Exclusive Diffractive Photon Bremsstrahlung at RHIC – Feasibility Study

Janusz Chwastowski\textsuperscript{1}, Łukasz Fulek \textsuperscript{3}, Radosław Kycia\textsuperscript{1}, Rafał Sikora\textsuperscript{3}, Jacek Turnau\textsuperscript{2}

\textsuperscript{1}Dept. of Physics, Mathematics and Computer Science, Cracow University of Technology, Warszawska 24, 31-155 Kraków, Poland

\textsuperscript{2}The Henryk Niewodniczański Institute of Nuclear Physics, Radzikowskiego 152, 31-342 Kraków, Poland

\textsuperscript{3}Faculty of Physics and Applied Computer Science AGH–UST, al. A. Mickiewicza 30, 30-059 Kraków, Poland

Abstract

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

1 Introduction

Bremsstrahlung is an attractive processes which, due to its final state simplicity, is easy to register. It served as a basic tool for the absolute luminosity measurement and the beam diagnostic at HERA (see for example \cite{1}). In 2011, V. Khoze \textit{et al.} \cite{2} proposed to supplement the LHC forward physics programme with the detection of elastic scattering of protons accompanied by radiative photons. It was proposed to use this process for the LHC absolute luminosity measurement.

*Corresponding author, e-mail address: Janusz.Chwastowski@ifj.edu.pl
Later, phenomenological investigations of exclusive diffractive photon bremsstrahlung in proton-proton interactions at large energies were considerably extended by Lebiedowicz and Szczurek [4]. They studied classical, electromagnetic bremsstrahlung including effects of non-point-like proton structure. Moreover, they took also into account the vector meson- Pomeron, photon-pion and photon-Pomeron exchanges. In the following only the Pomeron exchanges are considered. The exchanged Pomeron ensures the energy-momentum conservation in the diffractive bremsstrahlung process:

\[ p + p \rightarrow p + p + \gamma. \]

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

\[ \frac{d\sigma}{d\Theta_{\gamma}} \sim \frac{\Theta_{\gamma}}{(\frac{m_p^2}{E_p^2} + \Theta_{\gamma}^2)^2}, \]

where \( \Theta_{\gamma} \) 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 \( \sim 1/\gamma \) (\( \gamma \) is the radiating particle Lorentz factor). The final state particles can be registered in the dedicated parts of the detector and the events recognition may make use of the approximate energy conservation:

\[ E_p \approx E_\gamma + E_p'. \]

(1)

where \( E_\gamma, E_p' \) are the photon and the scattered proton energy, respectively.

In this paper a feasibility study of diffractive photon bremsstrahlung measurement at RHIC energies is carried out assuming the STAR detector Phase II configuration. Registration of bremsstrahlung photons in the Zero Degree Calorimeter (ZDC) [5] and the scattered protons in the STAR Roman Pots [6] is considered.

Simulation of the considered process was performed using a dedicated generator [7] which extends an earlier one, GenEx, described in [8]. Simulation of the experimental apparatus is simplified and only its basic properties as the 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 \[5\] and the Roman Pot stations \[6\].

Two ZDCs are placed symmetrically with respect to the nominal interaction point (IP) at the distances of 1800 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 consists 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 second module. The SMDs delivers the hadron shower position in the plane perpendicular to the beam axis.

There are foreseen four stations of the Roman Pots placed symmetrically with respect to the IP for the STAR Phase II programme. The stations will be located between the RHIC DX and D0 magnets. The DX is a dipol magnet and will help to analyse the scattered proton momentum. Each station contains 10 planes of silicon strip detectors with alternating direction of the strips. The spatial resolution of the space-point measurement is about 30 \(\mu\)m. The stations will allow to insert the silicon detector package in horizontal direction (approximately in the RHIC ring plane). As can be easily deduced 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

The distribution of the polar angle of a photon emitted in diffractive bremsstrahlung process in pp interactions at \(\sqrt{s} = 200\) GeV is shown in Figure 1. Its mean value is about 0.01 which nicely coincides with \(1/\gamma = 0.00938\) of incident protons of 100 GeV energy.

The distribution of the diffractive bremsstrahlung photon position in the plane transverse to the collision axis at the ZDC location, \(i.e.,\)
1800 cm away from the nominal interaction point, is shown in Figure 2 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 15 cm. As was already mentioned the ZDC geometric acceptance allows the registration of only a part of these photons.

