RESULTS FROM AN IMAGING BEAM MONITOR IN THE TEVATRON USING SYNCHROTRON LIGHT

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ABSTRACT
A prototype synchrotron light monitor has been installed in the Tevatron at the downstream edge of a superconducting dipole magnet. Synchrotron light produced at the upstream edge of the magnet is sufficiently separated from the proton beam to be picked off by the monitor's mirror and diverted into a telescope. The transverse image of the beam is detected by a micro channel plate - CCD camera. The read-out and analysis are performed on a commercially available hardware and software system. The performance of the total system will be discussed.

1 INTRODUCTION

A charged particle accelerated transversely to its direction of motion will emit synchrotron radiation. This radiation is sharply peaked in the forward direction of the particle, within a cone of half angle $\Delta\Theta = 1/\gamma$, where $\gamma = E/mc^2$, the ratio of total relativistic energy to the rest mass energy of the particle. This light, if collected by a telescope, can provide a transverse image of the beam. The utility of the image depends upon the beam size and the optical resolution. The resolution due to diffraction is ultimately set by the very narrow light cone and not the optical system. This limit is approximately $\lambda/2\Delta\Theta = \gamma\lambda/2$. The Tevatron proton beam can be characterized by a gaussian profile with RMS $\sigma = 0.5$ mm. In order to simplify the analysis of an observed synchrotron light beam profile, one needs a diffraction resolution on this order. For $\gamma = 959$, $\lambda \leq 1$ μm (the infrared region). The characteristic wavelength of conventional synchrotron light given by protons within a Tevatron dipole is 2.4 μm, much too long to provide a good image of the beam.

The first suggestion of using the edge effect (or short magnets) to enhance the short wavelength component of synchrotron radiation was due to R. Coisson [1]. A simple argument will illustrate the concept. The characteristic wavelength of this radiation can be estimated by a Fourier analysis. A radiating particle moving with velocity v over a path length s , will produce a pulse of time duration $\Delta t = (s/v)/2\gamma^2$ in the direction of motion. The factor of $2\gamma^2$ comes from the fact that the duration of the pulse depends upon the difference between the particle's velocity and the speed of light. This pulse when analyzed in the frequency domain will give rise to frequency components on the order of $\nu = (2\pi\Delta t)^{-1}$. In terms of wavelength,
$\lambda \sim \pi s/\gamma^2$. Reducing s correspondingly shortens λ. This is achievable if the length of the dipole is short compared to the bending arc $(2R/\gamma)$. One may think of the synchrotron light as being switched on and off as the particle traverses the short magnet. Similarly the sharp transition edge from a no field region to a full field region (or vice versa) of a dipole magnet also can be seen as a light switch.

The edge of a Tevatron dipole magnet can be approximated by an error function, whose gaussian σ is 3.2 cm. By the above analysis wavelengths down to order λ=0.1 μm (ultraviolet) are generated. It is technically easier to transmit and detect 0.4 μm (blue) light than ultraviolet. At 0.4 μm the diffraction effects are only 0.2 mm horizontally, and 0.1 mm vertically (referred to the object plane). The differences arise because the synchrotron radiation pattern is asymmetric) [2]. A group at Cern has used the technique in the SPS to image the beam [3].

2 APPARATUS

A pickup mirror [4], telescope, and a focal plane detector have been installed in the Tevatron, near the downstream edge of a 6.1 meter superconducting dipole magnet. Synchrotron light emitted from the upstream edge is deflected out of the beam pipe by an moveable aluminized flat mirror through a quartz window into a telescope assembly. The telescope is a folded 1.5^{o} off-axis (Herschel) design. The beam emerging from the window is reflected upward onto the telescope objective, a two meter focal length spherical mirror (5 cm diameter). The optical path length from the object to the objective mirror is 9.47 m. The light beam then travels downward where it is intercepted by and reflected horizontally to the focal plane detector. The folding of the optical path was due to space considerations in the Main Ring tunnel. The detector is located approximately (depending on the focusing) 2.5 m from the objective mirror. The ratio of image height (length) to object height (length) is 1/3.7 (1/14). The particular choice of optics was set by the desire to have a depth of focus at least equal to 10 cm (approximately the total edge length of the dipole magnet) and a large field of view (4 cm at the object). Also the expected beam image σ of 100 μm was well above the pixel dimensions of the detectors (10-20 μm). All mirrors are polished to a $\lambda/10$ tolerance. Off-axis aberrations are below the diffraction limit (27 μm) at the image plane. The worst is astigmatism which contributes 17 μm.

In addition to the fixed mirrors, two "flip-in" mirrors and photo multiplier tubes (pmt) are installed, one just after the quartz window, and the other before the detector. By flipping in a mirror and observing the pmt intensity signal, it is possible to ensure that the apparatus is in reasonable alignment. In addition, the pmt signal will be used to time in the fast gate of the intensified camera.

