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Main Parameters of γp Colliders

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Abstract

Main parameters of TeV energy γp colliders have been investigated for HERA+SBLC, HERA+TESLA, HERA+e-linac, LHC+TESLA, LHC+CLIC and LHC+e-linac proposals. Luminosity of γp 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 γp colliders on their bases [3, 4]. The high energy γ 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 γp 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 γp 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

$\gamma^{\star}p$ physics is investigated through Weizsäcker-Williams photons. Therefore, it is obvious that $\sqrt{s_{\gamma^{\star}p}} << \sqrt{s_{ep}}$.

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

$$L_{\gamma p} = \frac{n_\gamma n_p}{s_{eff}} \frac{k_e}{T_e} \tag{1}$$

where $n_\gamma(\approx n_e)$ and n_p are the number of particles in corresponding bunches, s_{eff} is the transverse area of bunches ($s_{eff} = 2\pi\sigma_p^2$ because of $\sigma_p >> \sigma_\gamma$, where σ_p and σ_γ 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

$$L_{ep} = \frac{n_e n_p}{s_{eff}} k_e \frac{c}{2\pi R} \tag{2}$$

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)

$$\frac{L_{\gamma p}}{L_{ep}} = \frac{2\pi R}{T_e c} \tag{3}$$

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_{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

$$L_{\gamma p} = \frac{n_\gamma n_p}{2\pi\sigma_p^2} f_\gamma \tag{4}$$

where $n_\gamma = n_e$ (conversion is taken one-to-one), $f_\gamma = n_b f_{rep}$. 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

$$L_{\gamma p} = \frac{n_\gamma n_p}{2\pi\sigma_p^2} \frac{k_p}{T_p} \tag{5}$$

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: $4.2 \cdot 10^{26} cm^{-2}s^{-1}$ for HERA+SBLC, $1.3 \cdot 10^{29} cm^{-2}s^{-1}$ for LHC+TESLA and $1.1 \cdot 10^{26} cm^{-2}s^{-1}$ for LHC+e-linac. Possible optimization will improve these values by one order. Therefore, for γp 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

$$L_{\gamma p} = \int_0^{\omega_{max}} \frac{dL_{\gamma p}}{d\omega} d\omega \tag{6}$$

where differential luminosity is given by [4]

$$\frac{dL_{\gamma p}}{d\omega} = \frac{f(\omega) n_\gamma n_p f_\gamma}{2\pi(\sigma_e^2 + \sigma_p^2)} exp[-z^2 \Theta_\gamma^2(\omega)/2(\sigma_e^2 + \sigma_p^2)]. \tag{7}$$

Here, ω 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 ω energy and electron beam direction. This angle is given by (for small Θ_γ)

$$\Theta_\gamma(\omega) = \frac{m_e}{E_e} \sqrt{\frac{E_e x}{\omega} - (x+1)} \tag{8}$$

where $x = 4E_e\omega_0/m_e^2$, ω_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]:

$$f(\omega) = \frac{1}{E_b \sigma_c} \frac{2\pi\alpha^2}{x m_e^2} [\frac{1}{1-y} + 1 - y - 4r(1-r) + \lambda_e \lambda_0 r x (1-2r)(2-y)] \tag{9}$$

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

$$\begin{aligned} \sigma_c &= \sigma_c^0 + \lambda_e \lambda_0 \sigma_c^1 \\ \sigma_c^0 &= \frac{\pi\alpha^2}{x m_e^2}[(2 - \frac{8}{x} - \frac{16}{x^2}) \ln(x+1) + 1 + \frac{16}{x} - \frac{1}{(x+1)^2}] \\ \sigma_c^1 &= \frac{\pi\alpha^2}{x m_e^2}[(2 + \frac{4}{x}) \ln(x+1) - 5 + \frac{2}{x+1} - \frac{1}{(x+1)^2}] \end{aligned} \tag{10}$$

In the equations above, λ_e and λ_0 are helicities of electron and laser photon. As one can see from equation (8), high energy photons with maximal energy

$$\omega_{max} = E_e \frac{x}{x+1} = 0.83 E_e \tag{11}$$

move in the direction of electron beam.

Table 1. Parameters of proton and electron machines.

