Synchrotron Radiation from Protons

Superconducting Super Collider Laboratory
Disclaimer Notice

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government or any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Superconducting Super Collider Laboratory is an equal opportunity employer.
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
Synchrotron Radiation from Protons*

S. Dutt

Superconducting Super Collider Laboratory†
2550 Beckleymeade Avenue
Dallas, Texas 75237

December 1992

†Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED.
Synchrotron Radiation from Protons

Samir K. Dutt
SSC Laboratory*
2550 Beckleymeade Avenue
Dallas, TX 75237

1 Introduction

Synchrotron radiation from protons, though described by the same equations as the radiation from electrons, exhibits a number of interesting features on account of the parameters reached in praxis[1]. In this presentation, we shall point out some of the features relating to (i) normal synchrotron radiation from dipoles in proton machines such as the High Energy Booster and the Superconducting Super Collider; (ii) synchrotron radiation from short dipoles, and its application to light monitors for proton machines, and (iii) synchrotron radiation from undulators in the limit when the deflection parameter is much smaller than unity. The material for this presentation is taken largely from the work of Hofmann[2], Coisson[3], Bossart[4], and their collaborators, and from a paper by Kim[5]. We shall emphasize the qualitative aspects of synchrotron radiation in the cases mentioned above, making, when possible, simple arguments for estimating the spectral and angular properties of the radiation. Detailed analyses can be found in the literature.

2 Dipole Radiation

A fundamental property[6] of the radiation emitted by an accelerated charged particle in relativistic motion (γ ≫ 1) is that the radiation is contained within a narrow cone with axis along the particle’s forward direction, and with opening angle ~ 1/γ . The observer in Fig. 1 would see a pulse of light emanating from an arc of length ~ 2ρ/γ, provided the dipole is at least this long. This is the usual case of synchrotron radiation from dipoles.

The time structure of the pulse received by the observer can be estimated from the particle’s time of flight across the arc

\[ Δt = \frac{2ρ}{γ} × \frac{1}{c} × (1 - β) \approx \frac{ρ}{cγ^3}. \]

The factor of (1 − β) above represents the difference between the velocity of the particle and the photons emitted by it (if the particle moves at almost the speed of the photons it emits, they bunch up in the same place, and the pulse duration becomes vanishingly small). The spectral bandwidth can thus be estimated as

\[ ω_c \sim \frac{2π}{cγ^3}. \]  

A more detailed calculation[6] gives the critical frequency\(^1\) of radiation from a normal dipole as

\[ ω_c = \frac{3}{ρ} cγ^3. \]

---

\(^1\)This way of defining the critical frequency places it close to the usual FWHM convention. Alternatively, one can take half of the above, which has the virtue of dividing the area under the angle-integrated spectral profile into equal halves[2].
The opening angle $\Delta \phi$ of synchrotron radiation can be estimated as follows. The transverse dimension of the pulse seen by the observer in Fig. 2 should be about the height of the arc above the observer’s line of sight. Thus

$$\Delta x \sim \rho (\Delta \phi)^2.$$  

(2)

The diffraction induced angular spread in this transverse spot should also be $\sim \Delta \phi$, so that

$$\Delta \phi \sim \frac{\lambda}{\Delta x}.$$  

(3)

Combining Eqs. (1) through (3) we obtain

$$\Delta \phi \sim \frac{1}{\gamma} \left( \frac{\omega_c}{\omega} \right)^{1/3}.$$  

The high frequency behaviour, $\omega \gg \omega_c$, differs from the above, in that

$$\Delta \phi \sim \frac{1}{\gamma} \sqrt{\frac{\omega_c}{\omega}},$$

with the spectral intensity falling off exponentially.[6]

Before applying these results, we present some relevant parameters for the Advanced Photon Source, the Tevatron, the High Energy Booster, and the Super Collider in Table I. The APS is an electron machine, and will serve to contrast the properties of synchrotron radiation from protons and electrons.

