

FEASIBILITY STUDIES OF EXCLUSIVE DIFFRACTIVE BREMSSTRAHLUNG MEASUREMENT AT RHIC ENERGIES*

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Feasibility studies of an observation of the exclusive diffractive bremsstrahlung at RHIC at $\sqrt{s} = 200$ GeV and $\sqrt{s} = 500$ GeV are reported. A simplified approach to the photon and the scattered proton energy reconstruction is used. Influence of possible backgrounds is discussed.

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1. Introduction

Electromagnetic bremsstrahlung is widely used in various applications. In high energy physics, it became a very attractive tool with advent of HERA. Owing to its simple and easy to register final state and relatively large and precisely calculable cross section, it served as an efficient tool for the determination of absolute and instantaneous luminosities of the machine as well as an efficient beam diagnostic and monitoring tool (see, for example, [1]). The measurements were based on the angular properties of the radiated photons.

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In 2011, Khoze *et al.* [2] proposed to supplement the LHC forward physics programme with the detection of elastic scattering of protons accompanied by radiative photons, the diffractive bremsstrahlung. One should note that diffractive bremsstrahlung was never studied at accelerator energies. Later, phenomenological investigations of exclusive diffractive photon bremsstrahlung in proton–proton interactions at large energies were considerably extended by Lebedowicz and Szczurek [3]. The most important extension of [2] was the inclusion of effects of the proton finite size, *i.e.*, the form factor. In their model, values of the parameters were based on an educated guess and are a subject to experimental verification. In fact, the Donnachie–Landshoff parameterisation [4] was used with linear Pomeron trajectory with intercept of 1.0808 and the slope of 0.25 GeV^{-2} . The elastic slope energy evolution was described as

$$B(s) = B_{\text{IP}}^{NN} + 2\alpha'_{\text{IP}} \ln \frac{s}{s_0}$$

with $s_0 = 1 \text{ GeV}^2$ and $B_{\text{IP}}^{NN} = 9 \text{ GeV}^{-2}$. Also, the cut-off parameter of a form factor related to the off-shell effects was set to 1 GeV. One should notice that this form factor plays an important role for the invariant mass of the γp system above 1 GeV which is not important for the present considerations. For the full account of the model parameters, see [3].

Lebedowicz and Szczurek calculated also other processes leading to the exclusive $pp\gamma$ final states, *e.g.* virtual photon re-scattering, however they found that these processes do not play an important role in the extremely forward direction investigated in the present study. The measurements of exclusive diffractive bremsstrahlung can be considered as complementary to the luminometers and luminosity monitors proposed in [5, 6].

The exchanged Pomeron ensures the energy-momentum conservation in the diffractive bremsstrahlung process

$$p + p \rightarrow p + p + \gamma.$$

The cross section is quite large and of the order of micro-barns. The photon angular distribution resembles the one observed for the classical, electromagnetic bremsstrahlung

$$\frac{d\sigma}{d\Theta_\gamma} \sim \frac{\Theta_\gamma}{\left(\frac{m_p^2}{E_p^2} + \Theta_\gamma^2\right)^2},$$

where Θ_γ is the polar angle of the emitted photon, m_p is the proton mass and E_p its energy. The photon angular distribution is peaked in the forward direction with a characteristic unit of $\sim 1/\gamma$ (γ is the radiating particle Lorentz factor). One should also note that the scattered proton angular

distribution is extremely narrow due to the large value of the nuclear slope parameter at high energies. Both final-state particles can be registered in the dedicated parts of the detector located at large rapidities.

In this paper, a feasibility study of diffractive photon bremsstrahlung measurement at the RHIC energies is carried out assuming the STAR detector Phase II configuration. Registration of bremsstrahlung photons in the Zero Degree Calorimeter (ZDC) [7] and the scattered protons in the STAR Roman pots [8] is considered. Simulation of the considered process was performed using a dedicated generator [9] which extends an earlier one, GenEx, described in [10]. This generator is based on calculations presented in [3]. Simulation of the experimental apparatus is simplified and only its basic properties, such resolutions, are used.

