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QCD EXPLORER BASED ON LHC AND CLIC-1

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Abstract

Colliding 7-TeV LHC super-bunches with 75-GeV CLIC bunch trains can provide electron-proton collisions at very high centre-of-mass energies, opening up a new window into QCD. At the same time, this QCD explorer would employ several key components required for both an LHC upgrade and CLIC. We here present a possible parameter set of such a machine, study the consequences of the collision for both beams, and estimate the attainable luminosity.

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QCD Explorer Based on LHC and CLIC-1

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Abstract

Colliding 7-TeV LHC super-bunches with 75-GeV CLIC bunch trains can provide electron-proton collisions at very high centre-of-mass energies, opening up a new window into QCD. At the same time, this QCD Explorer (QCDE) would employ several key components required for both an LHC upgrade and CLIC. We here present a possible parameter set of such a machine, study the consequences of the collision for either beam, and estimate the attainable luminosity.

INTRODUCTION

It has been suggested that a linac-ring type electron-proton collider (linac-ring colliders were first proposed in Refs. [1, 2]) could extend the low-x reach of HERA by at least two orders of magnitude and might provide discoveries that are as fundamental for the QCD as is the Higgs for the electro-weak interactions (see [3] and references therein).

The nominally 2808 LHC bunches are spaced at a typical distance of 25 ns and are spread out over a revolution period of about 100 μs. On the other hand, the CLIC beam consists of 154 bunches spaced by 0.66 ns, and extending over about 100 ns. If we were to collide these two beams, the luminosity would be bound to be low, as only few bunches of either beam would participate in the collisions. It is difficult to increase the length of the CLIC bunch train. On the other hand, one option for a future LHC luminosity upgrade yielding a luminosity of about ten times the nominal is to combine the 2808 small bunches into a few super-bunches with a total length of about 300 m. Tailored to a length of about 30 m an LHC proton superbunch would be the ideal counterpart of the CLIC bunch train. Then all CLIC bunches and a significant part of the LHC beam (10%) would contribute to the electron-proton luminosity. The advantage of the proton superbunch is evident from the schematic comparison in Fig. 1.

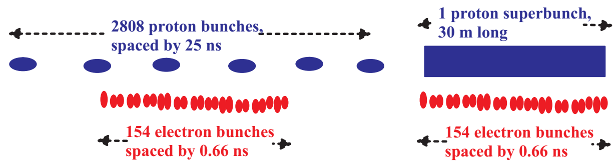

Figure 1: Bunch filling patterns in LHC and CLIC for the nominal LHC (left) and with an LHC superbunch (right).

PARAMETERS

Possible proton and electron beam parameters are listed in Table 1. The proton parameters are those considered for an LHC superbunch upgrade [4], while the electron beam parameters, especially emittances and IP beta functions, are relaxed compared with the ultimate CLIC target values and could be easily produced by a photo-rf gun without the need of a damping ring. For example, the transverse normalized electron-beam emittance is taken to be 73 μm in both planes. This is more than 100 and 10000 times larger than the 3-TeV CLIC design value of 0.45 μm for the horizontal emittance and of 3 nm for the vertical, respectively. While a smaller electron beam might have its merits, we have assumed, for simplicity, equal beta functions and equal geometric emittances for the two beams. This equality minimizes the nonlinear forces experienced by the proton beam, while at the same time it does not significantly sacrifice luminosity.

Highest luminosity and maximum symmetry is achieved by colliding the two beams head on over a length $l_{\rm IR}$. They can be separated easily by rather weak dipole magnets, since the electron beam-energy is only 1% of the proton energy. It could be advantageous to separate the beams at one side horizontally and on the other vertically, thereby cancelling part of the long-range beam-beam tune shifts [5]. A schematic of the IR layout is shown in Fig. 2.

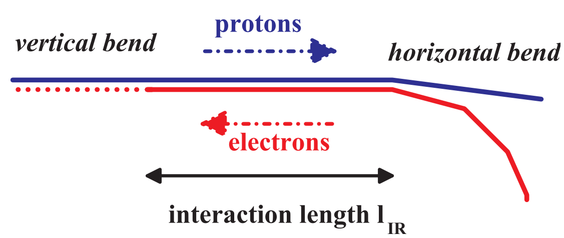

Figure 2: Schematic of IR layout, with horizontal and vertical dipoles for combining and separating the electron and proton beams.

LUMINOSITY AND TUNE SHIFT

We approximate the closely spaced electron bunches by a continuous beam with line density $\lambda_e = N_b/L_{\rm sep} \approx 2.3 \times 10^{10}$ m^{-1}. For comparison, from Table 1 the line density of the proton superbunch is 100 times larger: $\lambda_p \approx N_b/(\sqrt{6}\sigma_z) \approx 2.1 \times 10^{12}$ m^{-1}.

The luminosity for head-on collisions is given by

$$L = f_{\rm coll} \frac{l_b \lambda_e \lambda_p}{\pi \epsilon_{x,y}} \arctan\left(\frac{l_{\rm IR}}{2\beta^*}\right) , \qquad (1)$$

where l_b denotes the superbunch length, $l_{\rm IR}$ the total length of the interaction region, and $f_{\rm coll}$ the collision frequency. The proton beam-beam tune shift is $\xi = 2\lambda_e r_p l/(4\pi\gamma\epsilon_{x,y})$, where r_p is the classical proton radius.

