Proton-ring and Electron-linac Collider (PRELC) as a (first) TeV-range electron-proton or photon-proton collider

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The use of the existing proton storage rings combined with electron linear accelerator as a ring-linac type electron-proton or photon-proton collider is investigated. The total CM-energy of Proton-ring and Electron-linac Collider (PRELC) is in the range of 1.0 TeV. The most important physical issues are listed and the most critical machine aspects of the PRELC are studied. It is shown that the luminosities in the range of \(10^{31}\) to \(10^{32}\) could be achieved. The PRELC could be used simultaneously with the \(e^+e^-\)-collider if the refocused electron beam could be used as the electron beam for the PRELC.

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The verification of the quark-parton model has been one of the successes of the \(e^-p^+\)-collisions. The energy limitations of the fixed-target experiments and the results of HERA \([1]\) electron-proton collider have generally increased the interest to the electron-proton colliders. Due to the energy losses caused by synchrotron radiation at electron rings the future of storage ring type electron-proton colliders seems to be unrealistic and therefore one must consider ring-linac type colliders \([2,3,4,5,6,7]\) as an option. Furthermore, the PRELC (Proton-ring and electron-linac Collider) also offers us the option to have TeV range photon-proton collisions \([3,4]\). The high energy photon beam is produced by the Compton backscattering of laser photons off the high energy electron beam.

In this paper the possibility to construct electron-proton or photon-proton collider using the existing proton collider rings with linear accelerator of the proposed \(e^-e^+\) linear colliders is investigated. Studying the most critical machine aspects for this kind of ring-linac colliders we have been able to outline very robust and general principles for a realistic design proposal for the PRELC. Four different types of PRELC are presented, where the existing proton storage ring or the extracted proton beam from this ring is combined with the electron beam the \(e^-e^+\)-collider or combined with the photon beam (Compton backscattered laser beam). The possible options for the PRELC are shown in Table I and the most crucial machine parameters for two options are listed in Table II. The schematic view of PRELC is presented in Fig. 1. We also outline the most important physical issues which can be studied at the PRELC (see Tables III and IV).

From the machine point of view one has four different collider options at the PRELC: two different machine layouts for electrons and photons. One could collide the circulating proton beams with beams from the linac or one could arrange collisions between the extracted proton beams and beams from the linac. The first option is limited by the proton ring lattice and the beam characteristics of the proton ring (e.g. proton beam emittance, properties of proton ring lattice, etc.). For both options the luminosity of the collider is:

\[
\mathcal{L} = \frac{N_pN_e f}{4\pi\sigma_x\sigma_y} \times \epsilon, \tag{1}
\]

where \(\sigma_x = \max(\sigma_x^p, \sigma_x^e)\), \(\sigma_y = \max(\sigma_y^p, \sigma_y^e)\), \(f = \min(f_e, f_p)\) and \(\epsilon\) is the 'efficiency' of the collider. For simplicity we assume \(\epsilon = 1.0\) except when the proton and electron (photon) beam cross-sections are very unequal in size reflecting the higher particle densities (gaussian) in the central regions of the particle bunches, in which case we take \(\epsilon = 2.0\). The possible options for the PRELC are given in Table I (see also Fig. 2).

In the case of the circulating proton beam the luminosity is limited by the proton beam characteristics, namely, by the proton beam spotsize (see Table III). Furthermore, the optimal frequency matching is not very easy at circulating proton beam option since the particle bunch intervals of the proton rings and electron linacs do not match (see Table III). Using the 'design' values for both proton and electron beams (given in the Refs. \([8,9]\)) the maximum luminosity would be between \(1.0 \ldots 3 \times 10^{38} \text{ s}^{-1}\text{cm}^{-2}\) and \(4.0 \ldots 8 \times 10^{29} \text{ s}^{-1}\text{cm}^{-2}\) for different PRELC 'proposals'.

Of course one can change some of the beam characteristics, like the beam emittances, by building new modern injectors to the existing storage rings or by rebuilding (completely or partially) the proton ring lattice. The problem is that these changes could be quite expensive and furthermore, in the first case it might not be enough to lower the emittance of the injected beam since the characteristic values of the beams at the storage rings have the tendency to move towards the ones determined by the ring lattice.

