Results from a Prototype 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 downsteam edge of a superconducting dipole magnet. Synchrotron light produced at the upstream edge [1] of the magnet is sufficiently separated from the proton beam to be picked off by the monitor's mirror and diverted to its detector. The measured light intensity at different beam energies will be compared to the predicted values. The parameters of a beam profile monitor will be discussed.

I. INTRODUCTION

A charged particle accelerated transverse to its direction of motion will emit synchrotron radiation [2]. This radiation is sharply peaked in the forward direction, being almost completely contained within a cone of half angle $\Delta\theta = 1/\gamma = m/E$, where m is the mass of the particle and E its relativistic total energy. This radiation if imaged, can form a transverse profile of the beam itself. Synchrotron radiation profile monitors are quite common in electron machines due to the copious numbers of photons produced. Only relatively recently however [3] has such a device become available for routine use in a proton machine. The difficulty can be traced to two related factors. First the frequency of the typical synchrotron radiation is much too low to be easily detected. Secondly, the angular resolution of an imaging system which should be high to measure the profile of a narrow particle beam, will be limited by the extreme narrowness of the synchrotron radiation itself. This effect scales as $\lambda/\Delta\theta$. Since $\Delta\theta$ is set by the energy of the machine, the only way to improve resolution is to lower λ. As will be shown, the way to enrich the low wavelength region is to rely either upon short magnets (or an undulator which is a series of short magnets) or the sharp transition between the zero field region and the full field region of a dipole magnet.

Synchrotron Radiation - "Standard Theory"

The power emitted by a particle moving with velocity $c\boldsymbol{\beta}$ in a uniform magnetic field B can be estimated in the following way. Consider the particle in its own instantaneous rest frame. It is subjected to an effective electric field $\mathbf{E} = \gamma c\boldsymbol{\beta}\times\mathbf{B}$. The emitted power can be calculated by using Larmor's non-relativistic formula $P = (e^2/6\pi\varepsilon_o c^3)a^2$, a being the acceleration of the particle = F/m = eE/m. Assuming $\boldsymbol{\beta}$ and B are at 90°, $P = \dfrac{e^4\gamma^2\beta^2B^2}{6\pi\varepsilon_o m^2 c}$. In the rest frame this power is emitted symmetrically around the axis of acceleration in a toroidal shape. The power in the laboratory frame can be related to the rest frame by a Lorentz transformation. Recognizing that power $= \dfrac{\Delta\text{Energy}}{\Delta\text{time}}$, one needs to transform both the numerator and denominator. Due to the symmetry of the power around the acceleration axis, the average photon energy is just Lorentz boosted by a factor of γ, $\Delta E_{lab} = \gamma\Delta E_{rest}$. Since $\Delta t_{lab} = \gamma\Delta t_{crest}$, $P_{lab} = P_{rest}$. The power can be written in the more common form $P = \dfrac{e^2p^4}{6\pi\varepsilon_o m^4c^3R^2}$ where R and p are the radius of curvature and momentum of a charged particle in a magnetic field, ($R = \gamma mc\beta/eB = p/eB$).

The frequency spectrum of the radiation may be developed in a similar manner by considering the length of the radiation pulse at an observation point. Due to the directionality of the radiation this can be quite short. For a conventional synchrotron source, the beam arc length which can radiate in the direction of an observer is $R(2\Delta\theta) = 2R/\gamma$. Again from the perspective of the particle in its own series of instantaneous rest frames, this length is Lorentz contracted a factor of γ. Therefore the power radiated to reach the observer must occur in a time span of $2R/\gamma^2c\beta$. A simple Fourier analysis says that the radiation will have frequency components (in the rest frame) proportional to $\dfrac{1}{2\pi\Delta t} = \dfrac{\gamma^2c\beta}{4\pi R}$. In the lab frame these frequencies (or photons) will again be energy boosted another factor of γ as shown before. Putting a factor of 3 to reflect that Δt was actually the entire length of the pulse and also to end up with a familiar formula, one can define a critical frequency,

$\nu_{cr} = \dfrac{3\gamma^3c\beta}{4\pi R}$. For a 900 GeV/c proton in a Fermilab Tevatron dipole magnet, R = 754 m, $\beta \approx 1$, $\gamma = 959$, and the critical wavelength is $\lambda_{cr} = c/\nu_{cr} = 3.5\ \mu m$, the far infrared region.

"Short" Magnet

A magnet is defined to be short if its length is much shorter than $R(2\Delta\theta)$ the arc length defined above. Effectively the deflection angle of the particle due to the magnet is smaller than the synchrotron radiation cone. The development for a

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short magnet proceeds as above except for one detail. The path length is set by the magnet characteristic length L , not the arc length. Replacing $2R/\gamma$ by L the critical frequency becomes $\nu_{cr} = \frac{c\gamma^2}{2\pi L}$. For example a Gaussian magnet with $\sigma = 4.5$ cm length and a $\gamma = 959$ gives a critical wavelength of 307 nm, the ultraviolet region. Of course the total power emitted is less than in the standard case since the average field is less than the full magnet and the total path length is (in this case) roughly 10 times less. However in the short wavelength region around 300 nm, the standard case has a negligible intensity, down roughly $e^{-2(3500/300)}$ (using a rigorous formula) compared to the 3.5 μm region. Thus synchrotron radiation from a short magnet is much more intense in the short wavelength region.

