ERL High Energy e^+e^- sub-Panel Report

1: Introduction

The European Lab Director's Group (LDG) established a Panel to evaluate ERLs, as one of five technologies to be studied.

While the Panel was collecting information, an ERL concept was put forward to build the ILC as an energy recovery twin collider, termed ERLC (https://arxiv.org/pdf/2105.11015.pdf), with the prospect of a large increase of the e^+e^- instantaneous luminosity as compared to the ILC.

This caused the formation, in agreement with the LDG, of a sub-Panel to evaluate the prospects (primarily luminosity), involved R&D, and the schedule and cost consequences for the ERLC.

The sub-Panel was also asked to evaluate the concept to configure the FCC-ee as a high luminosity circular energy recovery collider, CERC (https://doi.org/10.1016/j.physletb.2020.135394), with the same criteria.

A sub-Panel with wide experience in accelerator design, construction and operation was formed with the following members.

Chris Adolphsen (SLAC)

Reinhard Brinkmann (DESY)

Oliver Brüning (CERN)

Andrew Hutton (Jefferson Lab) - Chair

Sergei Nagaitsev (Fermilab)

Max Klein (Liverpool)

Peter Williams (STFC, Daresbury)

Akira Yamamoto (KEK)

Kaoru Yokoya (KEK)

Frank Zimmermann (CERN)

For each concept, the sub-Panel looked at the published information and provided questions to the authors. The authors were invited to make a one-hour presentation to the subpanel followed by thirty minutes for questions. This meeting was followed up by another thirty-minute question and answer session after the sub-Panel had had time to go through the material provided.

This report is divided into two main sections; one on the CERC, the other on the ERLC, with an identical format for the two concepts.

2: CERC - Vladimir Litvinenko, Thomas Roser, Maria Chamizo-Llatas

General Andrew

The basic concept is described in Chapter 5

This is not enough if we want the report to be stand-alone. It needs a brief description, which can be added later if we publish it separately.

2.1: Findings

2.1.1: General

The concept is still in the early stages and is therefore difficult to compare with the FCC-ee design, which is the result of many years' work by a large group. This became evident in the discussions because the concept was being modified during the evaluation to answer to problems that had been identified. The sub-Panel decided to focus on a review of the published concept, but collected the improvements proposed by the authors and the sub-Panel members in Section 2.2.

The drivers for the proposal were to make the collider more "sustainable," and to increase the luminosity, particularly at higher energies. These areas were therefore a particular focus of the sub-Panel. However, the cost is always an important factor in choosing a design philosophy, so this was also evaluated.

2.2: Performance

2.2.1: Luminosity Kaoru

This section describes the luminosity issues including the emittance problems throughout the facility.

There were a few design-parameter sets of CERC presented in the subpanel meeting. Here, we mainly discuss the "updated parameter" set in troser166 with the long bunch choice.

The luminosity is defined somewhat differently for CERC and FCC-ee. Collisions in the CERC occur in only one of the up to three interaction regions at a time, so the luminosity is the total facility luminosity for the three interaction regions. In the FC-ee, the luminosity is per interaction region and to obtain the total facility luminosity, it should be multiplied by the number of installed detectors, two or four, with a slight dependence on the number of detectors.

2.2.1.1 Beam-Beam Interaction

One of the major issues that drive the whole parameter set is the beam-beam interaction. Let us take the collision parameter set for ttbar:

$N=1.4 \times 10^{11}$ (number of particles per bunch)

$s_z = 50$ mm (rms bunch length)

$b_x^* = 1$ m, $b_y^* = 2$ mm

$s_x^* = 4.7$ mm, $s_y^* = 6.6$ nm

$D_x = 5.0$, $D_y = 3500$

It is assumed the beams are kept focused during the collision by the focusing force of the opposite bunch owing to the matching of the b_y^* and the space-charge beta function b_{SC}, in spite of the long bunch $s_z = 25\ b_y^*$. This extremely long bunch has been chosen so that the energy spread due to the beamsstrahlung can be accepted by the deceleration beamline and the damping ring.

Whether this extreme choice of the collision parameters (D_x, D_y, s_z / b_y^*) is realistic or drives the entire scenario. In addition, compared with the original parameter set, the horizontal disruption parameter D_x in the updated parameter set is significantly larger than one (from D_x =22 for Z-pole to 4.4 for 300 GeV). Hence, the horizontal beam size will also change during the collision. Accurate simulations are very urgent. Obviously, the simulations must take into account the horizontal force in the same level as vertical.

A shorter bunch (~10mm) is suggested in Section 2.2.3 from the point of view of RF acceleration. In that case the critical energy of the beamsstrahlung would increase by factor 5, which makes the design of decompressor and the damping ring more demanding.

