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Nuclear Instruments and Methods in Physics Research A 576 (2007) 287–293
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
www.elsevier.com/locate/nima

Conversion efficiency and luminosity for gamma-proton colliders based on the LHC-CLIC or LHC-ILC QCD explorer scheme

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Received 21 November 2006; received in revised form 20 March 2007; accepted 20 March 2007
Available online 24 March 2007

Abstract

Gamma-proton collisions allow unprecedented investigations of the low x and high Q^2 regions in quantum chromodynamics. In this paper, we investigate the luminosity for "ILC" × LHC($\sqrt{s_{ep}} = 1.3$ TeV) and "CLIC" × LHC($\sqrt{s_{ep}} = 1.45$ TeV) based γp colliders. Also we determine the laser properties required for high conversion efficiency.

PACS: 13.60.Fz; 41.75.−i; 42.55.−f

Keywords: Photon–Proton collisions; Luminosity

1. Introduction

To extend the HERA kinematics region at least by an order of magnitude in both Q^2 and x_g, the QCD Explorer collider was proposed [1–3] by extrapolating earlier ideas of linac-ring type colliders [4–8] to a new kinematic range. The QCD Explorer is a linac-ring type electron–proton collider making use of a multi-GeV electron beam and the multi-TeV LHC proton or ion beam. An obvious advantage of the QCD Explorer as compared to the ring–ring type e–p colliders (i.e. LHeC [9]) is the possibility to transform it into a γp collider using the same infrastructure [10–13]. This possibility is further explored in the present paper.

For the QCD Explorer the protons would be stored at the LHC design energy of 7 TeV. The ions would have an equivalent energy, corresponding to the same magentic bending field, and depending on their mass and charge state. The high energy electron beam could either be the main-beam equivalent of a single CLIC drive beam unit of CLIC reaching about 75 GeV electron energy ("CLIC-1" [14]) or be produced by an ILC-type super conducting linac with an energy of 60 GeV. In both cases, the final energy could be increased in stages by either adding more drive beam units or further s.c. cavities and klystrons, respectively. A simple sketch of a linac-ring type γp collider based on LHC is displayed in Fig. 1. The ultimate energy-frontier γ-nucleon collider would employ a full 1.5-TeV CLIC linac colliding with the LHC [15]. "CLIC-1" comprises a single drive-beam unit which can accelerate the main beam to 75 GeV. The bunch structure of "CLIC-1" does not match well with the nominal bunch structure of the LHC. The mismatch in bunch spacing limits the achievable luminosity. Two remedial approaches were proposed. In the first scheme, LHC operates with a long superbunch, whose length equals the length of the CLIC bunch train. This scheme obviously requires a change in the bunch structure of LHC proton beam [16], which could be realized in a number of ways, e.g., Ref. [17]. Unfortunately, the superbunches are not compatible with simultaneous running of the upgraded ATLAS and CMS detectors [18]. In the second approach the CLIC linac parameters are modified, namely one considers a two times longer linac (in one of three possible incarnations, called "CLIC-15a", "CLIC-15b", and "CLIC-15c", which are detailed below) than "CLIC-1" with a lower accelerating gradient (75 MV/m)

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0168-9002/$ - see front matter
doi:10.1016/j.nima.2007.03.019

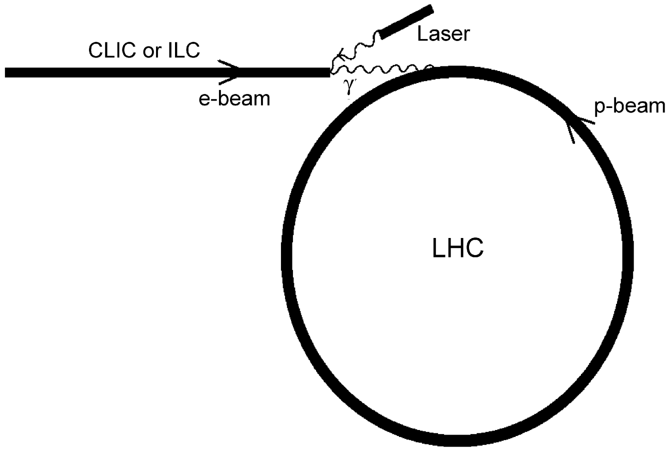

Fig. 1. Schematic of the proposed colliders.

and a two times lower RF frequency (15 GHz), which will make it possible to change the bunch charges, the bunch length and the bunch separation time in the linac.