The edge of a magnet behaves similarly to a short magnet in that a sharp transition from zero field to full field enriches the high frequency (low wavelength) portion of the synchrotron spectrum.

The rigorous derivation of the power spectrum for short magnets and the edge profiles of magnets can be found in Ref [1].

II. TEVATRON SYSTEM

Dipole field shape

The end field of a Tevatron superconducting dipole magnet was measured with a Hall probe. Figure 1 depicts the field intensity as the probe is inserted into the magnet. To facilitate calculations, several shapes were fit to the data. The best approximation was an error function with a characteristic width of 4.56 cm.

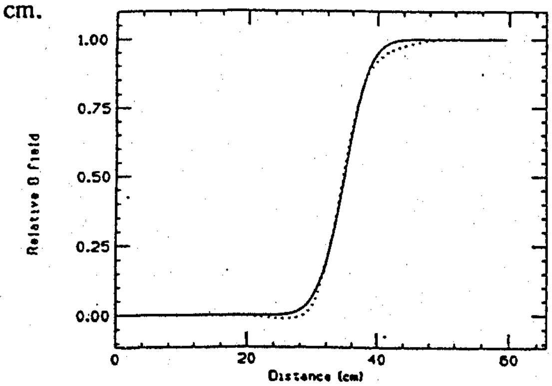

Figure 1: The relative magnetic field near the end of a Tevatron Superconducting Magnet. The dotted line represents the measured data. The solid line is an fit of the data to an Error Function.

Differential Power spectrum

With this function and width, the differential power spectrum [1] is

$$\frac{dW}{d\Omega d\lambda} = N\frac{C^2\gamma^6}{4\pi^2 c} f^2 B_o^2 \exp(-\pi^2\frac{Ly}{2\gamma^2\lambda}),$$

with N the number of particles, $C^2 = 9.47*10^{-11} m(s/kg)^{0.5}$ (for protons), $f^2 = f^2_{\perp} + f^2_{\parallel} = y^{-6}\,[(1-(\gamma\theta)^2)^2 + 4(\gamma\theta\sin^2\phi)^2]$ representing the planes of polarization perpendicular and parallel to the motion , and $y = 1 + (\gamma\theta)^2$. Figure 2 plots the power spectrum integrated over angles for several proton momenta.

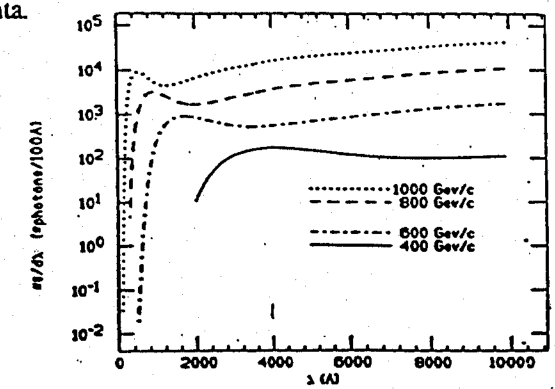

Figure 2: Photon Yield from the edge of a Tevatron dipole magnet vs wavelength for a $6*10^{10}$ proton bunch of various momenta.

Detector

A port was installed on the Tevatron beam pipe at the C11 location. This location is a meter downstream of a 6.1 meter Tevatron Dipole magnet. The proton beam is bent a total angle of 8.12 mr from its original direction. Synchrotron light, produced tangentially at the far upstream edge, is separated horizontally 2.5 cm from the proton beam at the downstream end. Since the proton beam width is on the order of 1 mm, it is possible to reflect the synchrotron light by a suitably placed mirror without interfering with the proton beam. Figure 3 schematically shows the arrangement of the port. The mirror is an aluminized flat which can be remotely driven in and out of the beam pipe by a total distance of 3.8 cm. The window is 2mm thick Suprasil.

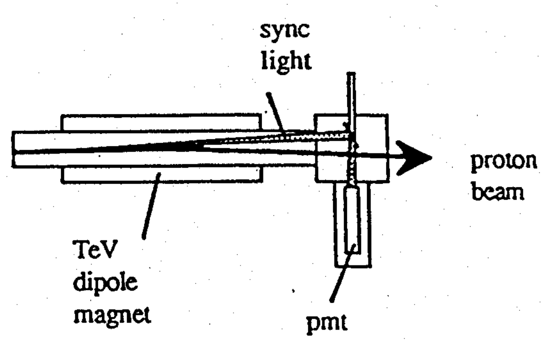

Figure3: Schematic view of prototype setup.