The most obvious difference in the radiation from electrons and protons is the vastly greater amount of energy radiated by electrons. Since the radiated power $P$ scales as $\gamma^4/\rho^2$, an electron radiates $10^{13}$ times more than a proton of the same energy, and with the same bending radius $\rho$. This is simply because a proton is almost 2000 times heavier than an electron. For the same reason, the critical frequency of bending magnet radiation, which scales as $\gamma^3/\rho$, is $6 \times 10^9$ times higher for an electron. In addition, the Lorentz factor $\gamma$ scales as $B_0\rho/m_0$, where $B_0\rho$ is the magnetic rigidity, and $m_0$ the rest mass. Since the dipole field strength $B_0$ is limited (6 – 7 Tesla), the bending radius $\rho$ in a proton machine has to be much longer than the bending radius in an equivalent electron machine, Table I. This reduces the instantaneous power, and the bandwidth, of synchrotron radiation from protons compared to electrons, even for the same value of $\gamma$. Another difference, arising from the much longer bending radius in proton machines, is the arc length $2\rho/\gamma$ over which a particle radiates—a few mm’s in the APS, as opposed to 10 m in the SSC at its injection energy of 2 TeV, and 1 m at 20 TeV.

What makes synchrotron radiation from protons interesting is that it is diffraction dominated. In analogy with the emittance of a particle beam, which is the average area occupied by the beam in phase space $(x, x')$ measured in units of $\pi$ m-rad, we can calculate the emittance of a beam of light as the product of its transverse dimension $D$ multiplied by the diffraction induced angular spread $\lambda/D$, or $\sim \lambda$. More precisely, it is found[5] to be $\lambda/4\pi$. When the particle emittance is smaller than the light emittance, one arrives at a fundamental threshold—image quality is diffraction dominated. This is one of the objectives of fourth generation light sources. Table II compares the particle and light emittance of synchrotron radiation from the APS, and from three proton machines at their respective critical wavelengths. We choose the critical wavelength as it is close to the peak intensity of the spectral profile. The proton machines are found to be diffraction dominated. The reason for this is twofold: (i) the critical wavelength of synchrotron radiation from proton machines is much longer, and (ii) the absolute emittance of the beam in these proton machines is smaller than the natural emittance of the APS.

**Table I: Machine Parameters**

<table>
<thead>
<tr>
<th>Machine</th>
<th>Energy $E$ [GeV]</th>
<th>Bending Radius $\rho$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>APS</td>
<td>7</td>
<td>38.96</td>
</tr>
<tr>
<td>Tevatron</td>
<td>$10^3$</td>
<td>754</td>
</tr>
<tr>
<td>HEB</td>
<td>$2 \times 10^3$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>SSC</td>
<td>$2 \times 10^4$</td>
<td>$10^4$</td>
</tr>
</tbody>
</table>

Figure 2: Transverse size of the apparent source as seen by an observer, from Ref. [5].
Table II: Emittance of Photon & Particle Beams

<table>
<thead>
<tr>
<th>Machine</th>
<th>Energy [TeV]</th>
<th>Photon Emittance [$\pi$ m-rad]</th>
<th>Particle Emittance [$\pi$ m-rad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>APS</td>
<td>$7 \times 10^{-3}$</td>
<td>$2.5 \times 10^{-12}$</td>
<td>$8.2 \times 10^{-9}$</td>
</tr>
<tr>
<td>Tevatron</td>
<td>1</td>
<td>$1 \times 10^{-7}$</td>
<td>$2.3 \times 10^{-9}$</td>
</tr>
<tr>
<td>HEB</td>
<td>2</td>
<td>$1.7 \times 10^{-8}$</td>
<td>$4.7 \times 10^{-10}$</td>
</tr>
<tr>
<td>SSC</td>
<td>20</td>
<td>$1.7 \times 10^{-10}$</td>
<td>$4.7 \times 10^{-11}$</td>
</tr>
</tbody>
</table>