Namely, the bunch charge can be increased by a factor of two for the reduced accelerating frequency. The drive beam bunches arrive at a frequency of 15 GHz, so that they can also drive 15 GHz accelerating structures. For this purpose, one would use scaled version of the CLIC accelerating structures. The structure dimensions would all be doubled. The input power per structure would remain unchanged but the gradient is halved. Due to the lower frequency the beam loading is reduced to a quarter of the original value. Taking into account the reduced gradient, this allows doubling the bunch charge. The distance between bunches needs to be doubled, leaving the beam current constant. The only drawback would be that the fill time for the main linac structures also doubles. Hence the number of bunches is reduced from 220 to 92. The corresponding beam parameters can be found in Table 1. It should be noted that this mode of operation can create a problem with the beam loading compensation in the drive beam accelerator. In the current system two pulses are produced at the same time for a reason explained in the next paragraph. If one wanted to avoid producing the second pulse, the beam loading compensation scheme would need modification. However, a simple means exists to avoid the problem and at the same time to increase the luminosity, as described below.

An improvement could be achieved by a modification of the delay loop of the drive beam generation complex. In the current scheme, this loop delays the trains by about 69.7 ns. This allows generating trains of 69.7 ns length which are then combined in the subsequent system of combiner rings. In order to avoid too small rings a pair of trains is produced simultaneously. An increase of the delay loop length to 139.4 ns would allow producing one pulse of twice the length instead. This would keep the ratio of fill time to pulse length constant and allow to use 220 bunches per train at 15 GHz (“CLIC-15b”). This mode of operation has the advantage compared to the previous one that there will be no problem with the beam loading in the drive beam accelerator.

In the nominal CLIC (and hence also in “CLIC-1”) one will not only produce a single drive beam pulse but rather a series of 22 pulses in order to power subsequent sections of the main linac. Since the heat load induced by the RF system is smaller at 15 GHz one could use more pulses per second than at 30 GHz. For the same Q-value this method would allow to increase the repetition rate by a factor of two, assuming that we are limited by the power transfer through the inner surface of the structure. The Q-value is expected to be larger at lower frequency scaling roughly as $\omega^{-1/2}$. This would allow to further increase the repetition rate by about a factor of 1.4 (“CLIC-15c”). It should be noted that it may be possible to improve the structure design to increase this gain even further. Therefore we assume that three pulses are produced at each drive beam RF pulse with a spacing of $32\times2\times139.4$ ns, where the factor 32 represents the nominal compression factor of the CLIC drive-beam complex.

Electron beam parameters for “CLIC-1”, “CLIC-15a” and “ILC” are summarized in Table 1. “CLIC-15b” has the same parameter set as ”CLIC-15a” except for the number of bunches which is 220. “CLIC-15c” has the same parameters as “CLIC-15b”, but a repetition frequency of 420 Hz instead of 150 Hz. Considering an interaction region of total length 200 cm, one proton bunch would collide with about 50 electron, or photon, bunches in the “CLIC-1” option and with 25 bunches for “CLIC-15a,b” and “c”. For the “ILC” option, each proton bunch would collide with a single photon bunch [13].

In this study we consider a γ-nucleon collisions based on QCD Explorer. In the γ-proton colliders, the high energy photons could be produced by Compton backscattering of laser photons off a high energy electron beam. To produce high energy photons, either the “ILC” or “CLIC” options can be used. The Compton backscattered photons collide with LHC’s protons in the interaction region. In Sections 2 and 3, we determine the electron beam and laser parameters yielding an effective conversion. The achievable luminosity for all cases is discussed in Section 4.

2. Conversion region, interaction region and beam parameters

The conversion to high energy photon of a laser beam by colliding with an electron beam is determined by the Compton cross-section. The total Compton cross-section (σ_c) for polarized beams is [19,20]

$$\sigma_c = \sigma^0 + 2\lambda_e\lambda_0\sigma^1 \quad (1)$$

$$\sigma^0 = \frac{2\pi\alpha^2}{xm_e^2}\left[\left(1-\frac{4}{x}-\frac{8}{x^2}\right)\ln(x+1)+\frac{1}{2}+\frac{8}{x}-\frac{1}{2(x+1)^2}\right] \quad (2)$$

$$\sigma^1 = \frac{2\pi\alpha^2}{xm_e^2}\left[\left(1+\frac{2}{x}\right)\ln(x+1)-\frac{5}{2}+\frac{1}{1+x}-\frac{1}{2(x+1)^2}\right] \quad (3)$$