Review of Linac-Ring Type Collider Proposals

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There are three possibly types of particle colliders schemes: familiar (well known) ring-ring colliders, less familiar however sufficiently advanced linear colliders and less familiar and less advanced linac-ring type colliders. The aim of this paper is two-fold: to present possibly complete list of papers on linac-ring type collider proposals and to emphasize the role of linac-ring type machines for future HEP research.

1. Introduction

Today, experimental high energy physics deal with three kind of devices, namely, fixed target experiments (using both accelerator and cosmic rays), collider experiments and others (including underground detectors and so on).

Collider experiments could be classified in two manners: keeping in mind accelerator types or colliding beams. Concerning the first classification there are three possible types, namely, ring-ring, linac-linac and linac-ring colliders. Second classification includes three types, too: hadron, lepton and lepton-hadron colliders. With regard to energy frontiers ring-ring corresponds to hadron collisions, linac-linac corresponds to lepton collisions and linac-ring corresponds to lepton-hadron collisions (see Table 1 and Figure

(1)
1). Ring-ring colliders are the most advanced ones from accelerator technology viewpoint and widespread around the (developed) world. Linear (linac-linac) colliders are less familiar, however, a lot of experience is handled through SLC operation and ILC/CLIC related workout.

| Colliders | Hadron | Lepton | Lepton-Hadron |
|-----------|--------|--------|---------------|
| 1990’s    | Tevatron | SLC/LEP | HERA          |
| $\sqrt{s}$ (TeV) | 2       | 0.1/0.2 | 0.3           |
| $L \left(10^{34} \text{ cm}^{-2}\text{s}^{-1}\right)$ | 1       | 0.1/1   | 1             |
| 2010’s    | LHC    | "NLC"  | "NLC"-LHC    |
| $\sqrt{s}$ (TeV) | 14      | 0.5     | 3.7           |
| $L \left(10^{34} \text{ cm}^{-2}\text{s}^{-1}\right)$ | $10^4$  | $10^4$  | $1 \div 10$  |
| 2020’s    | VLHC   | CLIC   | "CLIC"-VLHC  |
| $\sqrt{s}$ (TeV) | 200     | 3       | 34            |
| $L \left(10^{34} \text{ cm}^{-2}\text{s}^{-1}\right)$ | $10^3$  | $10^3$  | $10 \div 100$ |

Forty years ago John Rees proposed to collide 20 GeV SLAC electron beam with 3 GeV stored positrons [2] to handle 15.5 GeV center-of-mass energy electron-positron collisions with a luminosity of $5 \times 10^{29} \text{ cm}^{-2}\text{s}^{-1}$. Two years later this proposal reconsidered in [3] keeping in mind 2 GeV stored electrons (or positrons) which corresponds to 12.6 GeV center-of-mass energy with a luminosity of $2.4 \times 10^{29} \text{ cm}^{-2}\text{s}^{-1}$. Both proposals were considered as possible upgrades of SLAC accelerator [4]. During following fifteen years only one paper is published on the subject [5]. The reason was choosing a linear collider option for SLAC upgrade: the Stanford Linear Collider (SLC) construction began in 1983 and was completed in 1989. In 1979 linac-ring scheme was considered in short as an alternative option for SSC based ring-ring type 140 GeV + 20 TeV electron-proton collider [6] (see also [7]).

The idea was reborn in the mid of 1980’s in order to combine linear electron-positron and ring type proton colliders had to realize additional TeV scale lepton-hadron collider option. Namely, it was proposed to construct VLEPP tangentially to UNK [8]. This scheme will provide an opportunity to handle TeV scale $\gamma p$ colliders, too [9]. This line was go on by THERA, EIC/EPIC and QCD-E/LHeC projects (for references see corresponding sections below). An important stage in this direction was provided by the International Workshop held in Ankara in 1997 [10]. There are a number of reviews on the subject [11, 12, 13, 14, 15, 1].

Another line deals with particle factories (see Figure 2): in 1988 Grosse-
Wiesmann proposed linac-ring type B-factory [16, 17, 18, 19]. In 1993 linac-ring type charm-tau factory had proposed as the regional project for Turkey and abroad [20]. The last stage of this line is represented by Super Charm Factory as the part of the Turkic Accelerator Complex (TAC) Project [21].