Figures 3 and 4 display the luminosity and the proton tune shift as a function of the full interaction-region length,

Table 1: Beam Parameters

parameter	symbol	electrons	protons
beam energy	E_b	75 GeV	7 TeV
bunch population	N_b	4×10^9	6.5×10^{13}
rms bunch length	σ_z	35 μm (Gaussian)	12.4 m (uniform)
bunch spacing	$L_{\rm sep}$	0.66 ns	N/A
number of bunches	n_b	154	1
effective line density	λ	2.0×10^{10} m^{-1}	2.1×10^{12} m^{-1}
IP beta function	$\beta^*_{x,y}$	0.25 m	0.25 m
spot size at IP	$\sigma_{x,y}$	11 μm	11 μm
full interaction length	$l_{\rm IR}$	2 m	
norm. rms emittances	$\gamma\epsilon_{x,y}$	73 μm	3.75 μm
collision frequency	$f_{\rm coll}$	100 Hz	
luminosity	L	1.1×10^{31} cm^{-2}s^{-1}	
beam-beam tune shift	$\xi_{x,y}$	N/A	0.004

as computed from the analytical expressions, and assuming the parameters of Table 1. The slight loss in luminosity implied by an increase of β^* to 0.5 m (the nominal value for the LHC baseline design) is illustrated by the lower curve in Fig. 3. For a decreasing beta function, or for a rising interaction length, the arctangent in the luminosity expression asymptically approaches the value $\pi/2$. The beam-beam tune shift (Fig. 4) is independent of the IP beta function.

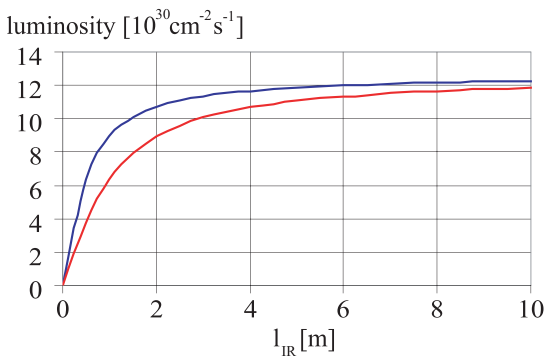

Figure 3: Luminosity in the LHC-CLIC QCD Explorer versus the length of the interaction region. The luminosity is shown for $\beta^* = 0.25$ m (top curve, blue) and for $\beta^* = 0.5$ m (bottom curve, red).

ELECTRON BEAM DISRUPTION

The electro-magnetic field of the proton beam is sufficiently strong that the electrons perform several oscillations around the centre of the proton beam. This is reflected in the large value of the effective electron 'disruption' parameter

$$D_{x,y} \equiv \frac{2\lambda_p r_e l_{\rm IR}}{\gamma\epsilon_{x,y}} \arctan\left(\frac{l_{\rm IR}}{2\beta^*}\right) \approx 430 \ , \qquad (2)$$

from which the number of electron oscillations during the collision can be estimated as $\sqrt{D_{x,y}}/(2\pi) \approx 3$. We simulated the collision dynamics over an interaction length $l_{\rm IR}$ of 2 m by the simulation code GUINEA-PIG [6]. Figure 5 shows some typical electron trajectories obtained in these simulations. Due to the electron-beam disruption, the beam-beam interaction reduces the luminosity compared to the rigid-beam case considered in Eq. (1). However, for the assumed parameters, the difference between the simulation and the analytical estimate is only about ten percent, part of which may be attributed to numerical noise.

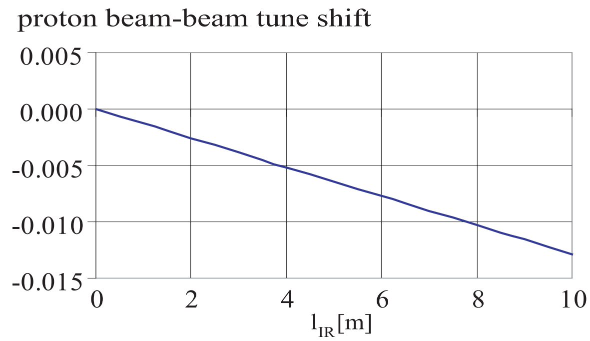

Figure 4: Proton tune shift in the LHC-CLIC QCD Explorer versus the length of the interaction region.

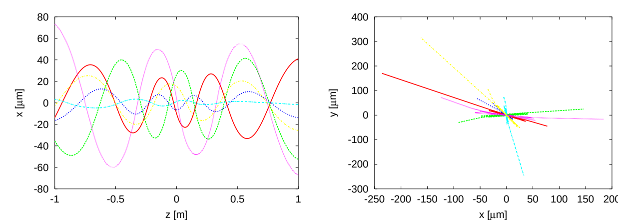

Figure 5: Simulated electron trajectories during the beam-beam collision. Left: Horizontal electron coordinate in microns as a function of the longitudinal position in m, for a 2-m long interaction region. Right: Projection of electron motion onto the $x-y$ plane.