The focal plane detector will eventually be an intensified Charge Injection Device (CID) camera [5], but as of this conference it is a Charge Coupled Device camera (CCD). The "second generation" intensifier has a blue sensitive 5 ns gateable photocathode, a single 18 mm diameter micro channel plate and a P20 phosphor screen. The output of the phosphor screen is a fiber optic faceplate. The CID detector also has a fiber optic faceplate to optically couple the light from the intensifier output. The active area of the CID has a 11.2 mm diagonal with 755 horizontal by 484 vertical pixels. Each pixel has horizontal (vertical) dimensions of 12.0 (13.7) μm. The camera head is mounted on a three axis motorized table allowing for focusing and transverse motion to center the beam.

The output of the camera is a standard (RS170) video signal. This signal is transmitted from the tunnel upstairs to the C0 electronics room by a 60 meter length RG59 cable. The data acquisition machine consists of a standard Macintosh CI computer, Nubus expansion box, and Nubus interface boards. These boards include a frame grabber which receives the video signal, a stepper motor control for the motorized camera table, a general purpose Analog/Digital control card for position readback, and a GPIB control card to control timing cards (for the gated intensifier) which are currently located in a Camac Crate. The Macintosh is networked via a Nubus Token Ring card to both the standard network as well as FNAL ACNET.

The software for the machine is based upon LabView 2 [6]. LabVIEW software support for the stepper motor control was purchased from the hardware vendor. Image Processing LabVIEW support for the frame grabber and the beam analysis are from third party vendors. All have have needed only minor modifications to satisfy our needs.

3 RESULTS

An ungated commercial CCD camera was installed at the focal plane since it was felt that the commissioning of the Main Ring and Tevatron would damage the more expensive fiber optically coupled CCD camera. Initial results were somewhat surprising. With a proton current of 2.7 mA (36 e10 protons), this camera began seeing a beam image during the acceleration ramp at a momentum between 5-600 GeV/c. This image saturated before the ramp reached 900 GeV/c. During the two weeks of machine turn-on, damage to the CCD sensor could be observed. The damaged CCD camera (although it was still functionally working) was replaced by a filtered (Corning Blue filter centered at 0.4 μ) CCD camera. With this filter the image no longer saturated. A single captured image represents an integration time of 1/30 of a second on the camera. For the 2.7 mA current, this is equal to 5.6 e14 protons passing this dipole edge. The following figure is an image taken under the above conditions.

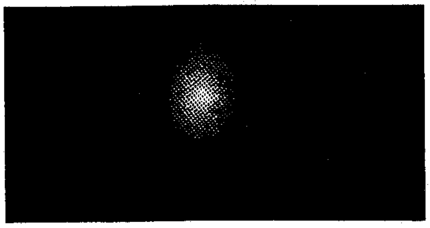

Image of 900 GeV/c Tevatron Beam. Image is rotated 90° counterclockwise compared to actual beam orientation. See text for details.

The horizontal and vertical beam profiles are fit by simple gaussian functions. The results for one case gave $\sigma_h = 0.53$ mm and $\sigma_v = 0.40$ mm. Unfolding the expected diffraction by quadrature subtraction (0.20 mm horizontal and 0.10 mm vertical) give $\sigma_h = 0.49$ mm and $\sigma_v = 0.39$ mm. These values compare quite well with the flying wire data. The largest uncertainty in the comparison (10%) comes from the knowledge of the lattice functions.

4 CONCLUSIONS

In the near future, we are planning to replace the CCD camera with a gated intensified CID camera. The CID is purported to be more resistant to radiation (up to 10^5 rads from a gamma ray source) than a CCD. We have made measurements of the radiation levels at the current camera location and against the inside wall of the Main Ring tunnel. Once the results are available, we may decide to fold the optical path over the tunnel ceiling to increase the lifetime of the camera.

The gated intensifier will be used primarily as a fast shutter rather than an intensifier. By varying the timing of the gate, it will be possible to make on-line bunch-by-bunch transverse beam measurements. Finally we plan to install 3 more systems, so that proton and anti-proton emittance measurements will be possible.

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References

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[4] A.A.Hahn and P.Hurh, " Results from a Prototype Beam Monitor in the Tevatron Using Synchrotron Light", in 1991 IEEE Particle Accelerator Conference, 1991, pp. 1177-1179

[5] CID3710 camera, CID Technologies, 101 Commerce Blvd., Liverpool, NY, USA (315)451-9410

[6] LabVIEW 2, National Instruments Corp., 6504 Bridge Point Parkway, Austin TX 78730-5039, USA (512)794-0100