs-long pulse train. However, the reflectivity of Ti is less than the Al mirror used in the electron beam case, and the proposed CID camera is less sensitive to light than the CCD technology. These factors reduce the system sensitivity by 50-100, but there still should be a strong video signal. Measurement of individual bunches could be done with a gated, intensified camera.

Table 1: A comparison of OTR imaging for electron beams to 120-GeV proton beams. The application looks feasible in context of signal strength, spatial resolution, and minimally intercepting foils.

Feature	Electrons	Proton
Beam size (σ)	200 μm	1 mm
Macropulse	8-40 ns	2 μs
Q (nC)	0.3	800
Particle #	1.8×10^9	5×10^{12}
γ	100-14000	129
Theta peak	10-0.07 mrad	8 mrad

SUMMARY

In summary, the very high-energy proton beams with their high particle intensity are strong candidates to be imaged by OTR techniques. An initial experiment in a transport line is being planned in CY03. Following a successful demonstration, a three-screen emittance measurement and beta-function matching configuration may be installed between the main injector and the Tevatron for both the proton and antiproton transfer lines. This would be used to evaluate and optimize beam conditions in support of Run II. Other possible applications involve the proton transport lines that support the neutrino experiments.

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