BNL-65134

A Possible Synchrotron Light Beam Profile Monitor in RHIC

D. Trbojevic, E. Courant, S. Peggs, BNL,
A. Hahn, FNAL

June 1998

RHIC Project

Brookhaven National Laboratory
Operated by
Brookhaven Science Associates
Upton, NY 11973

Under Contract with the United States Department of Energy
Contract Number DE-AC02-98CH10886

A Possible Synchrotron Light Beam Profile Monitor in RHIC

D. Trbojevic, E.D. Courant, and S. Peggs, Brookhaven National Laboratory, Upton, NY 11973, USA,
and A. Hahn, Fermi National Accelerator Laboratory, Batavia, Illinois, 60510, USA

Abstract

This report examines the possibility of observing transverse beam profiles by using synchrotron light emission from the 100 GeV/nucleon heavy-ion gold beam in the Relativistic Heavy Ion Collider (RHIC). Synchrotron radiation experiences a shift towards higher photon energy when the magnetic field at the end of a dipole varies rapidly over a short distance. Synchrotron light signals from high energy (larger than 400 GeV) proton beams have already been routinely used to observe the transverse beam profiles at the SPS in CERN and at the TEVATRON at Fermilab. Because of the modest relativistic factor of the fully stripped stored gold ions in RHIC this "push" towards higher critical energy is not large enough to place the synchrotron light within the visible region of the spectrum. The critical wavelength remains within the infrared region. A 77K cooled infrared array detector with 160 elements, made of PbSe (Lead salt) could be used for beam profile detection. It would cover the wavelength range between 1 and 6 microns, with maximum sensitivity at a wavelength of 4.5 microns.[1]

1 INTRODUCTION

Synchrotron light beam profile monitors are regularly used in relativistic electron synchrotrons. In large hadron colliders such as the CERN SPS and the Fermilab Tevatron they became a part of regular operations [1], [2] after it was realized that the critical frequency of the synchrotron radiation from the relativistic hadrons could be pushed towards the visible region under the influence of the dipole edge field effect. Recently the edge effect has been used to monitor the beam profiles even in lower energy electron transfer lines and storage rings. The Relativistic Heavy Ion Collider will accelerate heavy ions (for example gold $^{+79}Au^{197}$ ions) up to energy of 100 GeV/nucleon. The gold ions are fully stripped with a total charge of +79e. Charged particles emit radiation in the direction of motion within a cone of approximately $\Delta\theta \sim 1/\gamma$, where γ is the relativistic factor. The critical wavelength λ_c (or the critical frequency ν_c) divides the total power of the synchrotron radiation spectrum into two halves. The power of the photon spectrum at frequencies larger than ν_c falls rapidly above it. A pulse of radiation tangential to the curvature of the bending magnet is emitted towards a stationary observer during the path length L_o. If the radius of the curvature is ρ and the angle $\theta \sim 1/\gamma$, then the path length is $L_o = \rho/\gamma$. The corresponding time is $\Delta t = L_o/v = \rho/\gamma v$. The front end of the photon pulse travels in time Δt a distance $D = c\Delta t = \rho/\gamma\beta$ [3], while the rear end of the pulse is a distance $l = D - L_o = \rho/\gamma(1/\beta - 1) \sim \rho/2\gamma^3$ behind the front edge. The observation time τ_c [4], [3] is equal to L_o/c:

$$\tau_c = \frac{\rho}{2c\gamma^3} = \frac{m}{2\gamma^2 ZeB}, \tag{1}$$

where *m* is the rest mass (Am_u in the case of gold ions) and *B* is the magnetic field. The spectrum is then extended [4] up to a frequency $\nu_c = 1/\tau_c$. The critical frequencies ν_c or the wavelengths λ_c are recorded for SPS, Tevatron, and RHIC in Table 1.