Machines	$E_p(GeV)$	$E_e(GeV)$	$n_e(10^{10})$	$n_p(10^{10})$	$f_{rep}(Hz)$	$\sigma_x(10^{-6}m)$	$\sigma_y(10^{-6}m)$	$\sigma_z(cm)$	n_b
HERA	820	-	-	10	10.4×10^6	265	50	8.5	180
LHC	7000	-	-	10.5	6.05×10^6	16	16	7.5	2835
SBLC	-	250	1.1	-	50	0.335	0.0151	0.03	333
SBLC	-	362.5	1.2	-	50	0.303	0.0065	0.03	125
SBLC	-	500	1.7	-	50	0.357	0.0055	0.03	125
SBLC	-	1000	2.0	-	50	0.370	0.0035	0.03	70
TESLA	-	400	3.63	-	3	0.669	0.0094	0.07	1130
TESLA	-	800	1.8	-	3	0.475	0.0037	0.07	2260
TESLA	-	1600	1.0	-	3	0.300	0.0020	0.07	3000
e-Linac	-	300	2.0	-	10	8.600	8.6	0.1	6410
CLIC	-	500	0.8	-	2530	0.250	0.0075	20	10
CLIC	-	1000	0.8	-	4000	0.200	0.0060	20	10

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 $\sigma_e = \sqrt{\sigma_x \sigma_y}$. 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 $x = 4.83$.

Table 2. Luminosities and the minumum laser wave lengths for chosen linac-ring type γp colliders with unimproved proton parameters. The values in paranthesis are the beam energy of linac.

Colliders		$\sqrt{s_{\max}}$ (TeV)	$L(cm^{-2}s^{-1})$ at $z = 5m$	Min. Wave Length (μm)
HERA+SBLC	(250)	0.820	2.06×10^{28}	0.9887
HERA+SBLC	(362.5)	0.990	0.87×10^{28}	1.4343
HERA+SBLC	(500)	1.165	1.25×10^{28}	1.9784
HERA+SBLC	(1000)	1.648	0.83×10^{28}	3.9574
HERA+TESLA	(400)	1.042	1.43×10^{28}	1.5826
HERA+TESLA	(800)	1.474	1.45×10^{28}	3.1653
HERA+TESLA	(1600)	2.080	1.08×10^{28}	6.3322
HERA+e-linac	(300)	0.902	1.46×10^{29}	1.1871
LHC+CLIC	(500)	3.403	0.96×10^{30}	1.9784
LHC+CLIC	(1000)	4.813	1.81×10^{30}	3.9574
LHC+TESLA	(400)	3.045	5.38×10^{29}	1.5826
LHC+TESLA	(800)	4.305	6.58×10^{29}	3.1653
LHC+TESLA	(1600)	6.089	5.43×10^{29}	6.3322
LHC+e-linac	(300)	2.636	8.37×10^{30}	1.1871

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 ($\lambda_0 \to -\lambda_0$) and initial electron ($\lambda_e \to -\lambda_e$) helicities leads to opposite helicity of high energy photon ($\lambda_\gamma \to -\lambda_\gamma$). Laser beam can be prepared with helicity equal to ± 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 γ beam can be achieved by increasing the distance z.
- Opposite helicity values for laser and electron beams are advantageous for γ beam spectrum.
- Mean helicity of the γ beam approaches to one with increasing distance.

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

Table 3. Luminosities for chosen γp colliders with improved proton parameters.

Colliders		Improved proton parameters $L(cm^{-2}s^{-1})$		
		$z = 0m$	$z = 5m$	$z = 10m$
HERA+SBLC	(250)	2.55×10^{31}	1.12×10^{31}	0.64×10^{31}
HERA+SBLC	(362.5)	1.04×10^{31}	0.57×10^{31}	0.37×10^{31}
HERA+SBLC	(500)	1.48×10^{31}	0.92×10^{31}	0.65×10^{31}
HERA+SBLC	(1000)	9.73×10^{30}	7.68×10^{30}	6.07×10^{30}
HERA+TESLA	(400)	1.71×10^{31}	0.97×10^{31}	0.65×10^{31}
HERA+TESLA	(800)	1.69×10^{31}	1.26×10^{31}	0.96×10^{31}
HERA+TESLA	(1600)	1.25×10^{31}	1.09×10^{31}	0.93×10^{31}
HERA+e-linac	(300)	1.08×10^{32}	0.60×10^{32}	0.40×10^{32}
LHC+CLIC	(500)	2.63×10^{32}	0.86×10^{32}	0.40×10^{32}
LHC+CLIC	(1000)	4.16×10^{32}	2.13×10^{32}	1.35×10^{32}
LHC+TESLA	(400)	1.60×10^{32}	0.42×10^{32}	0.18×10^{32}
LHC+TESLA	(800)	1.59×10^{32}	0.72×10^{32}	0.42×10^{32}
LHC+TESLA	(1600)	1.17×10^{32}	0.74×10^{32}	0.53×10^{32}
LHC+e-linac	(300)	2.36×10^{32}	1.07×10^{32}	0.62×10^{32}

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