Main Parameters of $\gamma p$ Colliders

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Abstract

Main parameters of TeV energy $\gamma p$ colliders have been investigated for HERA+SBLC, HERA+TESLA, HERA+e-linac, LHC+TESLA, LHC+CLIC and LHC+e-linac proposals. Luminosity of $\gamma p$ collisions for these colliders are studied in terms of a distance between the conversion region and the collision point.

Building linac-ring type machines are required for reaching TeV scale energies in e-p collisions at constituent level (see Ref. [1] and references therein). These colliders do not only reach higher center of mass energies; also they provide better collision kinematics [2]. One of the most important advantages of linac-ring type ep colliders is the possibility of building $\gamma p$ colliders on their bases [3, 4]. The high energy $\gamma$ beam is obtained by the Compton backscattering of laser photons off linac’s electron beam. Estimations show that machines under consideration will give opportunity to achieve TeV scale at constituent level with sufficiently high luminosities. Since these machines are not conventional, number of design problems will be encountered but they are of solvable kind [5]. When it comes to physics which can be done with these machines: they have advantage in solving particle physics problems such as production of excited quarks, investigation of extremely small $x_g$, etc.

In this paper luminosity of $\gamma p$ collisions for HERA+SBLC, HERA+TESLA, HERA+e-linac, LHC+TESLA, LHC+CLIC and LHC+e-linac colliders are studied in terms of a distance between the conversion region and the collision point.

One may want to know why not to use standard type $ep$-colliders for the construction of $\gamma p$ machines. The first reason is the center-of-mass energy limitation. It is known that the first standard type $ep$ machine (HERA) has center-of-mass energy $\sqrt{s_{ep}} = 292$ GeV and luminosity $L_{ep} = 1.6 \cdot 10^{31} cm^{-2} s^{-1}$. The second standard type $ep$-collider could be LHC+LEP with $\sqrt{s} = 1.36$ TeV and $L_{ep} = 2.8 \cdot 10^{32} cm^{-2} s^{-1}$ [6], but now this option is out of question since it has kinematical disadvantage ($E_e/E_p = 1/100$). Further increase of $\sqrt{s_{ep}}$ for standard type $ep$ machines is restricted by enormous synchrotron radiation power increase in electron rings. As it is known, in standard type $ep$ colliders
γ*p physics is investigated through Weizsäcker-Williams photons. Therefore, it is obvious that $\sqrt{\sqrt{s_{\gamma p}}} << \sqrt{s_{ep}}$.

The second reason having a technical character is more important: namely, low luminosity of γp colliders based on standard type ep machines. Indeed, electron bunches after conversion need to be removed. Therefore, luminosity of γp-collisions has the form

$$L_{\gamma p} = \frac{n_{\gamma} n_{p} k_{e}}{s_{\text{eff}} T_{e}}$$

(1)

where $n_{\gamma}(\approx n_{e})$ and $n_{p}$ are the number of particles in corresponding bunches, $s_{\text{eff}}$ is the transverse area of bunches ($s_{\text{eff}} = 2\pi \sigma_{p}^{2}$ because of $\sigma_{p} >> \sigma_{\gamma}$, where $\sigma_{p}$ and $\sigma_{\gamma}$ are transverse sizes of proton and photon bunches at collision point), $k_{e}$ is the number of electron bunches in the ring and $T_{e} = T_{e}^{c} + T_{e}^{f}$. Here $T_{e}^{c}$ is the time of using all electron bunches accelerated in one cycle and $T_{e}^{f}$ is filling time. The expression for $L_{\gamma p}$ should be compared with the expression for luminosity of ep-collisions

$$L_{ep} = \frac{n_{e} n_{p} k_{e}}{s_{\text{eff}} c} \frac{2\pi R}{2\pi R}$$

(2)

where $c$ is speed of the light and $2\pi R$ is circumference of electron ring. Without optimization, one gets according to (1) and (2)

$$\frac{L_{\gamma p}}{L_{ep}} = \frac{2\pi R}{T_{e} c}$$

(3)

Using design parameters [6] for HERA ($2\pi R = 6.336$ km, $T_{e} > T_{e}^{f} = 900$ s), one has $L_{\gamma p}/L_{ep} < 2.3 \cdot 10^{-8}$, for LHC+LEP ($2\pi R = 26.659$ km, $T_{e} > T_{e}^{f} = 2400$ s) one obtain $L_{\gamma p}/L_{ep} < 3.7 \cdot 10^{-8}$. Possible optimizations, namely increasing the number of protons per bunch up to $10^{12}$ and decreasing $s_{\text{eff}}$, can improve these values at most by two orders.