Table 1: Critical Synchrotron Frequencies

Collider	γ	Radius(m)	$\lambda_c(\mu m)$	B(T)
CERN-SPS	426.3	740.0	5.74	1.50
Fermilab-TEV	959.2	754.0	2.91	3.98
BNL-RHIC	108.4	242.2	95.2	3.46

The modification of the critical wavelength due to the edge effect is easily understood by following Coïsson [5],[4],[6]. The critical wavelength is similarly modified by wigglers. Additional oscillations of the charged particles within a wiggler are similar to a new sequence of smaller bending magnets. The wiggler magnetic field oscillates within the wiggler length L_w as $B = B_o \sin(2\pi/\lambda_o)s$, where the period λ_o, produces enhanced synchrotron light with an output wavelength [5]:

$$\lambda = \frac{\lambda_o}{2\gamma^2}(1 + \gamma^2\theta^2), \tag{2}$$

where the θ is the angle of observation and γ is the relativistic factor. The flux per unit solid angle around $\theta = 0$ expressed as the number of photons per second [5]:

$$\frac{dN}{d\Omega} = \frac{1}{8\pi^2\epsilon_o}\frac{(Ze)^3}{hm^2c^3}\gamma^2 B_o^2\, I\, L_w\, \lambda_o, \tag{3}$$

where *I* is the current in the storage ring. An analogous wiggler in the SPS or RHIC could be defined as previously [5] with parameters $L_w = 10m, \lambda o = 10cm, B_o = 0.03T$. The output wavelength λ and corresponding number of photons, when the parameter $B_o^2\lambda_o L_w$ is kept the same for both the SPS and RHIC, is presented in Table 2:

These results encourage the use of a synchrotron light detector in RHIC. Unfortunately the wavelength is not in the visible but in the infrared region of the spectrum.

[1] Work performed under the auspices of the U.S. Department of Energy

Table 2: Photon flux from the equivalent wiggler

Collider	γ	$\lambda'_c(\mu m)$	photons/$srad^2$
CERN-SPS	426.3	0.55	$5.7{\cdot}10^8$
BNL-RHIC	108.4	4.25	$1.0{\cdot}10^9$

2 SYNCHROTRON RADIATION FROM THE EDGE FIELD

An ultra relativistic charged particle, with a charge Ze, emits synchrotron radiation over its trajectory of a length $L_o = mc/ZeB$. If a rapid variation of the magnetic field B, from zero to B_o, or vice versa occurs within a short length *L*, such that the deflection α of the particle $\alpha \ll 1/\gamma$ or equivalently [6] if the length $L \ll L_o$, then the spectrum changes. The *critical frequency* has a larger value than in the usual uniform magnetic field case. The fall or rise time τ_d at the observer who is looking at the edge [7], with the radius of curvature $\rho \sim L/\theta = L\gamma$ is:

$$\tau_d = \frac{L}{2c\gamma^2}. \tag{4}$$

Table 3 compares the previously calculated wavelength from a uniform magnetic field $\lambda_c = c\tau_c$ with the new value ($\lambda'_c = \lambda_d = c\tau_d$) when the magnetic field changes within a length L.

Table 3: Critical Synchrotron Frequencies

Collider	Eff. Length	$\lambda'_c(\mu m)$	γ
CERN-SPS	0.100 m	0.275	426.3
Fermilab-TEV	0.148 m	0.080	959.2
BNL-RHIC	0.100 m	4.255	108.4

2.1 Error Function Approximation of the Dipole End Field

Following previous work on the spectral distribution of synchrotron radiation from a "short" magnet [6], and with the end of the magnet approximated by an error function $B(s) = 1/2B_o(1{+}\text{erf(s/L)})$, the spectral distribution of the power density collected over the whole 4π solid angle is:

$$\frac{dW}{d\nu} = \frac{C^2 B_o^2 \gamma^4}{4\pi\nu^2}\, S(x) \quad (\frac{\text{Joule}}{\text{m}}), \tag{5}$$

$$S(x) = \int_1^\infty \langle f^2\rangle e^{-x^2y^2}\, dy, \tag{6}$$

where $\langle f^2\rangle = y^{-6}(y^2 - 2y + 2)$, $y = 1 + \gamma^2\theta^2$, $x = \sqrt{2}\nu/\nu_1$, $\nu_1 = 2\gamma^2 c/\pi L$, erfc(x)=1-erf(x) where erf(x) is the standard error function [8], and the constant:

$$C^2 = \frac{(Ze)^4}{(\pi m^2)^2\epsilon_o c} \quad \left(\frac{\text{m C}^2}{\text{kg s}}\right). \tag{7}$$

Values of the constants for the three large hadron colliders are presented in Table 4. When the magnetic field is represented by the error function the function *S(x)* is:

$$S(x) = \frac{e^{-x^2}}{15}\left(\frac{7}{2} - \frac{13}{2}x^2 + 8x^4\right) + \frac{2}{3}x^3\sqrt{\pi}(1 - \frac{4}{5}x^2)\,\text{erfc}(x) - \frac{x^4}{2}E_1(x^2),$$

where $E_1(x^2)$ is the exponential integral defined in [8].

