A Brief Review of Future Lepton-Hadron and Photon-Hadron Colliders

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Abstract

Options for future lepton − proton, lepton − nucleus, γ − proton, γ − nucleus and FELγ − nucleus colliders are discussed. In the spirit of this content, we consider TESLA⊗HERA, LEP⊗LHC, µ−ring⊗TEVATRON, e⊗RHIC, Linac⊗LHC, $\sqrt{s} = 3TeV \ \mu p$ and CLIC based colliders.

I. INTRODUCTION

It is known that lepton-hadron collisions have been playing a crucial role in exploration of deep inside of Matter. For example, the quark-parton model was originated from investigation of electron-nucleon scattering. HERA has opened a new era in this field extending
the kinematics region by two orders both in high $Q^2$ and small $x$ compared to fixed target experiments. However, the region of sufficiently small $x$ and simultaneously high $Q^2$ ($\geq 10$ GeV$^2$), where saturation of parton densities should manifest itself, is currently not achievable. It seems possible that eA option of HERA will give opportunity to observe such phenomena. Then, the acceleration of polarized protons in HERA could provide clear information on nucleon spin origin.

The investigation of physics phenomena at extreme small $x$ but sufficiently high $Q^2$ is very important for understanding the nature of strong interactions at all levels from nucleus to partons. At the same time, the results from lepton-hadron colliders are necessary for adequate interpretation of physics at future hadron colliders. Today, linac-ring type machines seem to be the main way to TeV scale in lepton-hadron collisions; however, it is possible that in future $\mu p$ machines can be added depending on solutions of principal issues of basic $\mu^+\mu^-$ colliders.

Construction of future lepton linacs tangentially to hadron rings (HERA, Tevatron or LHC) will provide a number of additional opportunities to investigate lepton-hadron and photon-hadron interactions at TeV scale (see [1-3] and references therein). For example:

$$\text{TESLA} \otimes \text{HERA} = \text{TESLA} \oplus \text{HERA}$$

- $\oplus$ TeV scale $ep$ collider
- $\oplus$ TeV scale $\gamma p$ collider
- $\oplus eA$ collider
- $\oplus \gamma A$ collider
- $\oplus \text{FEL } \gamma A$ collider.

It should be noted that $\gamma p$ and $\gamma A$ options are unique features of linac-ring type machines and can not be realized at LEP$\otimes$LHC, while it comparable with TESLA$\otimes$HERA $ep$ and $eA$ options.

There are a number of reasons [4,5] favoring a superconducting linear collider (such as TESLA) as a source of e-beam for linac-ring type colliders. First of all, spacing between
bunches in warm linacs, which is of the order of ns, doesn’t match with the bunch spacing in the HERA, TEVATRON and LHC. Also the pulse length is much shorter than the ring circumference. In the case of TESLA, which use standing wave cavities, one can use both shoulders of linac in order to double electron beam energy, whereas in the case of conventional linear colliders one can use only half of the machine, because the travelling wave structures can accelerate only in one direction.

The most transparent expression for the luminosity of linac-ring type $ep$ colliders is [5]:

$$L_{ep} = \frac{1}{4\pi} \cdot \frac{P_e}{E_e} \cdot \frac{n_p}{\epsilon_p} \cdot \frac{\gamma_p}{\beta_p^*}$$

for round, transversely matched beams. The lower limit on $\beta_p^*$, which is given by proton bunch length, can be overcome by applying a ”dynamic” focusing scheme [6], where the proton bunch waist travels with electron bunch during collision. In this scheme $\beta_p^*$ is limited, in principle, by the electron bunch length, which is two orders magnitude smaller. More conservatively, an upgrade of the luminosity by a factor 3-4 may be possible.

Earlier, the idea of using high energy photon beams, obtained by Compton backscattering of laser light off a beam of high energy electrons, was considered for $\gamma e$ and $\gamma\gamma$ colliders (see [7] and references therein). Then the same method was proposed for constructing $\gamma p$ colliders on the base of linac-ring type $ep$ machines in [8]. Rough estimations of the main parameters of $\gamma p$ collisions are given in [9]. The dependence of these parameters on the distance $z$ between conversion region and collision point was analyzed in [10], where some design problems were considered.