2. Experimental set-up

As was already mentioned, the most important parts of the apparatus for present study are the Zero Degree Calorimeters [7] and the Roman pot stations [8].

Two ZDCs are placed symmetrically with respect to the nominal interaction point (IP) at the distances of 1 800 cm. They were designed to detect and to measure the total energy of neutral particles emitted within a small solid angle in extremely forward directions. The ZDC extends from -5 cm to 5 cm in the horizontal direction and from -5 cm to 7.5 cm in the vertical one. The ZDCs are the Cherenkov-light sampling calorimeters. They consist of three modules and are approximately 5 interactions lengths deep. They can serve as triggering devices. The ZDCs were upgraded with the Shower Maximum Detectors (SMD) located between the first and the second module. The SMDs deliver the hadron shower position in the plane perpendicular to the beam axis.

There are four stations of the Roman pots placed symmetrically with respect to the IP for the STAR Phase II programme. The stations are located between the RHIC DX and D0 magnets. The DX is a dipole magnet and helps to analyse the scattered proton momentum. Each station contains 10 planes of silicon strip detectors with alternating direction of the strips inserted horizontally, approximately in the RHIC ring plane. The spatial resolution of the space-point measurement is about $30 \mu\text{m}$. The distance between the detector active part and the beam plays a crucial role in the measurement and decides about the detector acceptance. In real running conditions, this distance is a compromise between the accelerator and detector safety and the beam related backgrounds.

3. Final-state properties

Samples of diffractive bremsstrahlung events were generated for the two centre-of-mass energies used to measure proton–proton interactions at RHIC, namely 200 GeV and 500 GeV. Each sample contains 1 000 000 events. In the generation, it was requested that the photon is emitted in the $+z$ direction. The radiated photon energy varied between 0.5 GeV and 20 GeV at $\sqrt{s} = 200$ GeV, and 0.5 GeV and 50 GeV at $\sqrt{s} = 500$ GeV. Table I lists centre-of-mass energies, inverse of the Lorentz factor, MC predicted cross section and the average polar angle of the emitted photon characterising the generated samples. The average emission angles of the photon are in a good agreement with the inverse of the Lorentz factor of the colliding proton.

TABLE I

Quantities characterising the generated Monte Carlo samples.

$\sqrt{s}$ [GeV]	$1/\gamma$	Monte Carlo	
		σ_{MC} [μb]	$\langle\Theta_\gamma\rangle$
200	0.00938	0.6007 ± 0.0004	0.011
500	0.00375	0.9770 ± 0.0007	0.0045

The distribution of the diffractive bremsstrahlung photon position in the plane transverse to the collision axis at the ZDC location is shown in Fig. 1 for proton–proton interactions at $\sqrt{s} = 200$ GeV. One can observe a characteristic picture. Majority of the photons hits the ZDC plane within the circle with a radius of about 25 cm. As was already mentioned, the ZDC geometric acceptance allows the registration of only a part of these photons. At $\sqrt{s} = 500$ GeV, the percentage of photons reaching the ZDC increases considerably as the radiated photon angular distribution peaks more in the forward direction.

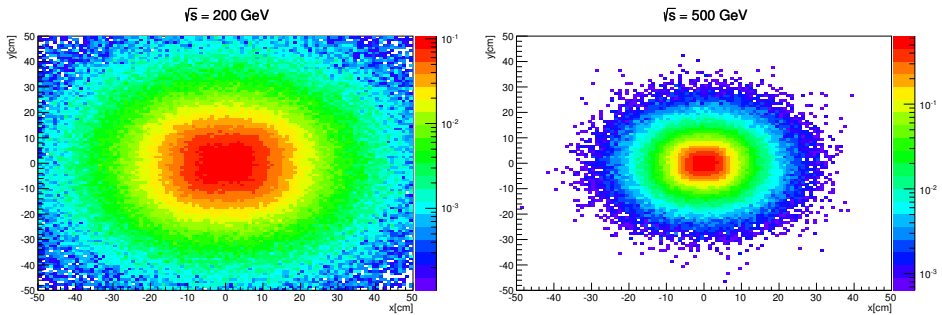


Fig. 1. Distribution of the photon impact point position at the ZDC face for $\sqrt{s} = 200$ GeV (left) and $\sqrt{s} = 500$ GeV (right). Colour scale is in percent.