Table 4: Error Function Approximation Constants

Collider	$(\frac{\text{m C}^2}{\text{kg s}})$	$\lambda_1(\mu m)$
CERN-SPS	$8.99\,10^{-21}$	0.389
Fermilab-TEV	$8.99\,10^{-21}$	0.078
BNL-RHIC	$9.15\,10^{-18}$	6.015

The magnetic end field in the RHIC dipoles was measured by a combination of *Hall* and nuclear magnetic resonance (NMR) probes. One of the measured results of the end field is presented in Fig. 1. The photon spectra of the synchrotron radiation in the three hadron colliders are presented in fig 2. At the wavelength of 4.5 μm a detector made of PbSe has a maximum in detectivity $D^*(=)cmHz^{1/2}W^{-1}$. The number of photons per turn for RHIC at $\lambda = 4.5\mu m$ is equal to $N_{photons}$=5433 at the bandwidth-wavelength interval equal to $\Delta\lambda = 0.5\mu$m.

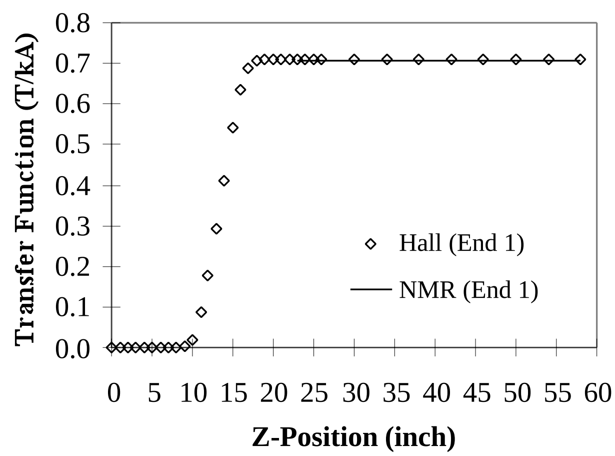

Figure 1: The RHIC dipole magnetic field end measurement result.

3 INFRARED DETECTOR ARRAYS

The short range *L* of the fast change of the magnetic field at the end of the dipole together with the value of relativistic factor γ determines the critical wavelength of the synchrotron radiation spectrum. Synchrotron light emitted from the $\gamma = 108.4$ heavy ion beams has a critical wavelength 4.5 μm, corresponding to a photon energy of E=0.275 eV. The difference in the photon energy from the visible light 1.6-3.1 eV changes the material needed for a photovoltaic p-n junction detector. Instead of using semiconductors like silicon with the en-

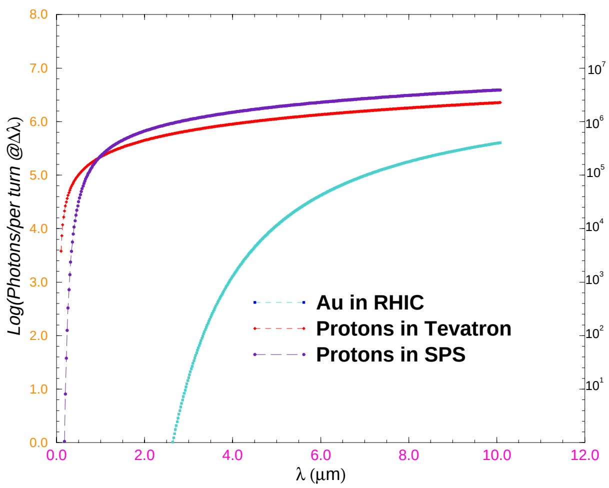

Figure 2: Number of photons per turn vs. wavelength in the three hadron colliders.

ergy gap of E_g=1.09 eV, infrared detectors are usually *semimetals* with an energy gap of approximately 0.3 eV. Commercially available detectors include *Lead-Salts* PbSe (TEXTRON), 2-5μm, *Indium-Antimonide* InSb 1-5.35 μm (Lockheed-Martin Corp.), and Pt-Si *Platinum-Silicide* 3-5 μm (NIKON Corp.). Other materials used for the near infrared photon detection are PbTe, PBS [9], InGaAsP, CdTe, HgTe-CdTe, PbTe-HgTe, $Pb_{0.97}Hg_{0.03}Te$ [10], et cetera.