The aim of this brief review is to draw the attention of the HEP community to future $lp, lA, \gamma p, \gamma A$ and FEL $\gamma A$ collider facilities.

II. FIRST STAGE: THERA, LEP$\otimes$LHC, $\mu$TEVATRON AND $E$RHIC
A. THERA

Recently, the work on TESLA TDR has been finished, and TESLA⊗HERA based \( ep, \gamma p, eA \) and \( \gamma A \) colliders are included [11] into TESLA project.

1. \( ep \) option

Main parameters of TESLA⊗HERA based on \( ep \) collider are given in Table I. It is seen that one has \( L_{ep} = 4.1 \cdot 10^{30} \text{ cm}^{-2}\text{s}^{-1} \) with \( E_e = 250 \text{ GeV} \) and \( E_p = 1 \text{ TeV} \). Also two additional versions (\( E_e = E_p = 500 \text{ GeV} \) with \( L_{ep} = 2.5 \cdot 10^{31} \text{ cm}^{-2}\text{s}^{-1} \) and \( E_e = E_p = 800 \text{ GeV} \) with \( L_{ep} = 1.6 \cdot 10^{31} \text{ cm}^{-2}\text{s}^{-1} \)) have been mentioned.

In principle, TESLA⊗HERA based \( ep \) collider will extend the HERA kinematics region by an order in both \( Q^2 \) and \( x \) and, therefore, the parton saturation regime can be achieved. A brief account of some SM physics topics (structure functions, hadronic final states, high \( Q^2 \) region etc.) which can be searched in TESLA⊗HERA \( ep \) collider is presented in [11]. The BSM search capacity of the machine will be defined by future results from LHC. If the first family leptoquarks and/or leptogluons have masses less than 1 TeV, they will be produced copiously (for couplings of the order of \( \alpha_{em} \)). The indirect manifestation of new gauge bosons may also be a matter of interest. In general, the physics search program of the machine is a direct extension of the HERA search program.

2. \( \gamma p \) option

Referring to [10] for details let us note that \( L_{\gamma p} \approx 2L_{ep} \) at \( z=0 \) (for \( \gamma \) options we use \( \varepsilon_e = 10^{-6} \text{ m} \)); where \( z \) is distance between conversion region and collision point. Then, as one can see from Fig. 1, luminosity slowly decreases with the increasing \( z \) (factor \( \sim 1/2 \) at \( z=10 \text{ m} \)) and opposite helicity values for laser and electron beams are advantageous (see Fig. 2). Additionally, a better monochromatization of high-energy photons seen by proton bunch can be achieved by increasing the distance \( z \) (Fig. 3).
The scheme with non-zero crossing angle and electron beam deflection considered in [10] for $\gamma p$ option lead to problems due to intensive synchrotron radiation of bending electrons and necessity to avoid the passing of electron beam from the proton beam focusing quadrupoles. Alternatively, one can assume head-on-collisions (see above) and exclude deflection of electrons after conversion. In this case residual electron beam will collide with proton beam together with high-energy $\gamma$ beam, but because of larger cross-section of $\gamma p$ interaction the background resulting from $ep$ collisions may be neglected. The problem of over-focussing of the electron beam by the strong proton-low-$\beta$ quadrupoles is solved using the fact of smallness of the emittance of the TESLA electron beam. For this reason the divergence of the electron beam after conversion will be dominated by the kinematics of the Compton backscattering. In the case of 250 (800) GeV electron beam the maximum value of scattering angle is 4 (1.5) micro-radians. Therefore, the electron beam transverse size will be 100 (37.5) $\mu m$ at the distance of 25 m from conversion region and the focusing quadrupoles for proton beam have negligible influence on the residual electrons. On the other hand, in the scheme with deflection there is no restriction on $n_e$ from $\Delta Q_p$, therefore, larger $n_e$ and bunch spacing may be preferable. All these topics need a further research.

Concerning the experimental aspects, very forward detector in $\gamma$-beam direction will be very useful for investigation of small $x_g$ region due to registration of charmed and beauty hadrons produced via $\gamma g \rightarrow Q\bar{Q}$ sub-process.