The relative energy loss

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

is a handy variable describing the scattered proton. The correlation plot of the scattered proton transverse momentum, $p_T$, versus its relative energy loss in diffractive bremsstrahlung events at $\sqrt{s} = 200$ GeV is shown in Figure 3. As can be observed a vast majority of the scattered protons is contained within the region limited by $0.1$ GeV/c $< p_T < 0.5$ GeV/c and $\xi < 0.1$. However, one should notice that quite a substantial part of protons with transverse momentum within
the interval (0.2; 0.4) GeV/c is characterised by the relative energy loss extending up to 0.14–0.16.

4 Analysis

Present study was performed using the Monte Carlo generated sample of 1 000 000 events. The generated diffractive bremsstrahlung photon energy varied between 0.5 GeV and 20 GeV. The generator delivers the cross-section $\sigma_{MC} = 0.68 \pm 0.01 \mu b$.

In the calculations the final state particles were transported using an application based on the Geant4 [9] code. This application makes use of the MAD-X [10] 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 proton trajectory was performed. The
reconstruction efficiency of a proton candidate track is about 98% [11].

The signal signature is an energy deposit in the ZDC accompanied by the Roman Pot track candidate in the same hemisphere of the reaction. The sum of the reconstructed energies of a proton and that of the photon should approximately fulfill the energy conservation of Eq. (1). 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.

The requirement of a photon within the ZDC geometric acceptance

Figure 3: Correlation between the relative energy loss of a proton, $\xi$, and its transverse momentum, $p_T$ for $\sqrt{s} = 200$ GeV.
passes about 84% events. If one demands in addition that the reconstructed photon energy is above 1 GeV then the fraction of accepted events drops to about 9.6% events.

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 1 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.

| detector-beam distance [mm] | fraction of events [%] |
|---------------------------|------------------------|
| 15                        | 3.0                    |
| 20                        | 2.9                    |
| 25                        | 2.6                    |

Table 1: Fraction of accepted events with the ZDC energy above 1 GeV as a function of the silicon detector-beam distance.

In the experimental procedure of an event selection the energy conservation relation of Eq. (1) should be re-formulated in the following way:

\[
|E_p - E_{\gamma, ZDC} - E_{p,RP}'| < \delta_r,
\]

where \(E_{\gamma, ZDC}\) is the photon energy seen by the ZDC, \(E_{p,RP}'\) is the reconstructed proton energy and \(\delta_r\) is the accepted width of the energy conservation requirement. The value of follows \(\delta_r\) from both the photon and the proton energy reconstruction resolutions.

The energy conservation relation, \(E_{\text{beam}} - E_{\gamma, ZDC} - E_{p,RP}'\), is presented in Figure 4 for events having \(E_{\gamma, ZDC} > 1\) GeV and assuming the silicon detector-beam distance of 20 mm for \(pp\) interactions at the centre of mass energy \(\sqrt{s} = 200\) GeV. Table 2 lists the fractions of the accepted events as a function of the beam-detector distance. In the calculations the ZDC energy was reconstructed as described above and the proton energy reconstruction resolution of 8% was assumed [12].

Also, a possible pile-up brings in limitations to the measurement. It is clear that an ideal occurrence of diffractive bremsstrahlung would
Figure 4: Distribution of the energy conservation, $E_p - E_{\gamma,ZDC} - E'_{p,RP}$ for the silicon detector-beam distance of 20 mm for the centre of mass energy $\sqrt{s} = 200$ GeV and the proton energy reconstruction resolution of 8%.

be in the bunch crossings in which there is no strong force mediated proton-proton interactions, *i.e.*, in the silent bunch crossings [13]. The probability of zero events depends on the total pp inelastic cross-section and the instantaneous luminosity delivered by the machine. Comparison of the total and the silent bunch crossing diffractive bremsstrahlung event rates is shown in Figure 5. 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 foreseen by Pythia 8 [16] 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 fraction listed in Table 2 assuming $\delta_r = 3$ GeV. This yields the visible cross-section value of about 20 nb.
Table 2: Fraction of events passing the energy conservation constraint – Eq. (2) – as a function of the silicon detector-beam distance assuming 8% resolution of the proton energy reconstruction and two values of $\delta_r$.