The relative energy loss

$$\xi = \frac{E_p - E'_p}{E_p}$$

is a handy variable describing the scattered proton.

The correlation plots of the scattered proton transverse momentum, p_T , *versus* its relative energy loss in diffractive bremsstrahlung events at the centre-of-mass energies of 200 GeV and 500 GeV are presented in Fig. 2. As can be observed, a vast majority of the scattered protons is contained within the region limited by $0.1 \text{ GeV}/c < p_T < 0.6 \text{ GeV}/c$ and $\xi < 0.1$. However, one should notice that some part of protons with transverse momentum within the interval $(0.2; 0.4) \text{ GeV}/c$ is characterised by the relative energy loss reaching up to 0.2. A similar picture is seen for the centre-of-mass energy of 500 GeV. Apparent peaking of the distribution at small ξ values reflects its minimum accessible value — fixed lower limit on the radiated photon energy. Higher, up to 0.2, ξ values are observed for $p_T \in (0.1; 0.5) \text{ GeV}/c$.

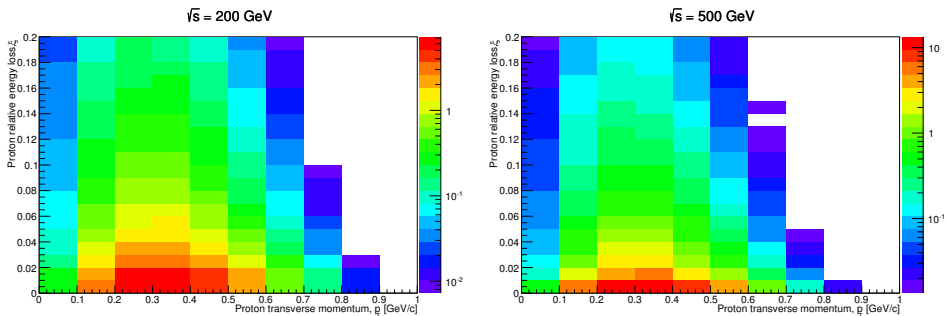


Fig. 2. Correlation between the relative energy loss of a proton, ξ , and its transverse momentum, p_T for $\sqrt{s} = 200 \text{ GeV}$ (left) and $\sqrt{s} = 500 \text{ GeV}$ (right). Colour scale is in percent.

4. Analysis

The present study was performed using the above mentioned Monte Carlo generated samples. In the calculations, the final-state particles were transported using an application based on the *Geant4* [11] code. This application makes use of the *MAD-X* [12] description of the RHIC magnetic lattice. The scattered protons were transported checking whether they will reach the silicon detectors placed in the Roman pots. A simplified simulation of the detector response was used to create the hits and a simplified reconstruction of the scattered proton trajectory was performed. The reconstruction efficiency of a proton candidate track is about 98% [13].

The signal signature is an energy deposit in the ZDC accompanied by the Roman pot track candidate in the same (+ z) hemisphere of the reaction. The sum of the reconstructed energies of a proton and that of the photon should be close to the incident proton energy. Also, the STAR detector should not register an interaction.

One should note that the ZDC is dedicated to the measurement of neutral hadrons, mainly neutrons, to trigger the ultraperipheral ion–ion interactions. Therefore, its quality of the electromagnetic measurements is rather limited. For the purpose of present analysis, it was assumed that the energy measurement resolution is $30\%/\sqrt{E}$ for photons with energy above 1 GeV and that the photons with smaller energies do not trigger the ZDC readout at all. If one demands in addition a realistic distribution of the interaction vertex and that the reconstructed photon energy is above 1 GeV, then the fraction of accepted events is about 18% and 76% at the centre-of-mass energy of 200 GeV and 500 GeV, respectively.