Prototype test

A Phillips 2" S20 photocathode photomultiplier tube (pmt) was installed adjacent to the Suprasil window. This tube was chosen since it was available and its quantum efficiency is similar to that of the eventual imaging detector. The pmt was calibrated with an LED with respect to gain so that using the manufacturer's nominal quantum efficiency values, an estimate to the number of photons seen could be made. Figure 4 gives the predicted number of photons seen for both this pmt and a commercially available CCD.

In order to verify that we were indeed detecting synchrotron light instead of particle losses, the internal mirror was pushed into the beampipe in small steps. While in the full out position, no signal could be seen on the pmt. As the mirror was pushed into the beam pipe the signal could be seen to increase, eventually reaching a plateau.

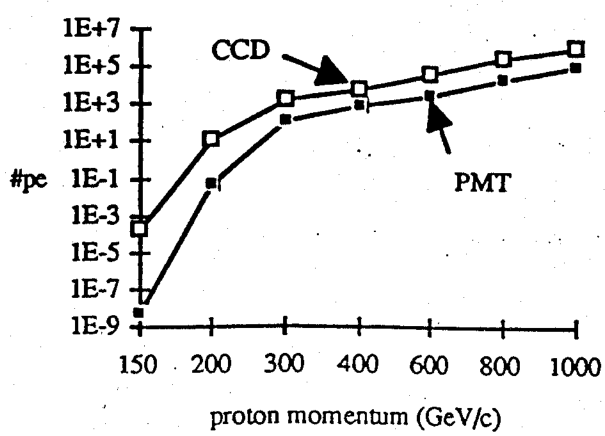

Figure 4: The photoelectron yield for a $6*10^{10}$ proton bunch from the edge of a Tevatron dipole magnet.

It is difficult to quantitatively compare the experimental intensity as a function of proton momenta since the beam pipe interferes with the synchrotron light beam at low momenta. Qualitatively, the light is first seen at a proton momentum of about 500 GeV/c, and the intensity increases rapidly as the acceleration ramp progresses. A comparison of the experimental yield at 800 GeV/c to the theoretical value gives twice the intensity expected. This is likely within the error of the known pmt response.

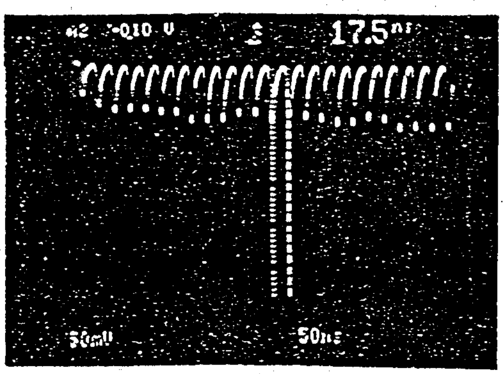

Figure 5: Oscilloscope photograph of response of pmt to a batch of 800 GeV/c protons. The individual buckets each contained approximately $0.6 * 10^{10}$ protons.

III. Future Imaging system

We are in the process of installing a complete imaging system. This system will use the same beam port as described above. In addition there will be two additional flat mirrors to fold the optical path, a spherical focusing mirror to make the image, and a intensified CCD camera.

Optics

The reflecting mirror is a 5 cm diameter spherical mirror with a focal length of 2 meters. Since the object distance is 7.5 meters away, the image is formed 2.7 meters from the mirror. The image height is 36% of the actual object (proton beam) size or approximately 360 μm. This configuration was chosen so that the area of the image plane (1.1 x 0.88 cm^2) would cover a large region of the beampipe at the object plane, thereby making it easier to find the beam image under startup conditions. The diffraction limit is 29 μm referred to the image plane. Note that 3.5 μm radiation diffraction limit would be 10 times worse. The depth of focus is $\pm$ 1 cm, well matched to the image length of 1.3 cm (for a 10 cm object length). Aberrations, dominated by astigmatism (due to a 1° off axis reflection on the primary mirror) are only 8μm, well below the diffraction limit and thus may be ignored.

Focal plane camera

Detection of the image will be done with a gateable microchannel-plate image-intensifier, optically coupled to a CCD camera. The gateable aspect (5ns time resolution) will allow single-bunch single-pass detection or single-bunch imultiple-pass integration. The CCD is a 483x378 pixel array with a fiber optic input window. Each pixel is spaced 30 μm horizontally, 18 μm vertically and is 12x18 μm^2 in size. Initial readout will be at video speeds.

We are exploring the possibility of including an optical scanning mirror. This device would be place near the camera so that the converging image could reflect off the mirror. In this manner it would be possible to record an multiple images of a single proton bunch on successive revolutions. Each image would be offset from the previous one due to the rotation of the scanner (a 10 element mirror rotating at 30000 rpm). At 10 images per line, and 10 lines a total of up to 100 images per video readout could be accomplished.

III. REFERENCES

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[3] J.Bosser et al., "Proton beam profile measurements with synchrotron light",preprint, CERN SPS/83-15, (1983)