The content of the review is following. In section 2, main parameters of linac-ring type lepton-hadron collider proposals are considered, namely, UNK+VLEPP, THERA, eRHIC, EIC, QCD Explorer (LHeC linac-ring option) and Energy Frontier. Photon-Hadron colliders would be constructed on the base of these colliders are considered in section 3. Section 4 is devoted to linac-ring type particle factory proposals. Finally, in section 5 some concluding remarks and recommendations are presented.
2. Lepton-Hadron Colliders

There are a number of reasons [22, 12] 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 traveling wave structures can accelerate only in one direction.

The most transparent expression for the luminosity of linac-ring type ep colliders is [12]:

\[
L_{ep} = \frac{1}{4\pi} \frac{P_e}{E_o} \frac{N_p \gamma_p}{\beta_p^*} 
\]

(1)

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 [23], where the proton bunch waist travel with electron bunch
During collision, $\beta_p^*$ is limited, in principle, by the electron bunch length, which is two orders of magnitude smaller. More conservatively, an upgrade of the luminosity by a factor 3-4 may be possible.

2.1. UNK+VLEPP (IHEP, Protvino)

In 1980’s there were two energy frontier collider projects in the former USSR, namely, $\sqrt{s} = 6$ TeV proton-proton collider UNK and $\sqrt{s} = 2$ TeV linear electron-positron collider VLEPP. The construction of the first one was started at IHEP (Protvino, Moscow region), and the second one was planned at BINP (Novosibirsk). In mid 1980’s the construction of VLEPP tangential to UNK was proposed in order to provide additional opportunity to handle energy frontier ep and $\gamma p$ colliders.

Luminosity estimations were given in [11]. Brief resume is followed. Two versions of placement of VLEPP regarding to UNK are possible, namely symmetric (Figure 3a) and asymmetric (Figure 3b). Two options of ep and $\gamma p$ collisions were considered for the UNK+VLEPP: on extracted proton beam (Figure 4a) or in proton ring (Figure 4b). It was shown that $L = 10^{30}$ cm$^{-2}$s$^{-1}$ and $L = 6 \times 10^{30}$ cm$^{-2}$s$^{-1}$ could be achievable for first and second option, respectively.

Note that this consideration was the main scientific reason for moving of VLEPP from Novosibirsk to Protvino. Unfortunately, in final design
VLEPP placement was chosen to cross the UNK ring, instead of tangential. Obviously, this choice closed ep and γp options (clear indication of collapse of Eastern Block).

The status of ep collider proposals in the end of 1990’s is presented in Table 2 (the consideration of the LHC+CLIC and SSC+LSC proposals was initiated by the A. Salam).

Table 2. Planned and possible ep colliders (as for 1989 [11])

| Machine                  | √s (TeV) | E_e (TeV) | E_p (TeV) | n_e (10^10) | n_p (10^10) | Coll. rate (f(Hz)) | L (10^30 cm^-2 s^-1) |
|-------------------------|----------|-----------|-----------|--------------|--------------|-------------------|---------------------|
| Standart ep machines    |          |           |           |              |              |                   |                     |
| HERA                    | 0.3      | 0.03      | 0.82      | 3.48         | 10           | 10^7              | 15                  |
| LHC+LEPI                | 1.3      | 0.05      | 8         | 8.2          | 30           | 5 x 10^6          | 200                 |
| LHC+LEPPI               | 1.8      | 0.1       | 8         | 8.2          | 30           | 5 x 10^6          | 10                  |
| UNK+e-ring              | 0.6      | 0.03      | 3         | -            | -            | -                 | 100                 |
| SSC+e-ring              | 2.8      | 0.1       | 20        | -            | -            | -                 | 100                 |
| New type ep machines^1  |          |           |           |              |              |                   |                     |
| UNK+VLEPP               | 2.4      | 0.5       | 3         | 20           | 100          | 100               | 1 + 10              |
| UNK+VLEPPII             | 3.5      | 1         | 3         | 20           | 100          | 100               | 1 + 10              |
| UNK+VLEPP^2             | 4.9      | 2         | 3         | 20           | 100          | 100               | 1 + 10              |
| LHC+CLIC^2              | 8        | 2         | 8         | 0.5          | 100          | 6 x 10^3          | 10 + 100            |
| LHC+CLIC^3              | 4.8      | 0.7       | 8         | 0.6          | 100          | 10^4              | 10 + 100            |
| SSC+LSC^2               | 28       | 10        | 20        | 0.08         | 100          | 8 x 10^4          | 100                 |
| LHC+e−linac^4           | 3        | 0.3       | 8         | 0.08         | 100          | 5 x 10^5          | 5 x 10^4            |
| SSC+e−linac^4           | 8        | 0.8       | 20        | 0.05         | 100          | 5 x 10^5          | 10^4                |
| Electron-proton linacs^5 |          |           |           |              |              |                   |                     |
| VLEPP+p10               | 2        | 1         | 1         | 20           | 20           | 100               | 1 + 10              |
| LSC+p10                 | 10       | 5         | 5         | 0.08         | 0.08         | 8 x 10^4          | 100                 |