There are a number of papers (see [2] and refs. therein), devoted to physics at $\gamma p$ colliders. Concerning the BSM physics, $\gamma p$ option of THERA does not promise essential results with possible exclusions of the first family excited quarks (if their masses are less than 1 TeV) and associate production of gaugino and first family squarks (if the sum of their masses are less than 0.5 TeV). The photo-production of W and Z bosons may be also the matter of interest for investigation of the their anomalous couplings. However, $\bar{c}c$ and $\bar{b}b$ pairs will be copiously photo-produced at $x_g$ of order of $10^{-5}$ and $10^{-4}$, respectively, and saturation of gluons should manifest itself. Then, there are a number of different photo-production processes (including di-jets etc.) which can be investigated at $\gamma p$ colliders.
3. *eA option*

The main limitation for this option comes from fast emittance growth due to intra-beam scattering. In this case, the use of flat nucleus beams seems to be more advantageous (as in the case of ep option [12]) because of luminosity lifetime increase of few times. Nevertheless, sufficiently high luminosity can be achieved at least for light nuclei. For example, $L_{eC} = 10^{29} \text{cm}^{-2}\text{s}^{-1}$ for collisions of 250 GeV energy electrons beam (Table I) and Carbon beam with and $n_C = 2.5 \cdot 10^9$ (rest of parameters as in Table I). This value corresponds to $L^{int} \cdot A \approx 10^7 \text{pb}^{-1}$ per working year ($10^7 \text{s}$), needed from the physics point of view [13,14].

As mentioned above, the large charge density of nucleus bunch results in strong intra-beam scattering effects and lead to essential reduction of luminosity lifetime ($\approx 1 \text{ h}$ for C beam at HERA). There are two possible solutions of this problem for TESLA⊗HERA. Firstly, one could consider the possibility to re-fill nucleus ring at appropriate rate with necessary modifications of the filling time etc. Alternatively, an effective method of cooling of nucleus beam in main ring should be applied, especially for heavy nuclei. For example, electron cooling of nucleus beams suggested in [15] for eA option of HERA can be used for TESLA⊗HERA, also.

The physics search program of the machine is the direct extension of that for eA option of HERA (see Chapter titled ”Light and Heavy Nuclei in HERA” in [16]).

4. *γA option*

In our opinion this is the most promising option of TESLA⊗HERA complex, because it will give unique opportunity to investigate small $x_g$ region in nuclear medium. Indeed, due to the advantage of the real $\gamma$ spectrum, heavy quarks will be produced via $\gamma g$ fusion at characteristic

$$x_g \approx \frac{4m_{e(b)}^2}{0.9 \times (Z/A) \times s_{ep}}$$

which is approximately $(2 \div 3) \cdot 10^{-5}$ for charmed hadrons.
As in the previous option, sufficiently high luminosity can be achieved at least for light nuclei. The scheme with deflection of electron beam after conversion is preferable because it will give opportunity to avoid limitations from $\Delta Q_A$, especially for heavy nuclei. The dependence of luminosity on the distance between conversion region and interaction point for HERA based $\gamma C$ collider is presented in Figure 4 and $L_{\gamma C} = 0.6 \cdot 10^{29}$ cm$^{-2}$s$^{-1}$ at $z = 5$ m. Let us remind you that an upgrade of the luminosity by a factor 3-4 may be possible by applying a ”dynamic” focusing scheme. Further increase on luminosity will be possible with the cooling of nucleus beam in the main ring. Finally, very forward detector in $\gamma$-beam direction will be very useful for investigation of small $x_g$ region due to registration of charmed and beauty hadrons.

Let us finish this section by quoting the paragraph, written for eA option of the TESLA\$\otimes$HERA complex but more applicable for $\gamma A$ option, from [13]:

"Extension of the $x$-range by two orders of magnitude at TESLA-HERA collider would correspond to an increase of the gluon densities by a factor of 3 for $Q^2 = 10$ GeV$^2$. It will definitely bring quark interactions at this scale into the region where DGLAP will break down. For the gluon-induced interactions it would allow the exploration of a non-DGLAP hard dynamics over two orders of magnitude in $x$ in the kinematics where $\alpha_s$ is small while the fluctuations of parton densities are large."