| distance [mm] | $\delta_r = 2$ GeV | $\delta_r = 3$ GeV |
|---------------|---------------------|---------------------|
| 15            | 2.8%                | 3.0%                |
| 20            | 2.7%                | 2.9%                |
| 25            | 2.5%                | 2.6%                |

As can be observed the requirement of the rate above 0.1 Hz can be achieved for the instantaneous luminosity above $\mathcal{L} > 4 \cdot 10^{30}$ cm$^{-2}$s$^{-1}$. Such a rate implies a sample of at least 1 80 events collected in a typical, 30 minutes long STAR data acquisition run. The maximum rate is close to 2 Hz for $\mathcal{L} \approx 2 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$. For larger values of instantaneous luminosity the accepted signal rate decreases what illustrates the influence of the pile-up.

5 Backgrounds

Among background processes associated with diffractive bremsstrahlung one can single out the following processes imitating the signal.

Classical, electromagnetic bremsstrahlung consists a irreducible background exactly the same signature and the radiative photon and proton have nearly identical kinematic properties. However, one should notice that the electromagnetic bremsstrahlung cross-section in the pp interactions at $\sqrt{s} = 200$ GeV is 17 nb in the considered kinematic domain, a factor of more than 30 smaller than the diffractive one. Moreover, the visible cross-section for the process of electromagnetic bremsstrahlung will be a subject to the same reduction factor as the diffractive one. Electromagnetic background influence was neglected in the following.

The other type of background is due the process of $\pi^0$-strahlung [14]. It is foreseen that the cross-section value for $pp \rightarrow pp\pi^0$ is of similar order to that of diffractive bremsstrahlung. Moreover, this process was also not measured at RHIC. A possible reduction of the $\pi^0$-strahlung rate could make use of the presence of two cascades in the ZDC. At the moment there does not exist a generator devoted to this process,
Figure 5: The rate of the diffractive bremsstrahlung events as a function of the machine instantaneous luminosity at $\sqrt{s} = 200$ GeV. The solid line – the total rate, the broken line – the rate in the silent bunch crossings. See text for details.

however, its construction is already started [15]. It is expected that the visible cross-section for $pp \rightarrow pp\pi^0$ will be reduced in a way similar to that of the diffractive bremsstrahlung.

Signature of an energy deposit in the ZDC and an associated track in the Roman Pots will have also 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. Study of this background type were performed using the PYTHIA 8 [16] 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 endcap 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.

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 GeV.

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 it were associated with a single photon or neutron and were a assumed to be measured with perfect resolution. One should note that such a procedure will tend to overestimate the background influence delivering, in such a way, the worst case scenario. Eventually, events are accepted as those imitating the diffractive bremsstrahlung signature if they have the following properties:

1. there is a proton with energy $E_p > 80$ GeV and the electromagnetic energy in the ZDC, $E_{EM,ZDC} > 1$ GeV in a given hemisphere and the neutral hadron energy seen by the ZDC in the same hemisphere is $E_{HAD,ZDC} < 1.0$ GeV,

2. in the hemisphere opposite to the signal one: $E_{EM,ZDC} < 1.0$ GeV, $E_{HAD,ZDC} < 1.0$ GeV and $E_p < 1$ GeV.

Such requirements were fulfilled by small fractions of events – $579 \cdot 10^{-9}$. If one requests that the proton hits the silicon detector in the Roman Pots and is reconstructed then this fraction drops to $182 \cdot 10^{-9}$. Requiring the energy conservation $|100 - E_{EM,ZDC} + E_p| < 3$ GeV implies further reduction to about $27 \cdot 10^{-9}$ which correspond to the visible cross-section for background processes of about 1 nb.

There is no doubt that the Zero Degree Calorimeter upgraded with an electromagnetic front part would help to achieve better results. The effect would be twofold. 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 $\delta_r$ parameter. Moreover, equipping the electromagnetic part with the shower position measurement capability would allow to discriminate the events with production of mesons decaying into multiple photons.

6 Signal/Background Ratio

The expected signal to background ratio is shown in Figure 6 as a function of the instantaneous luminosity.

![Signal/Background ratio graph]

Figure 6: Expected signal to background ratio as a function of the instantaneous luminosity for pp collisions at $s\sqrt{s} = 200$ GeV.