The measurement conditions concerning the scattered proton have a large impact on the visible cross section. Here, a crucial role is played by the distance between the silicon detector edge and the beam position at the detector location. It is clear that this distance defines the minimum value of the measurable relative energy loss of a proton. Table II lists the fraction of diffractive bremsstrahlung events having the ZDC energy above 1 GeV and an associated proton track reconstructed using the Roman pots measurements. The statistical errors on the quoted numbers are negligible.

TABLE II

Fraction of accepted events with the ZDC energy above 1 GeV and an associated track in the Roman pot as a function of the silicon detector–beam distance.

Distance [mm]	Fraction of events [%]	
	$\sqrt{s} = 200$ GeV	$\sqrt{s} = 500$ GeV
15	3.5	19.1
20	3.2	10.9
25	3.0	5.3

In the experimental procedure of an event selection, the energy conservation relation should be formulated as

$$|E_{\text{beam}} - E_{\gamma,\text{ZDC}} - E'_{p,\text{RP}}| < \delta_r, \quad (1)$$

where $E_{\gamma,\text{ZDC}}$ is the photon energy seen by the ZDC, $E'_{p,\text{RP}}$ is the reconstructed proton energy and δ_r is the accepted width of the energy conservation requirement. The value of δ_r reflects both the photon and the scattered

proton energy reconstruction resolutions. It was checked that in the generation, the *non-radiating* proton energy does not deviate from the beam energy by more than 0.1‰ in the considered kinematic domain and hence this factor can be safely neglected in Eq. (1).

The distribution of $E_{\text{beam}} - E_{\gamma, \text{ZDC}} - E'_{p, \text{RP}}$ is presented in Fig. 3 for events having $E_{\gamma, \text{ZDC}} > 1$ GeV and assuming the silicon detector–beam distance of 20 mm for both considered values of the centre-of-mass energy. In the calculations, the ZDC energy was reconstructed as described above and the proton energy reconstruction resolution of the form of $8\% \times \sqrt{E}$ was assumed which delivers uncertainties higher than the observed earlier [14]. The RMS values of the distributions shown in Fig. 3 are 1.07 GeV and 1.65 GeV at $\sqrt{s} = 200$ GeV and $\sqrt{s} = 500$ GeV, respectively. Eventually, a value of the δ_r parameter was set to the triple of the corresponding value. Table III lists the fractions of the accepted, *fully reconstructed* events as a function of the beam–detector distance.

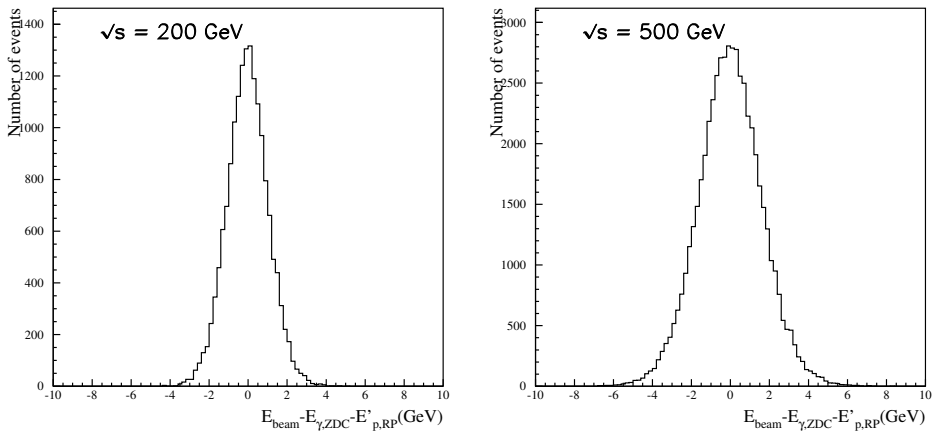


Fig. 3. Distribution of the energy conservation, $E_p - E_{\gamma, \text{ZDC}} - E'_{p, \text{RP}}$ for the silicon detector–beam distance of 20 mm for the centre-of-mass energy of 200 GeV and 500 GeV, and the proton energy reconstruction resolution of the form of $8\% \times \sqrt{E}$.