5. FEL $\gamma A$ option

Colliding of TESLA FEL beam with nucleus bunches from HERA may give a unique possibility to investigate ”old” nuclear phenomena in rather unusual conditions. The main idea is very simple [2,17]: ultra-relativistic ions will see laser photons with energy $\omega_o$ as a beam of photons with energy $2\gamma_A\omega_o$, where $\gamma_A$ is the Lorentz factor of the ion beam. Moreover, since the accelerated nuclei are fully ionized, we will be free from possible background induced by low-shell electrons. For HERA $\gamma_A = (Z/A)\gamma_p \approx 980(Z/A)$, therefore, the region $0.1 \div 10$ MeV, which is matter of interest for nuclear spectroscopy, corresponds to $0.1 \div 10$
keV lasers, which coincide with the energy region of TESLA FEL.

The excited nucleus will return to the ground state at a distance \( l = \gamma_A \cdot \tau_A \cdot c \) from the collision point, where \( \tau_A \) is the lifetime of the exited state in the nucleus rest frame and \( c \) is the speed of light. For example, one has \( l = 4 \) mm for 4438 keV excitation of \(^{12}\text{C}\). Therefore, the detector should be placed close to the collision region. The MeV energy photons emitted in the rest frame of the nucleus will be seen in the detector as high-energy photons with energies up to GeV region.

The huge number of expected events (\( \sim 10^{10} \) per day for 4438 keV excitation of \(^{12}\text{C}\)) and small energy spread of colliding beams (\( \leq 10^{-3} \) for both nucleus and FEL beams) will give opportunity to scan an interesting region with \( \sim 1 \) keV accuracy.

**B. LEP\(\otimes\)LHC**

The interest in this collider, which was widely discussed [18,19] at earlier stages of LHC proposal, has renewed recently [20]:

"We consider the LHC \( e^\pm p \) option to be already part of the LHC programme. The availability of \( e^\pm p \) collisions at an energy roughly four times that provided currently by HERA would allow studies of quark structure down to a size of about \( 10^{-17} \) cm... The discovery of the quark substructure could explain the Problem of Flavour, or one might discover leptoquarks or squarks as resonances in the direct channel..."

1. \( ep \) option

The recent set of parameters is given in a report [21] prepared at the request of the CERN Scientific Policy Committee. With these parameters the estimated luminosity is \( L_{ep} = 1.2 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1} \) and exceeds that of the HERA\(\otimes\)TESLA based \( ep \) collider. However, the latter has the advantage in kinematics because of comparable values of energies of colliding particles. Moreover, \( \gamma p \) collider can not be constructed on the base of LEP\(\otimes\)LHC (for reasons see [10]).
2. $eA$ option

An estimation of the luminosity for $e^\pm Pb$ collisions given in [21] seems to be over-optimistic because of unacceptable value of $\Delta Q_{Pb}$, which is $\sim 70 \cdot 10^{-3}$ for proposed set of parameters. The one order lower value $L_{e-Pb} \approx 10^{28}$ cm$^{-2}$s$^{-1}$ is more realistic. However, situation may be different for light nuclei. Again the main advantage of the TESLA⊗HERA complex in comparison with LEP⊗LHC is $\gamma A$ option.

C. $\mu$⊗TEVATRON

If the main problems (high $\mu-$production rate, fast cooling of $\mu-$beam etc.) facing $\mu^+\mu^-$ proposals are successfully solved, it will also give an opportunity to construct $\mu p$ colliders. Today only very rough estimations of the parameters of these machines can be made. Two sets of parameters for the collider with two rings, TEVATRON and 200 GeV muon ring, are considered in [22]. In our opinion, luminosity values presented in [22] namely, $L_{\mu p} = 1.3 \cdot 10^{31}$cm$^{-2}$s$^{-1}$ are over-optimistic. For comparison, recent set of 200 GeV muon beam parameters [23] leads to estimation $L_{\mu p} = 1.7 \cdot 10^{33}$ cm$^{-2}$s$^{-1}$ (for details see review [3]). Physics search program of this machine is similar to that of the ep option of the TESLA⊗HERA complex.