We can study the effects of these small modifications to the proton beam and the proton ring lattice using the formula for the beam size \(\sigma_{x(y)} = \sqrt{\varepsilon_{x(y)} \times \beta_0 x(y)}\), where \(\varepsilon_{x(y)}\)
is the emittance and the $\beta_0$ is the focal point value of the magnetic $\beta$-function, at the interaction point. If we can change the normalized emittance $\varepsilon_N = \frac{N}{\beta_0} \varepsilon$ of the proton beam to $\varepsilon_N = 1.0 \times 10^{-6} \pi$ rad-m, design value of SSC [8], the luminosity of the PRELC will increase by a factor of 5...9, depending on the design option. The maximum luminosity would be between $1 \ldots 3 \times 10^{29} \text{s}^{-1} \text{cm}^{-2} \text{cm}^{-1}$ and $2 \ldots 4 \times 10^{30} \text{s}^{-1} \text{cm}^{-1}$. One could also change the value of the magnetic $\beta$-function at the interaction point and one should realistically be able to gain additional factor of 2...5 which would increase the luminosity of the PRELC maximally to the level of $10^{31} \text{s}^{-1} \text{cm}^{-1}$.

In the case of the extracted proton beam the proton ring lattice limitations do not play a big role, since the proton beam need not be stable after the collision. This recirculation means that $N$ order of $10^{32}$ change the normalized emittance $\varepsilon$ of the proton beam to $\varepsilon_N = 1.0 \times 10^{-6} \pi$ rad-m, design value of SSC [8], the luminosity of the PRELC will increase by a factor of 5...9, depending on the design option. The maximum luminosity would be between $1 \ldots 3 \times 10^{29} \text{s}^{-1} \text{cm}^{-2} \text{cm}^{-1}$ and $2 \ldots 4 \times 10^{30} \text{s}^{-1} \text{cm}^{-1}$. One could also change the value of the magnetic $\beta$-function at the interaction point and one should realistically be able to gain additional factor of 2...5 which would increase the luminosity of the PRELC maximally to the level of $10^{31} \text{s}^{-1} \text{cm}^{-1}$.

For example using values $\varepsilon = 1.0 \times 10^{-6} \pi$ rad-m and $\beta_0 = 0.1$ m at the TEVATRON-TELESA option the luminosity of the PRELC would be $\mathcal{L} \approx 1.0 \times 10^{34} \text{s}^{-1} \text{cm}^{-1}$. In order to reach the luminosities of the order of $10^{32} \text{s}^{-1} \text{cm}^{-1}$ one must really try to 'fine-tune' the proton beam characteristic values (e.g. the proton bunches must be made shorter, more intense etc.), which seems to be quite expensive and difficult.

All the results presented above apply to the electron-proton collider options as well as to the photon-proton collider option. In the photon-proton collider option the photon beam is obtained by Compton backscattering of laser beam off the high energy electron beam. The electron beam conversion to photon beam is very efficient (≈ 100%), i.e. the conversion coefficient is 1.0, which means that $N_\gamma = N_{e-}$.

One very interesting possibility is to use a spent and refocused beam (recirculated beam) of the $e^+ e^-$-collider as an electron beam for the PRELC. This recirculation scheme is possible for the TESLA $e^+ e^-$ linear collider [10]. Actually, it does not matter if the characteristic values (e.g., emittance, etc.) of the electron beam are worse after the refocusing process since the spotsize is determined by the proton beam spotsize at the collision point. This option makes possible to use the PRELC and $e^+ e^-$-collider simultaneously, especially, for the photon-proton collider this seems to be very interesting option.

A typical reaction in the electron-proton collider is $e^- p^+ \rightarrow \ell + X$, where $\ell$ can be either charged lepton or neutrino and $X$ is some specified final state. The kinematics of such event is described by following equations:

$$Q^2 = -q^2 \approx 4 E_e E_p \sin^2 \left(\frac{9}{2} \theta\ell\right),$$

$$\gamma_{CM} = \frac{E_e + E_p}{\sqrt{E_e E_p}} = \left\{ \frac{\sqrt{E_e E_p} + \sqrt{E_e^2 + E_p^2}}{\sqrt{E_e^2 + E_p^2}} \right\},$$

$$m_p\nu = p_p \cdot q \approx 2E_p \left[ E_e - E_\ell \cos(\theta \ell) \right],$$

$$x = \frac{Q^2}{2p_p q} \approx \frac{E_e E_p \sin^2 \left(\frac{9}{2} \theta\ell\right)}{E_p \left[ E_e - E_\ell \cos(\theta \ell) \right]}. \quad (2)$$