^1Given parameters corresponds to ep collisions in the proton ring
^2asymmetric version (see Figure 3b)
^3ep version of Linac-LEP Collider with √s = 0.5 TeV proposed by C. Rubbia (see Ref 24)
^4P. Grosse-Wiesmann’s proposal: electron linacs parameters are optimized for ep collisions (see Ref 16)
^5One shoulder of the e^+e^- linac can be used for acceleration of protons, if 10 GeV proton ring will be added at its beginning.
2.2. THERA (DESY)

THERA activity had been initiated since 1996 by B. Wiik and S. Sultansoy [25]. A lot of work was down in 1999-2000 during preparation of the TESLA TDR, which include THERA [26] as inseparable part together with photon collider and fixed target options. Moreover, the THERA provided the main scientific reason for moving of TESLA from Zeuthen to Hamburg. Results of this two years study are published in the THERA Book [27]. Concerning beam energies and corresponding luminosities 3 alternatives were analyzed (see Table 3).

Table 3. THERA beam energies and luminosities

| Option | $E_{e}$, GeV | $E_{p}$, GeV | $\sqrt{s}$, TeV | L, $10^{30} cm^{-2}s^{-1}$ |
|--------|--------------|--------------|-----------------|---------------------------|
| 1      | 250          | 1000         | 1               | 4                         |
| 2      | 500          | 500          | 1               | 25                        |
| 3      | 800          | 800          | 1.6             | 16                        |

Unfortunately, the THERA paper [28] were submitted to LANL archive with wrong information (TESLA-N Study Group instead of THERA Working Group) and were not submitted for publication to journal. This event resulted in practical zero citation comparing with TESLA photon collider paper [29] with more than 160 citations.

2.3. EIC (USA)

The Electron-Ion Collider (EIC) is the proposed new facility to collide high-energy electrons with nuclei and polarized protons/light nuclei [30, 31] and refs therein). Two broad classes of goals of the future EIC are reflected in two physics working groups (WG) of the EIC collaboration: the eA WG concentrates on exploring the (strong) gluon fields in nuclei, and the ep WG focuses on the precision imaging of quarks and gluons in the nucleon.

The original design of the EIC involves two concepts: eRHIC on the base of RHIC (see Figure 5), where an additional energy recovering linac has to added, and ELIC at Jefferson Lab (see Figure 6), which requires a construction of a new hadron facility to be used with the existing CEBAF. The eRHIC concept allows for larger $\sqrt{s} = 60$-$90$ GeV and smaller luminosity $L \approx 10^{35} cm^{-2}s^{-1}$, while the ELIC concept corresponds to smaller $\sqrt{s} \leq 60$ GeV and larger luminosity $L \approx 10^{35} cm^{-2}s^{-1}$.

For more details see EIC, eRHIC and ELIC web pages [33, 34, 35].
Fig. 5. ERL-based eRHIC design [32].

Fig. 6. Schematic layout of ELIC at Jefferson Laboratory [35].
2.4. QCD Explorer (LHeC linac-ring option, CERN)

QCD Explorer means to construct a moderate energy electron LINAC (50-100 GeV) tangentially to LHC Ring. This construction will provide opportunity to utilize highest energy hadron beams for lepton-hadron collisions. QCD Explorer has two main goals:

* to get more precision data on PDF’s which will be necessary for adequate interpretation for future LHC data
* to enlighten fundamentals of QCD

For this purpose, the technologies for electron-positron colliders, which have developed up today can be used or new technologies can be created.

2.4.1. CLIC Based

In this case main problem is occurred by drastically different beam structure: bunch spacing of LHC is 25 ns comparing with 0.6 ns at CLIC. So that using CLIC bunches shall have a ratio 1/40. This problem can be solved by changing beam structure of the LHC or CLIC or both. Super bunch option was proposed for LHC based ep collider in [36, 37] and \( L = 10^{31} \text{ cm}^{-2}\text{s}^{-1} \) can be handled by this way.