D. $e$⊗RHIC

Recently, an addition of 10 GeV electron ring or linac to RHIC ring is discussed in order to investigate lepton-nucleus interactions [24]. Luminosity of electron-gold collision for the first case is expected as $6.4(45) \cdot 10^{30}$ cm$^{-2}$s$^{-1}$ with 360 (2520) bunches in each beam. For the second case expected luminosity is $5.6 \cdot 10^{30}$ cm$^{-2}$s$^{-1}$. However, in order to achieve these relatively high values an electron cooling of nucleus beam is needed.

Because of low value of the electron energy, $\gamma$ options with Compton backscattering photons are not sufficiently advantageous. On the other side, FEL $\gamma A$ options are the
matter of interest if the TESLA-like accelerator is chosen as an electron linac. Parameters of the FEL $\gamma$-Th collisions for e-linac$\otimes$RHIC are estimated in [25].

III. SECOND STAGE: LINAC$\otimes$LHC, $\sqrt{S} = 3$ TEV $\mu P$ AND CLIC BASED COLLIDERS

A. Linac$\otimes$LHC

The center-of-mass energies which will be achieved at different options of this machine [26,27] are an order larger than those at HERA are and $\sim$3 times larger than the energy region of TESLA$\otimes$HERA, LEP$\otimes$LHC and $\mu$$\otimes$TEVATRON. Following [4,5] below we consider electron linac with $P_e = 60$ MW and upgraded proton beam from LHC (Table II).

1. $ep$ option

According to parameters given in Table II, center-of-mass energy and luminosity for this option are $\sqrt{s} = 5.29$ TeV and $L_{ep} = 8 \cdot 10^{31}$ cm$^{-2}$s$^{-1}$, respectively, and additional factor 3-4 can be provided by the “dynamic” focusing scheme [6]. Further increasing will require cooling at injector stages.

This machine, which will extend both the $Q^2$-range and $x$-range by more than two order of magnitude comparing to those explored by HERA, has a strong potential for both SM and BSM research.

2. $\gamma p$ option

The advantage in spectrum of back-scattered photons (for details see ref. [7-10]) and sufficiently high luminosity ($L_{\gamma p} > 10^{32}$ cm$^{-2}$s$^{-1}$) will clearly manifest itself in a search for different phenomena. For example, thousands di-jets with $p_t > 500$ GeV and hundreds thousands single W bosons will be produced, hundred millions of $\bar{b}b$- and $\tau c$- pairs will give opportunity to explore the region of extremely small $x_\gamma$ etc [2].
In Fig. 5, the dependence of luminosity on the distance \( z \) between interaction point (IP) and conversion region (CR) is plotted (for \( \gamma \) options we use \( \varepsilon_e = 10^{-6} \) m and \( \beta_{e,x,y} = 0.1 \) m). In Fig. 6, we plot luminosity distribution as a function of \( \gamma p \) invariant mass \( W\gamma_p = 2\sqrt{E_\gamma E_p} \) at \( z = 10 \) m. In Fig. 7, this distribution is given for choice of \( \lambda_e = 0.8 \) and \( \lambda_0 = -1 \) at three different values of the distance between IP and CR.

3. \( eA \) option

In the case of LHC nucleus beam IBS effects in main ring are not crucial because of larger value of \( \gamma_A \). The main principal limitation for heavy nuclei coming from beam-beam tune shift may be weakened using flat beams at collision point. Rough estimations show that \( L_{eA} \cdot A > 10^{31} \) cm\(^{-2}\)s\(^{-1}\) can be achieved at least for light and medium nuclei [26].

4. \( \gamma A \) option

Limitation on luminosity due to beam-beam tune shift is removed in the scheme with deflection of electron beam after conversion. In Fig. 8, the dependence of luminosity on \( z \) is plotted for linac-LHC based \( \gamma - Pb \) collider, where we use \( 10^8 \) for number of lead nuclei per bunch and the rest of parameters are as in Table II.

The physics search potential of this option, as well as that of previous three options, needs more investigations from both particle and nuclear physics viewpoints.