where $s \approx 4E_e E_p$ and $\theta\ell$ is the lepton scattering angle. The Bjørken variable $x$ obeys $0 \geq x \geq 1$. If $E_p > E_e$, then the CM frame is moving to the direction of proton beam, and in the opposite case to the direction of electron beam. Using the fact that in CM-frame $Q^2 \approx (s - m_X^2) \sin^2 \left(\frac{9}{2} \theta\ell\right)$ the equations for maximum and minimum values are: $Q^2_{max} \approx s - m_X^2$ and $Q^2_{min} \approx 0$. Solving the equations in (3) one obtains the following equations:

$$\theta\ell = 2 \times \arctan \left\{ \pm \sqrt{\frac{x E_p Q^2}{E_p (x s - Q^2)} \right\}, \quad (3)$$

$$x \geq \frac{Q^2}{s}. \quad (4)$$

The equation (4) together with the minimal observable momentum transfer determines the lowest possible $x$ which can be studied at the $e^- p^+$-colliders. For example the smallest $x$ value at the TEVATRON-TELESA option is $x \geq 1.1 \times 10^{-5}$ ($Q^2 \geq 10 \text{GeV}^2$).

The quark, antiquark and gluon energies $E_j^i (j = q, \bar{q}, \text{and } g)$ of the proton are given by $E_j^i = x_j^i E_p$ ($i = 1, \ldots$), and hence the actual reaction energy is $\sqrt{s}$, where $s = x_j^i s$. The total reaction energies for different PRELC design options and actual reaction energies for TEVATRON-TELESA PRELC are shown in Figs. 3 and 4. The quark and gluon distributions are calculated using the PDFLIB program [4].

In the Table [4] we have listed some interesting physical issues for TeV-range electron-proton collider (for a more general review see Refs. [2,3] and the corresponding ones for the TEVATRON-TELESA option are presented in Table [3] (see also Ref. [3]). Using the probability distributions shown in Figs. 3 and 4 one can study the possible reactions (e.g. which reactions are possible for certain values of $Q^2$, etc.) and some physical properties of more specified reactions, for example, the quark contributions to the reaction $e^- p^+ \rightarrow \nu_e + n$ at very high energies.

The remarkable feature of the PRELC is that the electron-proton (photon-proton) collisions are not very asymmetric contrary to HERA (see Table [3]). This means that the CM-frame is not moving so fast in the laboratory frame ($1.04 < \gamma_{CM} < 1.67$), which makes the experimental setup more flexible than it is at HERA.

In conclusion we have shown that the ring-linac type $e^- p^+$-colliders will give us a unique and exciting opportunity to study (with reasonably high luminosities) TeV-scale physics phenomena together with the future
electron-positron linear accelerators and large hadron colliders. In addition, there are many physical processes which can only (or better) be studied in $e^{-}p^{+}$ or $\gamma p^{+}$-collisions, such as the proton and photon structure functions at very small $x$, and the existence of leptoquarks and excited leptons. In general the proposed options for the ring-linac type electron-proton or photon-proton colliders should be investigated properly and one should study the possibilities to build these types of PRELC’s in the near future.

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[1] The $e^{-}p$ storage ring HERA at DESY, Hamburg, Germany.
[2] P.L. Csonka and J. Rees, Nucl. Inst. Meth. 96 (1971) 149.
[3] S.I. Alekhin et al., Report No. IHEP 87-48 (1987); Z.Z. Aydin et al., in Proc. 27th International Conference on High Energy Physics, (Glasgow, Scotland, July 20-27, 1994), (to appear).
[4] P. Grosse Wiesmann, in Proceedings of European Workshop on Hadronic Physics with Electrons beyond 10 GeV, Nucl. Phys. A532, 545 (1991); P. Grosse Wiesmann et al., Report No. CERN-PPE/90-113 (1990); P. Grosse Wiesmann, Report No. CERN-PPE/91-96 (1991); S.F. Sultansoy, Turkish J. Phys. 17 (1993) 591; S.F. Sultansoy, in Proc. 27th International Conference on High Energy Physics, (Glasgow, Scotland, July 20-27, 1994), (to appear).
[5] S.I. Alekhin et al., Report No. IHEP 88-94 (1988); S.F. Sultansoy, Report No. IC/89/409 (1989); Z.Z. Aydin em et al., Report No. AU-94-05-HEP (1994).
[6] Z.Z. Aydin et al., in Proc. 27th International Conference on High Energy Physics, (Glasgow, Scotland, July 20-27, 1994), (to appear), and references therein.
[7] R. Keränen, J. Pennanen and R. Vuopionperä, Phys. Rev. D48, 4852 (1992).
[8] Review of Particle Properties, Part I, Phys. Rev. D50, 1246-1250 (1994), eds. L. S. Brown et al.
[9] G. Loew, in Proc. 5th International Workshop on Next-Generation Linear Colliders, (Stanford, California, October 13-21, 1993), Report No. SLAC-436, p. 460.
[10] P. Emma, in Proc. 5th International Workshop on Next-Generation Linear Colliders, (Stanford, California, October 13-21, 1993), Report No. SLAC-436, p. 371.
[11] H. Plothow-Besch, Comp. Phys. Comm. 75, 396 (1993).
[12] Ch. Berger et al., in Proc. Workshop on Physics at HERA, Vol. II, (Hamburg, Germany, October 29-30, 1991), eds. W. Buchmüller and G. Ingelman, p. 1029, and references therein.
[13] R. Rückl, in Proc. Large Hadron Collider Workshop, Vol. I, (Aachen, Germany, October 4-9, 1990), eds. G. Jarlskog and D. Rein, p. 229, and references therein.