Therefore, TeV energy γp colliders on the base of linac-ring type ep machines are the only choice. In this case, the luminosity values can be roughly estimated from the equation

$$L_{\gamma p} = \frac{n_{\gamma} n_{p}}{2\pi \sigma_{p}^{2}} f_{\gamma}$$

(4)

where $n_{\gamma} = n_{e}$ (conversion is taken one-to-one), $f_{\gamma} = n_{f_{\text{ep}}}$. In the above expression, effects of the distance between conversion region and collision point have been neglected.

As it is mentioned in Refs. [3, 7], two versions of γp collisions are possible: on the extracted proton beam and in the proton ring. In the first case, the luminosity is given by

$$L_{\gamma p} = \frac{n_{\gamma} n_{p} k_{p}}{2\pi \sigma_{p}^{2} T_{p}}$$

(5)

where $T_{p}$ is the time of full cycle of proton machine in γp regime and $k_{p}$ is the number of proton bunches accelerated in one cycle. It is obvious that $T_{p} = T_{p}^{c} + T_{p}^{f}$, where $T_{p}^{c} = k_{p} f_{\gamma}$ is the spending time of proton bunches accelerated in one cycle and $T_{p}^{f}$ is the filling time. Filling times for HERA and LHC proton beams are 1200 and 420 s,
respectively. Therefore, $T_p^c$ is much smaller than $T_p^f$. Consequently, luminosities for the version with collisions on extracted proton beam are obtained as: $4.2 \times 10^{26}$ cm$^{-2}$s$^{-1}$ for HERA+SBLC, $1.3 \times 10^{29}$ cm$^{-2}$s$^{-1}$ for LHC+TESLA and $1.1 \times 10^{26}$ cm$^{-2}$s$^{-1}$ for LHC+e-linac. Possible optimization will improve these values by one order. Therefore, for $\gamma p$ colliders under consideration, the version with collisions in proton ring is preferable.

The expression for the luminosity, that takes the distance into consideration, can be written as

$$L_{\gamma p} = \int_{0}^{\omega_{\max}} \frac{dL_{\gamma p}}{d\omega} d\omega$$

(6)

where differential luminosity is given by [4]

$$\frac{dL_{\gamma p}}{d\omega} = f(\omega) n_p n_p f_\gamma \frac{2\pi (\sigma_\gamma^2 + \sigma_p^2)}{\omega} \exp[-z^2 \Theta_\gamma^2(\omega)/2(\sigma_\gamma^2 + \sigma_p^2)].$$

(7)

Here, $\omega$ is high energy photon’s energy, $z$ is the distance between conversion region and collision point, $\Theta_\gamma(\omega)$ is the angle between high energy photons with $\omega$ energy and electron beam direction. This angle is given by (for small $\Theta_\gamma$)

$$\Theta_\gamma(\omega) = \frac{m_e}{E_e} \sqrt{\frac{E_e x}{\omega} - (x + 1)}$$

(8)

where $x = 4E_e\omega_0/m_e^2$, $\omega_0$ is laser photon energy. In order to avoid $e^+e^-$ pair creation in the conversion region, $x$ should be less than 4.83. In equation (7), $f(\omega)$ is the normalized differential Compton cross section [8]:

$$f(\omega) = \frac{1}{E_p \sigma_c x m_e^2} \frac{1}{1 - y} + 1 - y - 4r(1 - r) + \lambda_e \lambda_0 r x (1 - 2r)(2 - y)]$$

(9)

where $y = \omega/E_e$, $r = y/[x(1 - y)]$. The total Compton cross section is

$$\sigma_c = \sigma_c^0 + \lambda_e \lambda_0 \sigma_c^1$$

$$\sigma_c^0 = \frac{\pi \alpha^2}{x m_e^2} [(2 - \frac{8}{x} - \frac{16}{x^2}) \ln(x + 1) + 1 + \frac{16}{x} - \frac{1}{(x + 1)^2}]$$

(10)

$$\sigma_c^1 = \frac{\pi \alpha^2}{x m_e^2} [(2 + \frac{4}{x}) \ln(x + 1) - 5 + \frac{2}{x + 1} - \frac{1}{(x + 1)^2}]$$

In the equations above, $\lambda_e$ and $\lambda_0$ are helicities of electron and laser photon. As one can see from equation (8), high energy photons with maximal energy

$$\omega_{\max} = E_e \frac{x}{x + 1} = 0.83 E_e$$

(11)

move in the direction of electron beam.
In Table 1, electron and unimproved proton beam parameters for different accelerators are given. Additionally improved proton beam parameters are given in Ref. [9]. By using these numbers in above equations, we can calculate luminosities for some chosen distances, to demonstrate the effect of distance. In difference from linear $e^+e^−$ colliders, where flat beams are proposed in order to minimize beamstrahlung, for $γp$ colliders the use of round electron beams are more preferable. The values for electron’s transverse beam size are taken as $σ_x = √σ_xσ_y$. Obtained results are presented on Table 2 for unimproved proton beams and Table 3 for improved proton beams. In last column of Table 2 we give minimum wave lengths of laser photons corresponding to $x = 4.83$.