2.4.2. ILC (TESLA) Based

This option has advantages compare to CLIC; bunch spacing is larger so that it is more suitable for matching with LHC hadron beam. Estimations show that \( L = 10^{32} \text{ cm}^{-2}\text{s}^{-1} \) can be handled [38, 39].

2.4.3. Special e-linac

In the last two years this option is preferred keeping in mind pulsed mode, CW mode and energy recovery linac. Figure 7 shows different scenarios for the LHC based linac-ring type ep collider. Luminosity up to \( 3 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \) could be achieved with pulsed or cw linacs [40]. If energy recovery is used, the luminosity gain depend on recovery efficiency. 90 % recovery efficiency results in \( L = 3 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} \) (if recovery reach 98 % luminosity exceed \( 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)).

2.5. Energy Frontier (CERN)

If \( E_c \geq 500 \text{ GeV} \) LHC based ep colliders is named as Energy Frontier. These high energies are suspicion to use energy recovery. Nevertheless \( L = 10^{32} \text{ cm}^{-2}\text{s}^{-1} \) seem to be achievable with pulsed linac [41]. It is useful to compare physics search potential of three colliders which can be considered as energy frontiers in foreseen future. Namely,

\[ \sqrt{s} = 14 \text{ TeV pp collider with } L = 10^{34} \text{ cm}^{-2}\text{s}^{-1} \text{ (LHC)} \]
$\sqrt{s} = 0.5$ TeV $e^+e^-$ collider with $L = 10^{34}$ $cm^{-2}s^{-1}$ (ILC)
$\sqrt{s} = 3.7$ TeV ep collider with $L = 10^{32}$ $cm^{-2}s^{-1}$ ("ILC" x LHC)

Rough estimations [14] show that the total capacity of ep and $\gamma p$ options for BSM physics (SUSY, compositness etc) research essentially exceeds that of 0.5 TeV linear collider.

3. Photon-Hadron Colliders

In 1980’s, 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 review [43] and references therein). Then the same method was proposed for constructing $\gamma p$ colliders on the base of linac-ring type ep machines in [9]. Rough estimations of the main parameters of $\gamma p$ collisions are given in [11]. The dependence of these parameters on the distance between conversion region (CR) and interaction point (IP) was analyzed in [42], where some design problems were considered.

It should be noted that $\gamma p$ colliders are unique feature of linac-ring type ep colliders and could not be constructed on the base of standard ring-ring type ep machines (for arguments see [11, 42]).

This type colliders aren’t familiar, so that include many unsolved technical problems. These problems look like to $\gamma e$ colliders (see review [43] and references therein). Many studies are completed about $\gamma e$ colliders and many solutions are proposed about technical problems, which can be applicable for $\gamma p$ colliders, too. The last ones have advantage compare to $\gamma e$ colliders. This advantage is the distance between CR and IP [see Figure 8]. In $\gamma e$ colliders this distance is very short ($\sim$ mm) but $\gamma p$ colliders have 1000 times larger distance ($\sim$ m). Large transverse dimensions of proton bunch ($\sim$ 10 $\mu$m) compare to electron bunch ($\sim$ 3 nm) caused distance difference. High energy $\gamma$ beam contains a lot of residual electrons. These residual electrons have to be separate from $\gamma$ beam. In $\gamma e$ colliders this separation is not possible because of short distance between CP and IP. Residual electrons can be separated in $\gamma p$ colliders because of longer distance between CP and IP. For this purpose 0.01 Tesla magnetic field is enough to separate the residual electrons.

Different aspects of the THERA based $\gamma p$ colliders have been considered in [44]. In [45, 46] Linac*LHC based $\gamma p$ colliders have been considered for different linac scenarios.