In this connection, note that a comparison of the emittance of electron and proton beams is complicated by the different measures used to characterize them. Electron beams are characterized by their natural emittance $\epsilon_x$, which is the radiation damped equilibrium size of the phase space area of the beam. The natural emittance of a particle beam depends only on its Compton wavelength, on $\gamma$, and on the lattice\(^7\). An approximate relation is

$$\epsilon_x^n \approx \frac{R}{\rho} \frac{\gamma^2}{\nu_x^2} \lambda_C,$$

(4)

where $\rho$ is the magnetic bending radius, $R$ is the average radius of the ring, $\lambda_C$ is the particle's Compton wavelength divided by $2\pi$, and $\nu_x$ is the horizontal tune. Since an electron machine of a few GeV has a damping time $\sim$ milliseconds, the natural emittance is the appropriate measure of its phase space area. Proton beams, on the other hand, have damping times much greater than the beam lifetime. The natural emittance is now not useful. However, there exists an adiabatic invariant, the normalized emittance

$$\epsilon_x^n = \gamma \epsilon_x,$$

which remains approximately constant during the long acceleration chain required to boost a proton from rest to a substantial energy. For example, the SSC has a chain starting from about 1.2 GeV/c from the linac to 20 TeV/c in the Collider, and $\epsilon_x^n$ remains approximately constant. The absolute measure of phase space can be found at any stage by dividing $\epsilon_x^n$ by the appropriate value of $\gamma$.

It is interesting to calculate the natural emittance of the APS and the SSC from the approximate formula in (4). Table III provides the required parameter values and the result. Comparing the approximate value of the natural emittance of the APS in Table III with the more precise value in Table II we find them to be in very good agreement. The natural emittance of the Collider is found to be about 660 times smaller than its undamped absolute emittance, and about $10^5$ times smaller than the natural emittance of the APS. This is because the natural emittance scales linearly with the Compton wavelength, and inversely as the cube of the horizontal tune, both of which work to reduce the emittance of the SSC relative to the APS.

Table III: Natural Emittance of APS & SSC

<table>
<thead>
<tr>
<th>Machine</th>
<th>$R$ [m]</th>
<th>$\nu_x$</th>
<th>$\epsilon_x^n$ [$\pi$ m-rad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>APS</td>
<td>175.7</td>
<td>35.22</td>
<td>$7.5 \times 10^{-9}$</td>
</tr>
<tr>
<td>SSC</td>
<td>$1.39 \times 10^4$</td>
<td>123.28</td>
<td>$7.1 \times 10^{-14}$</td>
</tr>
</tbody>
</table>

How long would one have to wait to reach the natural emittance? The damping time constant for betatron oscillations is just twice the time it would take to radiate away the proton's total energy of 20 TeV. This works out to be about one day\(^8\). While this may appear long on the scale of electron machines where the damping time is $\sim$ milliseconds, one need
only calculate the damping time at the SSC injection energy of 2 TeV to realize how reasonable this is for protons. Recalling that the radiated power scales as $\gamma^4/\rho^2$, and the total energy as $\gamma$, the damping time scales as $p/\gamma^3$. This works out to be about 3 years at 2 TeV. The damping time of about a day at 20 TeV means that the natural emittance would be reached in about seven e-foldings, or seven days. However, the actual emittance achievable would be limited by intrabeam scattering.

3 Short Dipoles

If the bending angle $\alpha$ in a dipole (Fig. 1) is much smaller than the natural opening angle for synchrotron radiation

$$\alpha \ll \frac{1}{\gamma},$$

it is called a short dipole. The time structure of the resulting light pulse will be

$$\Delta t_s = \frac{L}{c} \times (1 - \beta) \approx \frac{L}{2\gamma^2 c},$$

so that the spectral bandwidth will extend out to

$$\omega_s \approx 2\pi \frac{2\gamma^2 c}{L}. \quad (5)$$

The ratio of $\omega_s$ to $\omega_c$ is the inverse of the ratio of the respective arc lengths, or

$$\frac{\omega_s}{\omega_c} = \frac{1}{\alpha \gamma} \gg 1.$$

To get a sense of how short a “short” dipole needs to be, we compute the arc length $2p/\gamma$ for normal synchrotron radiation from the APS at 7 GeV, which is about 6mm, and the SSC at 20 TeV, or about 1m. A dipole much shorter than a few millimeters being out of the question, radiation from short dipoles is not relevant for electron machines. For proton machines, too, one might wonder if a dipole much shorter than a meter could be achieved. However, one can use the edge of a regular dipole to achieve the same effect. This is because at the edge, the field dies on the scale of the dipole aperture, which is a few cm for the CERN SPS, the HEB, and the SSC. The edge effect does not extend to electrons since a dipole aperture much less than a few millimeters is also not achievable. Fig. 3 illustrates why a particle in the edge field of a dipole would behave as if it were moving in a very short dipole. If the dipole field were to remain unchanged, the particle would continue on a circular trajectory, Fig. 3(a). In Fig. 3(b), the field ends abruptly, so the particle moves at a tangent to the arc, and in Fig. 3(c) it accelerates over the length of the edge field and then moves in a straight line. Since the radius of the arc is $\sim 10^3$ to $10^4$ m, while the edge is about 10 cm, the difference between the circle, Fig. 3(a), and the gentler curve, Fig. 3(c), would be very small over the short distance in which the field decays to zero.