5. FEL \( \gamma A \) option

Due to a larger \( \gamma_A \) the requirement on wavelength of the FEL photons is weaker than in the case of TESLA⊗HERA based FEL \( \gamma A \) collider. Therefore, the possibility of constructing a special FEL for this option may be matter of interest. In any case the realization of FEL \( \gamma A \) colliders depends on the interest of ”traditional” nuclear physics community. The potential of these machine for investigations of Sm excitations is considered in [28].
The possible $\mu p$ collider with $\sqrt{s} = 4$ TeV in the framework of $\mu^+\mu^-$ project was discussed in [29] and again over-estimated value of luminosity, namely, $L_{\mu p} = 3 \cdot 10^{35}$ cm$^{-2}$s$^{-1}$, was considered. Using recent set of parameters [25] for high-energy muon collider with $\sqrt{s} = 3$ TeV, one can easily estimate possible parameters of $\mu p$ collisions from:

$$L_{\mu p} = \frac{n_p}{n_\mu} \cdot \frac{\beta^*_\mu}{\beta^*_p} \cdot \frac{m_\mu}{m_p} \cdot \frac{\varepsilon_\mu^N}{\varepsilon_p^N} \cdot L_{\mu^+\mu^-}$$

With $n_p = n_\mu = 2 \cdot 10^{12}$ we obtain $L_{\mu p} = 10^{32}$ cm$^{-2}$s$^{-1}$ (for details, see [3]).

This machine is comparable with the ep option of the Linac$\otimes$LHC.

### C. CLIC Based Lepton-Hadron and Photon-Hadron Colliders

The CLIC [30], an electron-positron collider with $\sqrt{s} = 3$ TeV and $L_{ee} = 10^{35}$ cm$^{-2}$s$^{-1}$, is considered as one of the future options for post-LHC era at CERN. If a $\sim 5$ GeV proton ring is added at the beginning of positron shoulder of CLIC an opportunity to construct an ep collider with $\sqrt{s} = 3$ TeV and $\gamma p$ collider with $\sqrt{s} \approx 2.8$ TeV will appear. In order to coincide with CLIC parameters we need a proton ring with $\sim 50$ m circumference and repetition frequency $>100$ Hz. The luminosity of ep collisions can be roughly estimated as $L_{ep} \approx (m_e/m_p) \cdot L_{ee} \approx 5 \cdot 10^{31}$ cm$^{-2}$s$^{-1}$ if the parameters of proton beam coincide with those of CLIC positron beam. In principle, this value can be increased by an order of magnitude due to improvement of proton beam parameters. The work on the subject, as well as on $\gamma p, eA, \gamma A$ and FEL $\gamma A$ options is under progress.

### IV. CONCLUSION

It seems that neither HERA nor LHC$\otimes$ LEP will be the end points for lepton-hadron colliders. Linac-ring type ep machines and possibly $\mu p$ colliders will give an opportunity to go far in this direction (see Table III). However, more activity is needed both in accelerator
(further exploration of "dynamic" focusing scheme, a search for effective cooling methods etc.) and physics search program aspects.

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TABLE I. Main parameters of an ep collider based on HERA and TESLA

| Electron beam parameters |            |
|--------------------------|------------|
| Electron energy          | $E_e = 250$ GeV |
| Number of electrons per bunch | $N_e = 2 \cdot 10^{10}$ |
| Bunch length             | $\sigma_{ze} = 0.3$ mm |
| Invariant emittance      | $\varepsilon_e = 100 \cdot 10^{-6}$ m |
| Beta function at IP      | $\beta^e_{x,y} = 0.5$ m |
| Bunch spacing            | 211.37 ns   |
| Number of bunches        | 5264       |
| Repetition rate          | 5 Hz       |
| Beam power               | 22.6 MW    |

| Proton beam parameters   |            |
|--------------------------|------------|
| Proton energy            | $E_p = 1$ GeV |
| Number of protons per bunch | $N_p = 10^{11}$ |
| Number of bunches        | 94         |
| Bunch length             | 10 cm      |
| Beta function at IP      | $\beta^p_{x,y} = 0.1$ m |
| Normalized emittance     | $\varepsilon_p = 1 \cdot 10^{-6}$ m |
| IBS growth time          | $\tau_s = 2.88$ h, $\tau_x = 2$ h |
# TABLE II. Main parameters of an ep collider based on LHC and e-linac