### Table I

| Option                               | $E_{p}$ [GeV] | $\sqrt{s}$ [GeV] | $\gamma_{CM}$ |
|--------------------------------------|---------------|------------------|---------------|
| HERA(p)+HERA(e) (30)                 | 820.0         | 313.7            | 2.70970       |
| SPS+LEP50                           | 450.0         | 300.0            | 1.66667       |
| SPS+LEP90                           | 450.0         | 402.5            | 1.34164       |
| SPS+LINAC250                        | 450.0         | 670.8            | 1.04350       |
| HERA(p)+LINAC100                    | 820.0         | 572.7            | 1.60639       |
| HERA(p)+LINAC250                    | 820.0         | 905.5            | 1.18162       |
| TEVATRON+LINAC100                   | 900.0         | 600.0            | 1.66667       |
| TEVATRON+LINAC250                   | 900.0         | 948.7            | 1.21221       |
| DI-TEVATRON+LINAC100                | 1800.0        | 848.5            | 2.23917       |
| DI-TEVATRON+LINAC250                | 1800.0        | 1341.6           | 1.52798       |

### Table II

| $N_{e}/N_{e} \times 10^{10}$ | $f_{e}/f_{e}$ [kHz] | $\sigma_{p}^{e}/\sigma_{p}^{\mu}$ | $\sigma_{p}^{\mu}/\sigma_{p}^{e}$ | $\mu_{p}/\mu_{e}$ | $\gamma$ (s/cm$^{-1}$) |
|-------------------------------|----------------------|-----------------------------------|-----------------------------------|-------------------|-------------------------|
| 15/5/15 (a)                   | 286/8/8              | 36/1.0/36                         | 16/0.0/36                         | 56/0.6/36         | 76.0 $\times 10^{28}$   |
| 10/5/15 (b)                   | 10417/8/8            | 265/1.0/265                       | 84/0.0/84                         | 3.0 $\times 10^{28}$|

### Table III

| Physical Issue                                                                 | Description                                                                 |
|-------------------------------------------------------------------------------|-----------------------------------------------------------------------------|
| **Beyond SM**                                                                 | Extended models : New currents and gauge bosons.                             |
| Supersymmetry : First generation of superpartners                               | Compositeness : Excited fermions and bosons, leptoquarks and leptogluons.  |
|                                                                                   | Standard Model                                                               |
| Real photoproduction of : elementary particles, heavy quarks, $W^{\pm}$ and $Z^{0}$. | Strong interactions : Parton distributions of proton and photon.            |
| EW interactions : Total cross-sections of $\gamma p^{+}$ interactions.          |                                                                            |

### Table IV

The same as Table III but for photon-proton collider.
FIG. 1. Schematic view of proton-ring and electron-linac collider.

FIG. 2. Possible values of total $\sqrt{s}$ of the proton-ring and electron-linac collider.

FIG. 3. Probability distributions for different types of reactions for the momentum transfer $Q^2 = 10^4$ GeV$^2$.

FIG. 4. Same as Fig. 3 but for $Q^2 = 10^5$ GeV$^2$. 
This figure "fig1-1.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9411242v1
FIG. 1. Schematic view of proton-ring and electron-linac collider.

FIG. 2. Possible values of total $\sqrt{s}$ of the proton-ring and electron-linac collider.

FIG. 3. Probability distributions for different types of reactions for the momentum transfer $Q^2 = 10^3$ GeV$^2$.

FIG. 4. Same as Fig. 3 but for $Q^2 = 10^5$ GeV$^2$. 