The opening angle of the radiation from the edge can be estimated as before. The transverse spot size $\Delta x \sim \rho \alpha \times \Delta \phi$. Since

$$\Delta \phi \sim \frac{\lambda}{\Delta x},$$

we get

$$\Delta \phi \sim \sqrt{\frac{\lambda}{L}} \sim \frac{1}{\gamma} \sqrt{\frac{\omega_s}{\omega}}.$$

An important application of synchrotron radiation from the edge of a dipole field is its use in making light monitors for proton beams[4]. The critical frequency of normal synchrotron radiation from protons in a ring of radius $\sim 10^3$ m lies below the optical threshold at energies under 1.4 TeV. Since the intensity of radiation above the critical frequency decreases exponentially, the use of synchrotron light monitors was infeasible until edge radiation was first utilized at the SPS for monitoring a 270 GeV proton beam. A light monitor for the Tevatron is presently under construction[9], and monitors for the HEB and the SSC are contemplated. In this connection we note that a further useful property of edge radiation is that the opening angle remains $\frac{1}{\gamma}$ for frequencies up to $\omega_s$. This helps in extending the diffraction-imposed limit to resolving the transverse image of the
Table IV: Critical wavelength and opening angle of radiation from long and short dipoles.

<table>
<thead>
<tr>
<th>Dipole Type</th>
<th>Wavelength</th>
<th>Opening Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long ($\alpha \geq \frac{1}{\gamma}$)</td>
<td>$\lambda_c = \frac{2\pi\rho}{3\gamma^3}$, $\frac{1}{\gamma} \sqrt{\frac{\lambda}{\lambda_c}}$, $\lambda \geq \lambda_c$</td>
<td></td>
</tr>
<tr>
<td>Short ($\alpha \ll \frac{1}{\gamma}$)</td>
<td>$\lambda_a = \frac{L}{2\gamma^2}$, $\frac{1}{\gamma} \sqrt{\frac{\lambda}{\lambda_a}}$, $\lambda \geq \lambda_a$</td>
<td></td>
</tr>
</tbody>
</table>

$\rho =$ Bending radius $\quad L =$ Dipole edge length

beam, and makes edge radiation preferable even at the SSC peak energy of 20 TeV, where radiation from normal dipoles lies well beyond the optical threshold. Table IV summarizes the relevant properties of radiation from long and short dipoles. Table V compares the critical frequency of radiation from long and short dipoles for the CERN SPS, the HEB, and the SSC.

4 Undulator Radiation

Synchrotron radiation from protons moving in an undulator, Fig. 4 & Fig. 5, has a particularly simple structure on account of the much greater mass of the proton. The deflection parameter $K$ for electrons and for protons is

$$K_e \approx \lambda_u \text{[cm]} B_0 \text{[Tesla]},$$

$$K_p \approx 5 \times 10^{-4} \lambda_u \text{[cm]} B_0 \text{[Tesla]}.$$

For any reasonable choice of the undulator wavelength $\lambda_u$ and the magnet field strength $B_0$, $K_p \ll 1$. The angular deflection suffered by the proton is $\sim K_p/\gamma$, or much less than the natural opening angle of synchrotron radiation. In this respect, we expect the radiation from an undulator to behave like radiation from a short dipole, just as radiation from a wiggler is similar to bending magnet radiation[3],[5]. It is instructive to work out the properties of radiation from a weak field undulator[2]. Taking the magnet field to be

$$B(z) = B_y = B_0 \cos \left(\frac{2\pi}{\lambda_u} z\right) = B_0 \cos k_u z,$$

we integrate the Lorentz force equation to obtain

$$\dot{x} = -\frac{eK}{\gamma} \sin k_u z,$$

$$\dot{z} = \beta c \left(1 - \frac{K^2}{4\beta^2 \gamma^2}\right) \left[1 + \frac{K^2}{4\beta^2 \gamma^2} \cos 2k_u z\right].$$