4. Particle Factories

As mentioned in Introduction the second purpose of linac-ring type colliders is constructing of high luminosity particle factories, namely, B-factory
Today, linac-ring type B-factory has lost its attractiveness with KEK-B and PEP-B colliders under operation and, especially, Super B proposals. In addition, Super-B factories will copiously produce $\tau$ leptons (the moderate decreasing of the $\tau$ pair production cross section at $\sqrt{s} \approx 10$ GeV is compensated by high luminosity). As a result only a charm factory option of linac-ring type factories still preserves its actuality. In order to search for charm mixing and CP violation by exploiting quantum coherence and to search for rare decays by using a background-free environment, unique opportunities is offered by $\Psi(3S)$. Therefore, the center of mass energy is
fixed by the mass of $\Psi(3770)$ resonance. The CLEO-c worked with $L = 10^{32} \text{cm}^{-2}\text{s}^{-1}$, whereas the BEPC charm factory has design luminosity of $10^{33} \text{cm}^{-2}\text{s}^{-1}$. Therefore, charm factory with $L > 10^{34} \text{cm}^{-2}\text{s}^{-1}$ will contribute charm physics greatly. It was shown in [50] that linac-ring option gives opportunity to achieve $L = 10^{34} \text{cm}^{-2}\text{s}^{-1}$. The main restriction on luminosity coming from linac beam power can be relaxed by using of energy recovery linac (ERL). In principle, ERL technology will give opportunity to construct super-charm factory with $L$ well exceeding $10^{35} \text{cm}^{-2}\text{s}^{-1}$ [51]. Linac-ring type charm factory is one of the four main parts of the TAC (Turkic Accelerator Complex) Project [21], which is developed since 1997 with the support of Turkish State Planning Organization and planned to be realized before 2020 (see Fig. 9). Recently, a ring-ring tau-charm factory based on the crab waist collision with luminosity of $10^{35} \text{cm}^{-2}\text{s}^{-1}$ has been proposed at Novosibirsk Budker Institute of Nuclear Physics [52] and high intensity linear $e^-e^+$ collider for a tau-charm factory with same luminosity is discussed in [53].

Different aspects of linac-ring type lepton-hadron, photon-hadron and electron-positron colliders have been considered in [54-70], too.
5. Conclusion

Let us repeat that today linac-ring type colliders present sole realistic way to TeV scale in lepton-hadron and photon-hadron collisions. QCD Explorer requires special attention, because it will be necessary both for exploration of the QCD fundamentals and adequate interpretation of future LHC data. Especially $\gamma A$ option promises crucial results on strong interactions at all levels from quarks to nuclei.

Concerning particle factories LR type colliders will provide opportunity to construct super charm factory with luminosity well exceeding $10^{35} \text{ cm}^{-2}\text{s}^{-1}$.

We appeal to ICFA, ECFA and so on, to organize two worldwide working groups, one on QCD Explorer and second on Super Charm Factory. It should be noted that appropriate ERL designs are crucial for both of them.

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Appendix 1. Ankara Workshop on Linac-Ring Type ep and \( \gamma p \) Colliders

1.1. Preface

The first International Workshop on Linac-Ring Type ep and gp Colliders held in Ankara between 9-11 April 1997. The workshop was organized with the supports from Scientific and Technical Research Council of Turkey (TUBITAK), Ankara University and Deutsches Elektronen-Synchrotron DESY Directorate. During the workshop more than thirty reports have been presented and most of the are published in this proceedings. The recently proposed lepton-hadron machines, which open a fourth way to investigate TeV scale physics, are discussed thoroughly from the machine and physics aspects.

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1.2. Workshop Conclusion and Recommendations
New linac-ring type ep, γp and µp colliders will be constructed after operation of basic $e^+e^-$, γe, γγ, pp and $\mu^+\mu^-$ colliders. They have advantages in study of quarks and gluons in the proton because probing particles (e,γ, µ) have in general well known structures. These type of collisions are also optimum for production and study of some new particles such as leptoquarks. The expected luminosity of ep and γp colliders is lower than that of above mentioned basic colliders. Nevertheless, there are a number of physical problems, which can be solved at these new type colliders. These are

- QCD in the new region of parameters
- Leptoquarks, leptogluons and new contact interactions
- Searching for SUSY and wide spectrum of problems beyond the SM, etc.

In order to obtain there really new results complementary to those at basic colliders, the luminosities $L(ep) \geq 10^{31}$ and $L(\gamma p) \geq 10^{30}$ are necessary in units of $cm^{-2}s^{-1}$ and seem to be sufficient. Higher luminosities require cooling of the proton beams which needs additional studies. Concerning the µp colliders rough estimates give the luminosity $L(\mu p) \geq 10^{33}cm^{-2}s^{-1}$, however this topic calls for more detailed investigation. As a result of the workshop, participants came to the point that it will be useful to organize two workshops, one on the machine parameters and the other on the physics research program, during the next year.

Proceedings of the workshop were published as a special issue of the Turkish Journal of Physics, Vol 22, No 7, 1998.