| Electron beam parameters | Proton beam parameters |
|--------------------------|------------------------|
| **Electron energy** | **Proton energy** | $E_e = 1$ TeV | $E_p = 7$ GeV |
| **Number of electrons per bunch** | **Number of protons per bunch** | $N_e = 7 \cdot 10^9$ | $N_p = 4 \cdot 10^{11}$ |
| **Bunch length** | **Number of bunches** | $\sigma_{ze} = 1$ mm | 700 |
| **Invariant emittance** | **Bunch length** | $\varepsilon_e = 10^{-6}$ m | 7.5 cm |
| **Beta function at IP** | **Beta function at IP** | $\beta_{e,x,y}^e = 0.2$ m | $\beta_{p,x,y}^p = 0.1$ m |
| **Bunch spacing** | **Normalized emittance** | 100 ns | $\varepsilon_p = 0.8 \cdot 10^{-6}$ m |
| **Number of bunches** | **IBS growth time** | 5000 | $\tau_s = 2.5$ h, $\tau_x = 5.2$ h |
TABLE III. Future lepton-hadron colliders:

a) First stage (2010-2015)

|                     | TESLA⊗HERA | LEP⊗LHC | μ⊗TEVATRON | e⊗RHIC |
|---------------------|------------|---------|------------|--------|
| $\sqrt{s}$, TeV     | 1.0→1.6    | 1.37    | 0.89       | 0.1    |
| $E_l$, TeV          | 0.25→0.8   | 0.0673  | 0.2        | 0.01   |
| $E_p$, TeV          | 1          | 7       | 1          | 0.25   |
| $L$, 10$^{31}$ cm$^{-2}$s$^{-1}$ | 1-10       | 12      | 1-10       | 46     |
| Main limitations    | $P_e, \varepsilon_p, \beta_p^*$ | $\Delta Q_e, \Delta Q_p$ | $n_\mu, \varepsilon_\mu, \Delta Q_p, \varepsilon_p, \beta_p^*$ |
| Additional options  | $eA, \gamma_p, \gamma A, FEL\gamma A$ | $eA$ | $\mu A(?)$ | $eA, FEL\gamma A$ |

b) Second stage (2015-2020) and third (>2020) stages

|                     | Linac⊗LHC | $\mu p$ | CLIC based |
|---------------------|-----------|---------|------------|
| $\sqrt{s}$, TeV     | 5.29      | 3       | 3          |
| $E_l$, TeV          | 1         | 1.5     | 1.5        |
| $E_p$, TeV          | 7         | 1.5     | 1.5        |
| $L$, 10$^{31}$ cm$^{-2}$s$^{-1}$ | 10-100    | 10-100  | 10         |
| Options             | $eA, \gamma_p, \gamma A, FEL\gamma A$ | $\mu A(?)$ | $eA, \gamma_p, \gamma A, FEL\gamma A$ |
FIGURE CAPTIONS

Fig. 1. Luminosity dependence on distance $z$ for the TESLA⊗HERA based $\gamma p$ collider.

Fig. 2. Luminosity distribution as a function of $\gamma p$ invariant mass at $z = 10$ m for the TESLA⊗HERA based $\gamma p$ collider.

Fig. 3. Luminosity distribution as a function of $\gamma p$ invariant mass for $\lambda_e\lambda_0 = -0.8$ at three different values of distance $z$ for the TESLA⊗HERA based $\gamma p$ collider.

Fig. 4. Luminosity dependence on distance for the TESLA⊗HERA based $\gamma C$ collider.

Fig. 5. Luminosity dependence on distance $z$ for the Linac⊗LHC based $\gamma p$ collider.

Fig. 6. Luminosity distribution as a function of $\gamma p$ invariant mass at $z = 10$ m for the Linac⊗LHC based $\gamma p$ collider.

Fig. 7. Luminosity distribution as a function of $\gamma p$ invariant mass for $\lambda_e\lambda_0 = -0.8$ at three different values of distance $z$ for the Linac⊗LHC based $\gamma p$ collider.

Fig. 8. Luminosity dependence on distance $z$ for the Linac⊗LHC based $\gamma Pb$ collider.