The average velocities in the $x$ and $z$ directions are

$$<\dot{x}> = 0, \quad <\dot{z}> = \beta \left(1 - \frac{K^2}{4\beta^2 \gamma^2}\right) c = \beta^* c.$$

The particle moves with a drift velocity $c\beta^*$ along the $z$ axis, with a corresponding Lorentz factor

$$\gamma^* = \frac{\gamma}{\sqrt{1 + K^2/2}}.$$

The particle’s trajectory in the undulator is

$$x = \frac{K}{\beta^* \gamma k_u} \cos \Omega_u t + O \left(\frac{K^3}{\gamma^2}\right),$$

$$z = \beta^* c t + \frac{K^2}{8\beta^2 \gamma^2 k_u} \sin 2\Omega_u t + O \left(\frac{K^3}{\gamma^2}\right),$$

where $\Omega_u = \beta^* \omega_u$. We now perform a Lorentz transform to a frame moving along $z$ with the drift velocity of the particle. Using primes to denote the new coordinates, the trajectory equations become

$$x' = a \cos \Omega_u t,$$

$$z' = \frac{aK}{8\beta \sqrt{1 + K^2/2}} \sin 2\Omega_u t,$$

where

$$a = \frac{K}{\beta^* \gamma k_u},$$

and we have retained the laboratory time $t$. Eqn. (6) gives for the trajectory in the moving frame

$$(z'/a)^2 = \frac{K^2}{16\beta^2(1 + K^2/2)} \left[(x'/a)^2 - 1 - (x'/a)^2\right].$$
Table V: Critical frequency for long and short dipoles: SPS, Tevatron, & SSC

<table>
<thead>
<tr>
<th>Machine</th>
<th>Energy</th>
<th>Bending Radius</th>
<th>Critical Frequency $\nu_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GeV</td>
<td>m</td>
<td>long (THz)</td>
</tr>
<tr>
<td>CERN SPS</td>
<td>270</td>
<td>740</td>
<td>1.9</td>
</tr>
<tr>
<td>Tevatron</td>
<td>900</td>
<td>754</td>
<td>167.6</td>
</tr>
<tr>
<td>SSC</td>
<td>$2 \times 10^4$</td>
<td>$10^4$</td>
<td>$1.387 \times 10^5$</td>
</tr>
</tbody>
</table>

* Dipole edge length $L = 10$ cm.

Figure 5: Undulator radiation in the moving frame and the laboratory frame, from Ref. [2].
The trajectory is in the shape of a figure eight, Fig. 6. For $K \sim 1$ or more, the motion in $z'$ and $z''$ becomes strongly coupled—since the particle's energy is conserved in a static magnetic field, large velocity variations along the $x'$ axis are accompanied by commensurate variations along the $z'$ axis. For values of $K \ll 1$, the ratio of the displacement along the two axes is

$$\frac{x'_{\text{max}}}{x''_{\text{max}}} \approx \frac{K}{8} \ll 1,$$

so we can treat the particle's motion as a simple harmonic oscillation along the $x'$ axis.

The above picture of the particle's motion in the drift frame allows us to understand in a simple way the main qualitative features of synchrotron radiation from weak field and strong field undulators. In the weak field case, the particle's motion in the laboratory is approximately sinusoidal, Fig. 5. In the moving frame, it appears as a simple harmonic oscillation along $x'$ with frequency $\gamma' \Omega_u \approx \gamma \omega_u$. The increased frequency comes from the Lorentz contraction of the undulator period $\lambda'_u = \lambda_u / \gamma$. The simple harmonic motion of the particle in the moving frame creates a dipole radiation field, emitted primarily in the direction perpendicular to the oscillation, or along $z'$. The opening angle of this radiation is large, with the intensity falling to zero on the $x'$ axis, Fig. 5. Transforming back to the laboratory frame an angle of $\pi/2 \rightarrow 1/\gamma' \approx 1/\gamma$, which explains the confinement of the radiation to a cone of opening angle $\sim 1/\gamma$. The dipole radiation in the moving frame is monochromatic, with frequency $\omega' = \gamma' \Omega_u \approx \gamma \omega_u$. In the laboratory frame it becomes Doppler shifted to a higher frequency, and also becomes angle dependent

$$\omega(\theta) = \frac{\omega'}{\gamma(1 - \beta \cos \theta)} \approx \frac{2\gamma^2}{1 + \gamma^2 \beta^2} \omega_u.$$

