EXPERIMENTAL SET-UP TO MEASURE COHERENT BREMSSRAHLUNG AND BEAM PROFILES IN RHIC

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Abstract

A proposal for an experiment to detect and measure with an array infrared detector either the infrared radiation from the beam-beam coherent bremsstrahlung or from the synchrotron light from the edge effect of large *DX* RHIC magnet is described. Predictions for the 100 GeV/nucleon gold and 250 GeV proton signals from both bremsstrahlung and synchtrotron radiation magnet edge effect are shown.

1 INTRODUCTION

This is a proposal for an experiment in RHIC to measure the radiation of particles of one bunch in the collective field of the oncoming short bunch, called coherent bremsstrahlung (CBS). The effect of the CBS would be measured for the first time in the hadron colliders. The main characteristics of CBS for Au-Au, Au-p and p-p collisions at RHIC are calculated. An experimental set-up and a measurement plan to detect both edge magnet effect and CBS are presented. There are very important advantages to be considered from the RHIC operational side: First, the CBS can be a potential tool for optimizing collisions The bunch length σ_z can be found from the critical wavelength of the CBS spectrum $\lambda_c \propto \sigma_z$. The transverse bunch size $\sigma_\perp$ is related to the photon rate $\dot{N}_\gamma \propto 1/\sigma_\perp{}^2$. A specific dependence of $\dot{N}_\gamma$ on the impact parameter between the beams allows for a fast control over the beam displacement and a possibility for feedback. This experiment will allow us to measure the beam sizes using both effects. The emitted photons are in the infrared region of the spectrum, and they do not affect conditions of the stored beams during collisions.

1.1 Coherent bremsstrahlung

Coherent bremsstrahlung (CBS) is the radiation of one bunch particles in the short collective electro-magnetic field of the bunch from the opposite beam. Let us consider the photon emission by a single ion with a charge $Z_1 e$ moving through a bunch of ions with the charge $Z_2 e$. **Incoherent** bremsstrahlung of ions at colliders has a relatively small cross section. The number of emitted photons is proportional to this cross section and to the number of particles in the first and second bunch [1]:

$$dN_\gamma \; \propto \; N_1 \; N_2 \; \frac{dE_\gamma}{E_\gamma} \; . \qquad (1)$$

With decreasing photon energies E_γ, a coherence length $\sim 4\gamma_1^2 \, \frac{\hbar c}{E_\gamma}$ becomes comparable or larger than the length of the second bunch σ_{2z}. Here $\gamma_1 = E_1/(m_1 c^2)$ is the Lorenz factor of the Z_1 ion. At photon energies

$$E_\gamma \lesssim E_c = 4\frac{{\gamma_1}^2 \hbar c}{\sigma_{2z}} \;\; or \;\; \lambda \gtrsim \lambda_c = \frac{\pi}{2}\frac{\sigma_{2z}}{\gamma_1^2}, \qquad (2)$$

the radiation becomes **coherent**, i.e. the radiation arises from the interaction of the Z_1 ion with the second bunch as **a whole**, but not with each ion **separately**. In this case the second bunch looks like a “particle” with the huge charge $Z_2 e \cdot N_2$. Therefore, the number of the emitted photons dN_γ is already proportional to the **square** number of particles in the second bunch:

$$dN_\gamma \; \propto \; N_1 \; {N_2}^2 \; \frac{dE_\gamma}{E_\gamma} \; . \qquad (3)$$

A quantum treatment of CBS based on the rigorous concept of colliding wave packets and some applications of CBS to modern collides were considered in [1]. For the first time the possibility to use CBS at the RHIC collider was mentioned in RHIC Note [3] in 1995. A detailed consideration of CBS at relativistic heavy-ion colliders was given in [4]. In [5] the quantum effects in CBS were calculated. A new simple method to calculate CBS based on the equivalent photon approximation for the collective electro-magnetic field of the bunch from the opposite beam is presented in [6].It was recently realized that the infrared detector for measuring radiation of gold ions from the edge of a splitting magnet can be used for observation of CBS photons emitted exactly from the interaction point. We discuss such a possibility in detail in Sect.2. All necessary formulas are taken from [4].

1.2 Approximation and input parameters

The used method of CBS calculation is valid if the ion deflection angle θ_d in the field of the oncoming bunch is small compared with the typical radiation angle $\theta_r \sim 1/\gamma_1$.

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[1] We use the following notations: $N_{1,2}$ is the number of particles in the first (second) bunch, σ_{jz} is the longitudinal, $\sigma_{j\perp}$ is the transverse sizes of the j-th bunch, $\gamma_1 = E_1/(m_1 c^2)$, $r_1 = (Z_1 e)^2/(m_1 c^2)$ is the classical radius of the particle in the first bunch and τ is the time between bunch collisions at a given interaction point.