3.1 A Possible Detector Setup at RHIC

Synchrotron light is emitted in a cone of $1/\gamma$. The RHIC *DX* dipole considered for the synchrotron light application has a length of 3.7 m and a magnetic field of 4.279 T at the top energy when fully stripped gold ions collide. An infrared reflector mirror can be introduced at a distance of 4.85 m from the front edge of the magnetic field. The spot size at the reflector will then have a radius of 2.2 cm. An infrared transparent vacuum window above the reflector and an additional lens above it are required to match the reflected photons to the infrared detector array surface.

4 CONCLUSIONS

Synchrotron radiation from heavy ions like fully stripped gold can be successfully used in a beam profile monitor application in RHIC. Due to the relatively small value of the relativistic factor $\gamma = 108.4$, the emitted synchrotron radiation from the fast changing field at the end of the magnet is within the infrared region. Due to the large charge state (in gold +79), the number of photons obtained should be large enough to be recorded by a standard infrared detector array within a wavelength range of 1-6 μm. Operational experience with synchrotron light monitoring at the Fermilab Tevatron for both proton and antiproton stored beams has shown high reliability and accuracy of 5% in providing the transverse *rms* beam sizes. Synchrotron light monitors could be easily installed in the RHIC rings to provide continuous information about the beam profiles and the transverse emittances of the two colliding ion beams.

5 REFERENCES

[1] R. Bossard, J. Bosser, L. Burnod, E. D'Amico, G. Ferioli, J. Mann, and F. Meot, "Proton Beam Profile Measurements with Synchrotron Light", Nucl. Instr. & Methods, Vol. 184 (1981), pp. 349-357.

[2] A.A.Hahn and P. Hurh, "Results from a Prototype Beam Monitor in the Tevatron Using Synchrotron Light", Proc. IEEE, PAC 1991, San Francisco, MAY(1991), pp. 1177-1179.

[3] J.D. Jackson , "Classical Electrodynamics", Second Edition, J. Wiley, New York, 1975, p. 666.

[4] R. Coïsson, "On Synchrotron Radiation in Non Uniform Magnetic Fields", Optics Communications, Vol. 22, No.2, August (1977), pp. 135-137.

[5] R. Coïsson, "Narrow Band Visible Synchrotron Radiation from High Energy Proton Beams", Nucl. Instr. & Methods, Vol. 143 (1977), 241-243.

[6] R. Coïsson, "Angular-spectral Distribution and Polarization of Synchrotron Radiation from a 'short' magnet", Phys. Rev. A, Vol. 20, No. 2, (1970), pp. 524-528.

[7] R. Bossard, J. Bosser, L. Burnod, R. Coïsson, E. D'Amico, A. Hofmann, and J. Mann, "Observation of Visible Synchrotron Radiation Emitted by a High-Energy Proton Beam at the Edge of a Magnetic Field", Nucl. Instr. & Methods, Vol. 164 (1979) pp. 375-380.

[8] M. Abramovitz and I. Stegun, "Handbook of Mathematical Functions", Dover, New York, December 1972, pp. 231 and 297.

[9] D. Trbojevic, P. Nikolic, B. Perovic, and V. Cvekic, "Photovoltaic Detectors in SnS Produced by Sb^+ Ion Implantation", Appl.Phys. Lett., Vol. 38, 1 March (1981), pp. 362-364.

[10] D. Trbojevic, B. Perovic, P.Nikolic, and V. Cvekic, "Photovoltaic Detectors in $Pb_{0.97}Hg_{0.03}Te$ Produced by Sb^+ Ion Implantation", Infrared Physics, Vol.20, (1980), pp. 193-198.