As can be observed for $\mathcal{L} < 3 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$ this ratio is above 10. For larger luminosities it drops rapidly reflecting the influence of the pile-up.
7 Summary and Conclusions

Feasibility study of the diffractive bremsstrahlung process at the RHIC energies was carried out. These study shows the the visible cross-section would be of the order of 20 nb if the accepted proton energy is above 80 GeV and that of the photon is within $[1; 20]$ GeV interval at the centre of mass energy $\sqrt{s} = 200$ GeV. These values imply the rates above 0.1 Hz for the instantaneous luminosity $\mathcal{L} > 4 \cdot 10^{30}$ cm$^{-2}$s$^{-1}$. The signal to background rate is above 2 for $\mathcal{L} > 5 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$.

It is quite clear that larger signal to background ratio values could be obtained if the present Zero Degree Calorimeters are equipped with an electromagnetic front part have a capability of both precise measurement of 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. Moreover, such upgrade of the ZDC would help the measurement of the $\pi^0$-strahlung process at RHIC energies

The considered process could also be used to calibrate the relative energy loss measurement of a proton using the Roman Pot stations. One should also note that it may provide a tool for the Roman Pot alignment cross-check as well as the instantaneous luminosity monitoring.

Acknowledgements

We are very much indebted to P. Lebiedowicz and A. Szczurek for many stimulating discussions. This work was supported in part by Polish National Science Centre grant UMO-UMO-2011/01/M/ST2/04126.

References

[1] J. Andruszkow et al., Luminosity measurement in the ZEUS experiment, Acta. Phys. Pol. B32 (2001) 2025,
L. Adamczyk et al., Measurement of the luminosity in the ZEUS experiment at HERA II, Nucl. Instrm. Meth. A744 (2014) 80.
[2] V. A. Khoze, J. W. Lämsä, R. Orava, M. G. Ryskin, Forward Physics at the LHC: Detecting Elastic pp Scattering by Radiative Photons, JINST 6 (2011) P01005.

[3] V. A. Khoze, A. D. Martin, R. Orava, M. G. Ryskin. Luminosity measuring processes at the LHC, Eur. Phys. J C19 (2001) 313.

[4] P. Lebiedowicz and A. Szczurek, Exclusive diffractive photon bremsstrahlung at the LHC, Phys. Rev. D87 (2013) 114013.

[5] C. Adler et al., The RHIC Zero Degree Calorimeter, Nucl. Instrum. Meth. A470 (2001) 488, M. B. Bitters et al., Analysis of STAR ZDC SMD Data for Polarimetry, unpublished.

[6] STAR Collaboration, L. Adamczyk et al., Single Spin Asymmetry AN in Polarized Proton-Proton Elastic Scattering at $\sqrt{s} = 200$ GeV , Phys.Lett. B719 (2013) 62.

[7] R. Kycia, J. Turnau, in preparation.

[8] R. Kycia, J. Turnau, R. Staszewski and J. Chwastowski, GenEx: A simple generator structure for exclusive processes in high energy collisions, arXiv:1411.6035 [hep-ph].

[9] Geant4 Collab., S. Agostinelli et al., Nucl. Instrum. Meth. A506 (2003) 250, Geant4 Collab., J. Allison et al., IEEE Trans. Nucl. Science 53 (2006) 270.

[10] F. Schmidt, Mad-X User’s Guide, CERN 2005, BE/ABP Accelerator Physics Group: http://mad.web.cern.ch/mad/.

[11] R. Sikora, Master Thesis, AGH UST 2014, unpublished.

[12] R. Staszewski and J. Chwastowski, Transport Simulation and Diffractive Event Reconstruction at the LHC, Nucl. Instrum. Meth. A609 (2009) 136.

[13] M. W. Krasny, J. Chwastowski and K. Słowikowski, Luminosity measurement method for LHC: The theoretical precision and the experimental challenges, Nucl. Instrum. Meth. A584 (2008) 42.

[14] P. Lebiedowicz and A. Szczurek, Exclusive $pp \to pp\pi^0$ reaction at high energies, Phys. Rev. D87 (2013) 7, 074037.
[15] P. Lebiedowicz, R. Staszewski and M. Trzebinski, private communication.

[16] T. Sjöstrand et al., An Introduction to PYTHIA 8.2, arXiv:1410.3012 [hep-ph], submitted to Computer Physics Communication.