The beam related pile-up brings in limitations to the measurement. It is clear that an ideal occurrence of diffractive bremsstrahlung would be in a bunch crossing in which there is no additional strong force mediated proton–proton interactions. The probability that there are no additional strong force mediated interactions depends on the total pp inelastic cross section and the instantaneous luminosity delivered by the machine.

TABLE III

Fraction of events passing the energy conservation constraint — Eq. (1) — as a function of the silicon detector–beam distance assuming $8\% \times \sqrt{E}$ resolution of the proton energy reconstruction.

Distance	$\sqrt{s} = 200$ GeV	$\sqrt{s} = 500$ GeV
[mm]	$\delta_r = 3.21$ GeV	$\delta_r = 4.95$ GeV
15	1.7%	9.5%
20	1.6%	5.4%
25	1.5%	2.6%

Comparison of the total and the pile-up-free diffractive bremsstrahlung event rates is shown in Fig. 4 for the two considered values of the centre-of-mass energy. To calculate the predictions, the silicon detector–beam distance was set to 20 mm. In the calculations, the total inelastic pp cross section of 43 mb at $\sqrt{s} = 200$ GeV (49 mb at $\sqrt{s} = 500$ GeV) foreseen by PYTHIA 8 [15] generator was used. The luminosity was assumed to be evenly distributed over all bunch crossings. The diffractive bremsstrahlung cross section was reduced to the visible one using the fractions listed in Table III. This procedure yielded the visible cross section values of about 19.2 nb and 105.5 nb at the centre-of-mass energy of 200 GeV and 500 GeV, respectively.

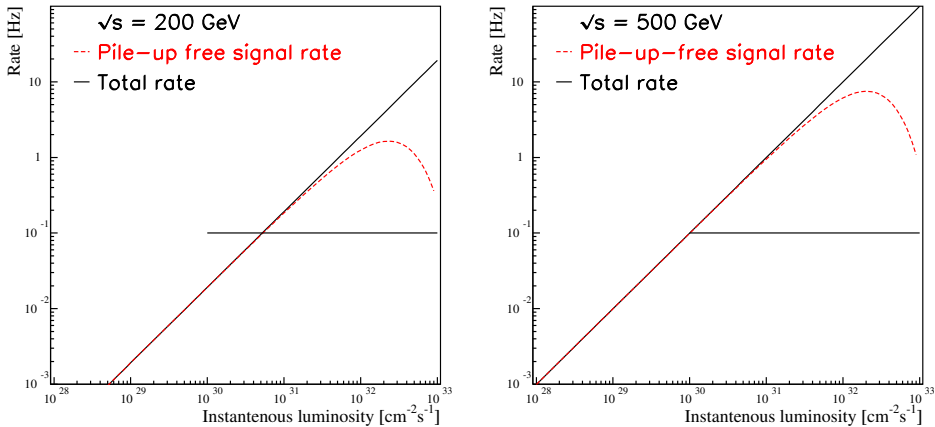


Fig. 4. The rate of the diffractive bremsstrahlung events as a function of the machine instantaneous luminosity. The solid line — the total rate, the dashed line — the rate in pile-up-free bunch crossings. See the text for details.