The ratio of these angles is easily estimated knowing the electric and magnetic fields of the second bunch which are approximately equal in magnitude, $|\mathbf{E}| \approx |\mathbf{B}| \sim 2Z_2eN_2/(\sigma_{2z}\sigma_{2\perp})$ (for the RHIC collider the effective field $|\mathbf{E}| + |\mathbf{B}| \sim 0.15$ T)

$$\frac{\theta_d}{\theta_r} \sim \eta = \frac{Z_2}{Z_1}\frac{r_1 N_2}{\sigma_{2\perp}} \tag{4}$$

where $\sigma_{2\perp}$ is the transverse size of the second bunch and $r_1 = {Z_1}^2e^2/(m_1c^2)$ is the classical ion radius. For RHIC in the Au-Au mode (as well as for LHC in the Pb-Pb mode) the parameter η is small: $\eta \sim 10^{-3}$, so the above mentioned method is valid.

In calculating CBS effect we have assumed that the densities of the bunches do not change during the collisions and that the bunches in the interacting region have Gaussian particle distributions with mean-squared transverse $\sigma_{j\perp}$ and longitudinal σ_{jz} radii, $j = 1, 2$. All standard parameters which are necessary for the calculation are: number of gold ions per bunch $N = 10^9$, $\gamma = 108$, $\sigma_z = 10$ cm, $\sigma_\perp = 0.1$ mm, and $\tau = 0.228$ μs. For collisions of identical beams we assume $N_1 = N_2 = N$.

1.3 *Spectrum of CBS photons*

The number of CBS photons, emitted in the wavelength interval from λ to $\lambda + d\lambda$ for a single collision of the beams, is equal to

$$dN_\gamma = N_0\,\Phi(x)\,\frac{d\lambda}{\lambda},\; x = \frac{\lambda_c}{\lambda},\text{ and } \lambda_c = \frac{\pi}{2}\frac{\sigma_{2z}}{\gamma_1^2}, \tag{5}$$

where λ_c is the critical wavelength. Here for the round Gaussian bunches with $\sigma_{1\perp} = \sigma_{1x} = \sigma_{1y}$, and $\sigma_{2\perp} = \sigma_{2x} = \sigma_{2y}$, the constant N_0 is

$$N_0 = \frac{4}{3}\,\frac{\alpha}{\pi}\,N_1\left(\frac{Z_2r_1N_2}{\sigma_{1\perp}}\right)^2 \ln\frac{(\sigma_{1\perp}^2+\sigma_{2\perp}^2)^2}{2\sigma_{1\perp}^2\,\sigma_{2\perp}^2+\sigma_{2\perp}^4} \tag{6}$$

where the classical ion radius $r_1 = 4.9 \cdot 10^{-15}$ cm for the Au ion. For identical beams $\sigma_{1\perp} = \sigma_{2\perp} = \sigma_\perp$ the formula (6) simplifies to:

$$N_0 = 8.91 \cdot 10^{-4}\,N_1\left(\frac{Z_2r_1N_2}{\sigma_\perp}\right)^2 \tag{7}$$

The function $\Phi(x)$ is defined as follows

$$\Phi(x) = \frac{3}{2}\int_0^\infty \frac{1+z^2}{(1+z)^4}\,\exp[-x^2(1+z)^2]\,dz \tag{8}$$

with normalization condition $\Phi(x) = 1$ at $x = 0$. At large values of the parameter x we have

$$\Phi(x) = \frac{3}{4x^2}\cdot \mathrm{e}^{-x^2}\left(1 - \frac{5}{2x^2} + \frac{37}{4x^2} + ..\right) \text{ at } x \gg 1. \tag{9}$$

For the RHIC parameters we have $\lambda_c = 13.5$ μm , $N_0 = 1330$.

Below we consider two wavelength intervals. The first interval $\lambda = 4.5$ μm, $\frac{\Delta\lambda}{\lambda} = 0.1$ is discussed in [7]. It corresponds to the maximum sensitivity of the infrared detector. In this case $x = 3$, $\Phi(3) = 8.6 \cdot 10^{-6}$, and the rate of the CBS photons for the standard RHIC parameters from Table 1 is $\dot{N}_\gamma = \frac{\Delta N_\gamma}{\tau} \approx 5000$ photons per second. Here $\tau = 12.8/56$ μs $= 0.228$ μs is the time between bunch collisions at a given interaction point. The second wavelength interval at $\lambda = 5.7$ μm, with $\frac{\Delta\lambda}{\lambda} = 0.1$, corresponds to 50 % sensitivity of the infrared detector discussed in [7], but to greater rate of CBS photons. The sharp dependence of the photon rate on the bunch length σ_{2z} in both these intervals can be seen from Table 1.

Table 1: Photon rate on the bunch length σ_z

σ_z (cm)	9	11	13
$\dot{N}_\gamma$ (1/s) for 4.5 μm	32800	660	6.7
0.5 $\dot{N}_\gamma$ (1/s) for 5.7 μm	361000	28800	1520

Note the following features of the CBS spectrum:

(i) the constant N_0 is proportional to $1/\sigma_\perp^2$;

(ii) the shape of the spectrum strongly depends on the bunch length σ_{2z}. Therefore, measuring the photon rate and the shape of the spectrum one can obtain information about the beam sizes.