Another property, important from physics point of view, is the helicity of colliding particles. The use of polarized particles for collisions provides us with further information, in particular, about the space-time structure of interactions. The helicity of high energy...
photons obtained after conversion is given by \[8\]

\[
\lambda_\gamma(\omega) = \frac{\lambda_0(1 - 2r)(1 - y + \frac{1}{1 - y}) + \lambda_e r x[1 + (1 - y)(1 - 2r)^2]}{1 - y + \frac{1}{1 - y} - 4r(1 - r) - \lambda_e \lambda_0 r x(2r - 1)(2 - y)}. \tag{12}
\]

According to this equation, change of signs of both laser photon (\(\lambda_0 \rightarrow -\lambda_0\)) and initial electron (\(\lambda_e \rightarrow -\lambda_e\)) helicities leads to opposite helicity of high energy photon (\(\lambda_\gamma \rightarrow -\lambda_\gamma\)). Laser beam can be prepared with helicity equal to \(\pm 1\), whereas electron beam helicity can not achieve extreme values. When it comes to the protons, up to 70% polarization can be achieved by using the modern accelerator technology.

As concluding remarks:

- Luminosity slowly decreases with the distance between the conversion region and the collision point.
- A better monochromatization for high energy \(\gamma\) beam can be achieved by increasing the distance \(z\).
- Opposite helicity values for laser and electron beams are advantageous for \(\gamma\) beam spectrum.
- Mean helicity of the \(\gamma\) beam approaches to one with increasing distance.

When the luminosity and energies considered, linac-ring type \(\gamma p\) colliders will be very promising and interesting addition to the research tool inventory of high energy physics. While \(\gamma p\) collider is very interesting by itself, it is an important option of linac-ring type ep collider.

<table>
<thead>
<tr>
<th>Colliders</th>
<th>Improved proton parameters</th>
<th>L((cm^{-2}s^{-1}))</th>
<th>(z = 0m)</th>
<th>(z = 5m)</th>
<th>(z = 10m)</th>
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<tbody>
<tr>
<td>HERA+SBLC (250)</td>
<td></td>
<td>2.55(\times 10^{34})</td>
<td>1.12(\times 10^{34})</td>
<td>6.04(\times 10^{34})</td>
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<tr>
<td>HERA+SBLC (362.5)</td>
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<td>1.04(\times 10^{33})</td>
<td>0.57(\times 10^{33})</td>
<td>0.37(\times 10^{33})</td>
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<td>HERA+SBLC (500)</td>
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<td>1.48(\times 10^{33})</td>
<td>0.92(\times 10^{33})</td>
<td>0.65(\times 10^{33})</td>
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<td>HERA+SBLC (1000)</td>
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<td>9.73(\times 10^{30})</td>
<td>7.68(\times 10^{30})</td>
<td>6.07(\times 10^{30})</td>
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<td>HERA+TESLA (400)</td>
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<td>1.71(\times 10^{31})</td>
<td>0.97(\times 10^{31})</td>
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<td>HERA+TESLA (800)</td>
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<td>1.69(\times 10^{31})</td>
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<td>0.96(\times 10^{31})</td>
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<td>HERA+TESLA (1600)</td>
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<td>1.25(\times 10^{31})</td>
<td>1.09(\times 10^{31})</td>
<td>0.93(\times 10^{31})</td>
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<td>HERA+e-linac (300)</td>
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<td>1.08(\times 10^{32})</td>
<td>0.60(\times 10^{32})</td>
<td>0.40(\times 10^{32})</td>
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<td>2.63(\times 10^{32})</td>
<td>0.86(\times 10^{32})</td>
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<td>0.42(\times 10^{32})</td>
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Acknowledgments

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References

[1] S. Sultansoy, Four Ways to TeV Scale, in this proceedings.


[9] Ö. Yavaş, Space Charge and Beam-Beam Tune Shifts at Linac-Ring Type ep Colliders, in this proceedings.