As can be observed in Fig. 4, the requirement of the rate above 0.1 Hz can be achieved for the instantaneous luminosity values $\mathcal{L} > 8 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$ for the centre-of-mass energy of 200 GeV. In the case of pp interactions at $\sqrt{s} = 500 \text{ GeV}$, the rate above 0.1 Hz is seen for $\mathcal{L} > 2 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$. Such a rate implies a sample of at least 180 events collected in a typical, 30 minutes long STAR data acquisition run. The maximum rates are reached for $\mathcal{L} \approx 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ and are about 1 Hz and 4 Hz at the c.m. energy of 200 GeV and 500 GeV, respectively. For larger values of instantaneous luminosity, the accepted signal rates rapidly decrease what illustrates the influence of the pile-up.

One should note that classical, electromagnetic bremsstrahlung yields the final state of exactly the same signature as the diffractive one. Moreover, kinematic properties of the radiative photon and those of the scattered proton are nearly identical for both processes. However, in diffractive bremsstrahlung, the distribution of the scattered proton transverse momentum is broader. The electromagnetic bremsstrahlung cross section values calculated for pp interactions at $\sqrt{s} = 200 \text{ GeV}$ and $\sqrt{s} = 500 \text{ GeV}$ are, respectively, close to 12 nb and about 14 nb in the kinematic domains considered in the present paper. These values are nearly 60 and 140 times smaller than the diffractive cross section values delivered by the diffractive bremsstrahlung generator. Moreover, the visible cross section for the process of electromagnetic bremsstrahlung will be a subject of the same reduction factor as the diffractive one, *i.e.*, the resulting values will be well below 1 nb. Therefore, the influence of the electromagnetic bremsstrahlung was neglected in this work.

5. Backgrounds

The single diffractive events in which there is a neutral (electromagnetic) energy produced within the ZDC acceptance and a fast, forward proton created in the recombination process may have a signature of an energy deposit in the ZDC and an associated track in the Roman pots and, therefore, imitate events of diffractive exclusive bremsstrahlung. A study of this background type was performed using the PYTHIA 8 [15] generated sample of 1 000 000 000 events.

The events were rejected from the analysis if they fulfilled the following criteria:

- presence of a charged particle with transverse momentum larger than 0.1 GeV/ c and the pseudorapidity, $|\eta| < 1$ (the STAR TPC acceptance),
- presence of charged particle in the pseudorapidity regions: $1.086 \leq |\eta| \leq 2$ (STAR end-cap calorimeter) or $3.3 \leq |\eta| \leq 5$ (STAR BBC counters),

- presence of neutral particle with energy not smaller than 1 GeV in the above mentioned pseudorapidity regions.

The remaining events were accepted for further analysis during which the following requirements were imposed:

- the total neutral electromagnetic energy reaching the ZDC was not smaller than 0.5 GeV,
- events contained a proton with energy greater than 60% of the incident beam energy.

For events passing these criteria, the energies of photons and neutral hadrons within the ZDC geometric acceptance were calculated. In the subsequent analysis, these energies were treated as if they were associated with a single photon or neutron and were assumed to be measured with perfect resolution. One should note that such a procedure will tend to overestimate the background influence delivering the worst case scenario. Eventually, events were accepted as those imitating the diffractive bremsstrahlung signature if they had the following properties:

1. there was a proton with energy $E_p > 0.8 E_{\text{beam}}$ and the electromagnetic energy in the ZDC, $E_{\text{EM,ZDC}} > 1$ GeV in a given hemisphere and the neutral hadron energy seen by the ZDC in the same hemisphere is $E_{\text{HAD,ZDC}} < 1.0$ GeV,
2. in the hemisphere opposite to the signal one: $E_{\text{EM,ZDC}} < 1.0$ GeV, $E_{\text{HAD,ZDC}} < 1.0$ GeV and $E_p < 1$ GeV.