1.4 *Edge magnet radiation*

More details about the edge effect in RHIC were published earlier [7]. The radiation from the whole length of the *DX* magnet can be safely neglected. The modification of the critical wavelength due to the edge effect is easily understood by following Coïsson [8]. From the RHIC magnetic measurements the edge effect of the *DX* magnet could be presented by the error function Fig 1. A photon rate de-

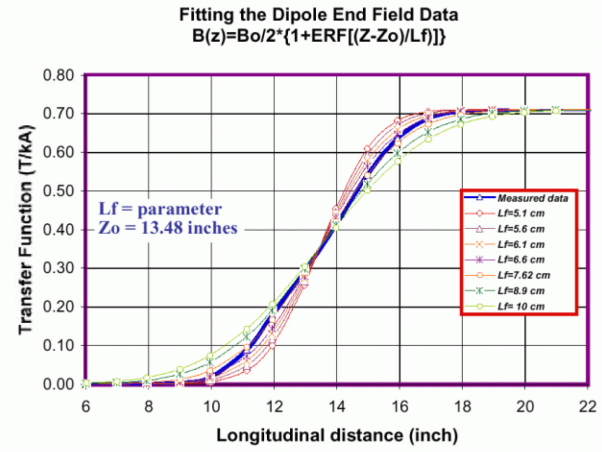

Figure 1: The RHIC dipole magnetic field end measurement result.

pendence on the wavelength where the edge effect dependence is used as a parameter had been previously presented [7]. It assumes for a scanning width $\Delta\lambda$=0.1μm, the number of gold ions per bunch is 1 x 10^9 with 56 bunches, and the magnetic field of the *DX* magnet of 4.28 T.

2 EXPERIMENTAL SET-UP

The optical radiation from the coherent bremsstrahlung (CBS) or from the *DX* magnetic field edge effect is in the infrared region around the λ $\sim$4 μm. The infrared detectors are made of *semimetals* due to their 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.). 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. 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. At the end of the RHIC *DX* magnet at IP2 a special vacuum chamber was designed and already installed as shown in Fig 2.

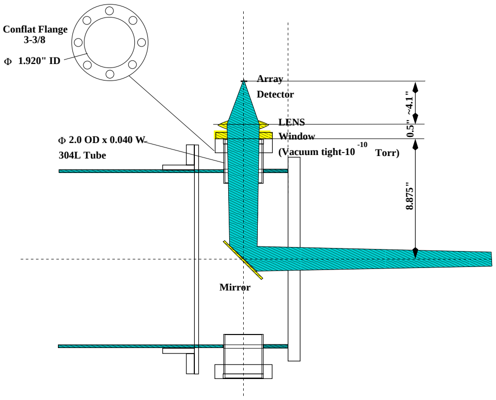

Figure 2: A schematic presentation for the detector set up.

A transfer of the data will be provided the same way as in the case of the present RHIC “flag” monitors. A remote control of the mirror with the stepping motor will be a copy of the RHIC existing collimator controls as well as the corresponding software.

3 SUMMARY

We have calculated the main characteristics of coherent bremsstrahlung photons for the RHIC collider. It seems that CBS can be recorded by the infrared array detector discussed in report [7]. In this case CBS can be a potential tool for optimizing collisions and for measuring beam parameters directly at the interaction point. Obtaining the critical wave length λ_c from the CBS spectrum, the bunch length σ_z can be found since λ_c is proportional to σ_z. The transverse bunch size $\sigma_\perp$ is related to the rate of photons $\dot{N}_\gamma \propto 1/{\sigma_\perp}^2$. Furthermore, CBS may be very useful for a fast control over the impact parameter between the colliding bunch axes because the photon rate depends on this parameter in a very specific way. The transverse beam profile from the synchrotron radiation at the magnetic field edge has been successfully used at both CERN and Fermilab in the visible optical region. This time due to lower value of the relativistic factor γ the optical signals are within the infrared region where the wave length is $\lambda \sim 4.5\mu$m. The experiment will provide the coherent bremsstrahlung data never shown and measured in the hadron colliders before and at the same time will provide very essential and useful beam parameters. To discriminate CBS from edge magnet radiation the following procedure could be used:

- Remove the second beam;
- Move one of the beam away and watch the signal at the detector. The intensity of CBS has a very specific dependence on the beam axis displacement;
- Reduce the number of particles in the second beam N_2. The CBS signal is proportional to N_2^2 while the edge magnet radiation does not depend on N_2 at all;
- Decogg of the beam, i.e. move them longitudinally out of collision point and watch the signal difference;
- Use a specific azimuthal asymmetry and polarization of CBS.

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