PROTON BEAM EMITTANCE GROWTH

For the protons the linear part of the electron beam-beam force acts like an additional quadrupole of integrated strength $K_{\rm eff} = r_p N_{be}/(\gamma_p \sigma^2_{x,y}) = 4\pi\xi_{x,y}/(\beta^*_{x,y})$, where the $\xi_{x,y}$ is the beam-beam tune shift experienced by the protons on a turn at which they collide with the electrons. The additional collision introduces a beta mismatch, which is characterized by the parameter $B_{\rm mag} \equiv (1/2)(\beta\gamma_0 - 2\alpha\alpha_0 + \beta_0\gamma)$, where the Twiss parameters with subindex 0 denote the design values and those without are the mismatched values. In our case, the mismatch parameter is $B_{\rm mag} = 1 + (K_{\rm eff}\beta^*_{x,y})^2/2 = 1 + (4\pi\xi_{x,y})^2/2$, and, pessimistically assuming complete filamentation between successive collisions, the proton-beam emittance growth per unit time becomes $(\Delta\epsilon_{x,y})(\Delta t) = (B_{\rm mag} - 1)\epsilon_{x,y} f_{\rm coll}$. Inserting the numbers of Table 1, we obtain an intolerable emittance growth of 10% per second. However, alternatively we could consider the proton ring including electron collisions as equivalent to a larger storage ring with about 100 times the LHC circumference and a single electron-proton interaction point per turn. For such a configuration the beta functions are static and no mismatch would be introduced by the electron collision.

We have modified the code HEADTAIL, originally written for electron-cloud studies [8], to simulate the effect of the electron-beam collision on the proton beam emittance. The superbunch was frozen longitudinally. Only the incoherent effect was simulated, by suppressing the centroid motion. Figure 6 illustrates that the initial emittance growth rate is less than 0.20% per second, and, hence, much smaller than our pessimistic estimate above. In addition, increasing the number of macroparticles demonstrates that the simulated emittance growth is dominated by numerical noise, and that the real emittance growth rate remains below the limit accessible in this simulation.

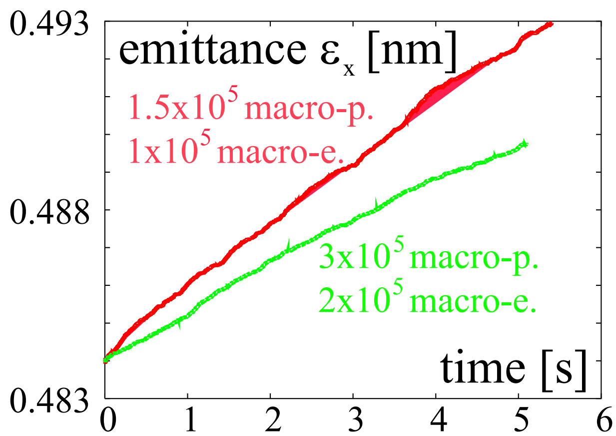

Figure 6: Simulation of proton-beam emittance growth due to collision with 75-GeV electron beam at $\xi \approx 0.005$ on every 111th turn, for two different numbers of macroparticles. A modified version of the program HEADTAIL was employed.

SYNERGIES

The CERN site offers the unique opportunity to explore QCD in electron-proton collisions at very high beam energies that are not readily achieved elsewhere, since with LHC and CLIC the two energy-frontier machines of either particle species are under construction or under design, respectively, at CERN.

The QCD Explorer would be complementary to an LHC luminosity upgrade based on superbunches and it would immediately profit from any such upgrade. If the length of the QCDE superbunch is tailored to the CLIC bunch train, for a total proton beam current of 1 A at least 90% of the LHC proton beam would be unperturbed by QCDE operation and available for LHC experiments running in parallel.

The approach described expands the physics reach of a future LHC upgrade. It favors a certain direction of upgrades, based on superbunches, that is compatible with a tenfold increase in the proton-proton luminosity. At the same time, in the QCDE facility a first full CLIC unit could be demonstrated in practical operation, with rather soft requirements on the main beam.

SUMMARY

We have described a novel scheme for an ultimate QCD Explorer based at CERN, where a portion of the 7-TeV LHC proton beam is repeatedly collided with 75-GeV electron bunch trains generated by a single CLIC drive-beam unit. This concept is attractive, since it exploits and fosters a large number of possible synergies between the LHC upgrade and the CLIC development in addition to its complementary physics-discovery potential. The estimated luminosity is in excess of 10^{31} cm^{-2}s^{-1}. If the nominal CLIC bunch spacing and train length were to be reduced in the future, the length and the total charge of the proton superbunch could be decreased as well for the same total luminosity.

Finally, the collider concept outlined in this note strongly encourages further research in wide-band rf technologies required to create and maintain intense proton superbunches in the LHC. We remark that first machine experiments with suitable novel rf units are underway at the KEK PS [7] and, starting more recently, at CERN [9].

ACKNOWLEDGEMENTS

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