In the strong field case the particle moves in a figure eight. The motion may be viewed approximately as harmonic oscillations along the two axes, with odd harmonics of $\gamma' \Omega_u$ along $x'$ and even harmonics along $z'$. This creates two dipole radiation fields, with odd harmonics radiated primarily along $z'$, and even harmonics along $z''$. The transformation back to the laboratory frame leads to radiation primarily in the forward direction, with odd harmonics inside a cone of angle $\sim 1/\gamma'$. The even harmonics appear in a ring around this cone. The radiation in the moving frame is a discrete spectrum consisting of odd and even harmonics of $\gamma' \Omega_u$. In the laboratory frame the spectral lines are Doppler shifted to odd and even harmonics of $2\gamma^2 \omega_u / (1 + K^2/2)$, and pick up an angular dependence, Fig. 5. The detailed spectral profile can be worked out by Lorentz transforming the EM-field of an oscillating electric dipole to the laboratory frame [2]. Finally, we note that for small angular deflections, exemplified by the motion of a proton in the edge field of a dipole, or in an undulator, the spectral profile acquires a very simple form, with the angular dependence of the spectrum becoming independent of the detailed nature of the magnetic field in which the particle accelerates. A number of interesting examples can be found in the work of Coisson [3].

Synchrotron radiation from an undulator placed in an SSC straight section has a wavelength determined simply by the undulator wavelength

$$\lambda = \frac{1 + K^2/2}{2\gamma^2} \lambda_u,$$

$$\approx \frac{\lambda_u}{2\gamma^2}.$$

If we ask for radiation in the diffraction dominated regime, or $\lambda_{\text{photon}} \geq \lambda_{\text{proton}}$, we get

$$\frac{\lambda}{4\pi} \geq \frac{\epsilon_{\text{photon}}}{\gamma},$$

Using the normalized SSC emittance of $\pi$ mm-mrad, the first harmonic of undulator radiation at 20 TeV is about 6 Å, or 2 KeV. This is in the hard x-ray region, and could be used, for example, for x-ray holography of molecules. The wavelength of the undulator
\( \lambda_u \approx 2\gamma^2 \lambda \) works out to 50 cm. Such an undulator should be relatively easy to make. We can do much better if we wait long enough for the SSC to reach its natural emittance of \( 7.1 \times 10^{-14} \text{ m-rad} \) (ignoring, for the moment, the higher limit which would be imposed on the equilibrium emittance by intrabeam scattering). This would increase the energy of a photon at the edge of the diffraction dominated region by a factor of 660. However, the undulator wavelength would also reduce by the same factor to less than a tenth of a mm, and would probably be unworkable. We do not, of course, have to use such a small wavelength undulator—an undulator with a wavelength less than 50 cm would produce proportionately more energetic photons, and allow operation in the diffraction dominated regime once the beam emittance reduces below the photon emittance.

5 Discussion

Synchrotron radiation from protons exhibits a number of interesting features on account of the much greater mass of the proton. Bending magnet radiation in proton rings like the Tevatron, the HEB, and the SSC is diffraction dominated. Radiation from a 50 cm period undulator is diffraction dominated for photons of energy less than 2 KeV. This may have application to x-ray holography. At the SSC peak energy of 20 TeV, the damping time for transverse emittance is about a day, with a natural emittance of \( \sim 10^{-13} \text{ m-rad} \). This allows for the use of smaller period undulators to achieve diffraction dominated photons of higher energy. Also, the very small emittance of the proton beam will produce high brightness. In these respects, it is possible to think of the SSC as a fourth generation light source. Further study of the brightness and coherence of synchrotron radiation from high energy proton beams appears to be warranted.

Acknowledgements


References