Such requirements were fulfilled by small fractions of events: 584×10^{-9} at 200 GeV and $33\,040 \times 10^{-9}$ at 500 GeV. If one requests that the proton hits the silicon detector in the Roman pots and is reconstructed, then this fraction drops to 223×10^{-9} and $9\,072 \times 10^{-9}$, respectively. Requiring the energy conservation $|E_{\text{beam}} - E_{\text{EM,ZDC}} + E_p| < 3$ GeV implies further reduction to about 39×10^{-9} at $\sqrt{s} = 200$ GeV and 330×10^{-9} at $\sqrt{s} = 500$ GeV which correspond to the visible cross section for background processes of about 2 nb and 16 nb, respectively.

There is no doubt that the Zero Degree Calorimeter upgraded with an electromagnetic front part would help to achieve even better results. The effect would be twofold. On the one hand, a precise electromagnetic calorimeter would allow to lower the limit on the minimum photon energy. On the other hand, it would also diminish the influence of the photon energy measurement on the δ_r parameter. Moreover, equipping the electromagnetic part with capability of a precise shower position measurement would allow to discriminate the events with production of mesons decaying into multiple

photons. Such events are mainly due to the production of π^0 , η and N^* . PYTHIA 8 delivers a good description of these processes based on the experimental data parameterisations. Moreover, owing to the relatively low energies of π^0 , η or N^* , the photons created in their decays are produced with quite large polar angles in the laboratory frame. Therefore, they have a considerable chance to miss the ZDC acceptance and in such a way, an event would not pass the signal selection criteria.

6. Signal/background ratio

The expected signal to background ratio (S/B) was calculated as a function of the instantaneous luminosity for both considered values of energy. In calculations of the S/B ratio, it is assumed that both the signal and the background events are created in pile-up-free bunch crossings. The S/B values of 10 for $\sqrt{s} = 200$ GeV and nearly 100 for $\sqrt{s} = 500$ GeV were obtained independently of the instantaneous luminosity. It has to be reminded that the useful range of the instantaneous luminosities is related to the minimal value of the rate of signal events.

7. Summary and conclusions

Feasibility study of the measurement of diffractive bremsstrahlung process in pp interactions at the RHIC energies was carried out. This study shows that the visible cross section would be of the order of 20 nb if the accepted proton energy is above 80% of the beam energy and that of the photon is within [1; 20] GeV interval at $\sqrt{s} = 200$ GeV. At the centre-of-mass energy of 500 GeV, the visible cross section is about 106 nb. These values imply the event rates above 0.1 Hz for the instantaneous luminosity of the machine $\mathcal{L} > 8 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$ for the centre-of-mass energy of 200 GeV and for $\mathcal{L} > 2 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$ at $\sqrt{s} = 500$ GeV. A maximum rate of signal events of about 2 Hz and 10 Hz is expected for $\mathcal{L} \sim 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ at $\sqrt{s} = 200$ GeV and $\sqrt{s} = 500$ GeV, respectively. The signal to background rate is nearly 10 (100) for the whole region of considered instantaneous luminosities at centre-of-mass energy of 200 GeV (500 GeV).

It is quite clear that larger signal to background ratio values could be obtained if the present Zero Degree Calorimeters were equipped with an electromagnetic front part having a capability of precise measurement of both the electromagnetic energy and the electromagnetic cascade position in the transverse plane. The former feature would allow decreasing the requirement on the minimum photon energy and to improve its energy measurement and reconstruction, while the latter would help to discriminate the events with production of neutral mesons decaying into multi-photon final state.

One may conclude that the measurement of the cross section for diffractive bremsstrahlung at the RHIC energies is feasible and, especially at the centre-of-mass energy of 500 GeV, for the instantaneous luminosity value of about $2 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$, the event sample collected within a typical DAQ run would allow to obtain the 1% statistical precision. Such samples will help to experimentally determine values of the model parameters.

For the instantaneous luminosity values greater than about $10^{30} \text{ cm}^{-2}\text{s}^{-1}$, the samples gathered with a typical run can be used for the RHIC instantaneous luminosity monitoring. Moreover, they will deliver a possibility to calibrate the relative energy loss measurement of a proton using the Roman pot stations and to cross-check the stations alignment.

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