2.2.1.2 Final focus system

The emittance increase due to the beam-beam interaction is large. The authors expect factor ~5 increase for D_y ~100. The increase must be re-evaluated for the larger D_x and D_y. The quality of the beams before and after the collision is significantly different. The present design adopts a head-on collision and uses the same optics for the beams after collision. We suggest adopting a finite crossing angle, crab crossing, and different optics for defocusing the beams after collision.

2.2.1.3 Damping Rings

The normalized vertical emittance 8nm is not as small as those of damping rings, e.g., compared with CLIC (5nm), but the vertical/horizontal emittance ratio ~1000 is large compared with existing linear collider parameters (~100 for CLIC, ~200 for ILC). However, this is not very small compared with light sources. Nonetheless, tolerances should carefully be evaluated under the requirements of the short damping time.

Because the vertical emittance 8 nm is small and the bunch charge is very high (13 to 25 nC), the effects of the intrabeam scattering should be evaluated (the effect is already visible at ILC with 20 nm and 3.2 nC though at 5 GeV). The electron cloud instability in the positron damping ring must also be examined since the beam current is rather high – up to ~5A.

We would need more concrete design parameters of the damping rings (circumference, damping time, beam stay time, etc.), together with that of the decompressor, for a more detailed assessment.

2.2.1.4 Arcs

Most problems related to the 100 km arcs come from the orbit length ~400 km each for the acceleration and deceleration.

The focusing system has already been proposed (combined function, with sextupole component also included, 16m period FODO, phase advance per cell 90 degree). Presumably, weaker focusing (lower phase advance) would be better for the arcs of lower energies.

The increase of the horizontal emittance increase due to the synchrotron radiation has been estimated and found to be acceptable. The most important issue is the preservation of the small vertical emittance of 8nm over the 400 km orbit with strong focusing magnets. This comes both from the misalignment of the magnets and the ground motion. Tolerances are normally tighter for stronger focusing. It should be easy to estimate the tolerance of the alignment jitter (though this can be presumably cured by the feedback system). The next step will be estimation of the vertical emittance growth under misalignment and ground motion. The orbit correction algorithm must be studied (the dispersion free method, in which the beam energy is changed, cannot be used).

For these purposes the studies for CLIC will be very helpful (ILC is somewhat different because of the large aperture and weak focusing system). In the case of CLIC, a strong focusing system is required due to the strong wakefield of the high frequency cavities. CERC arcs do not have cavities but a strong focusing system is needed for the synchrotron radiation.

The effects of the wake-fields should be studied, in particular because of the small beam pipe (15mm radius) and the high bunch charge. The long bunch may also be important for the transverse wake, although there are no RF cavities. The resistive wall wake should also be studied because of the long orbit.

Another issue may be the scattering by the residual gas as pumping will be difficult in the small-bore magnets. The fast ion instability from residual gas ionization will probably not be an issue because of the long bunch distance.

We do not yet know the effects of up-down orbit before/after RF (vertical emittance preservation).

2.2.1.5 Linacs

Cumulative beam breakup due to the deflecting HOMs should be studied in the linacs because the beam current is high (4x or 8x compared with the arcs), but presumably acceptable. The effects of the short-range wake will define the alignment tolerance of the linac components (cryomodule and quadrupole magnets). Definite quantitative conclusions cannot be made since the important parameters, the RF frequency, the bunch length and the focusing system are unknown. However, even with favorable choices for these parameters, the tolerance would be tighter than for ILC (~200 microns), even if the target vertical emittance is the same as in ILC.

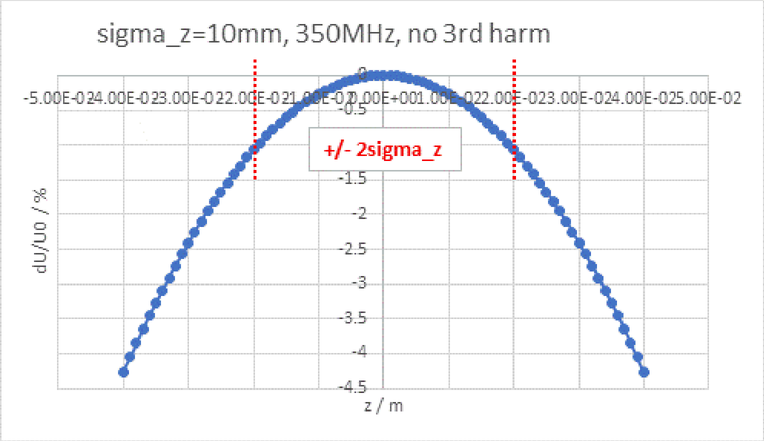
2.2.2: RF

Chris

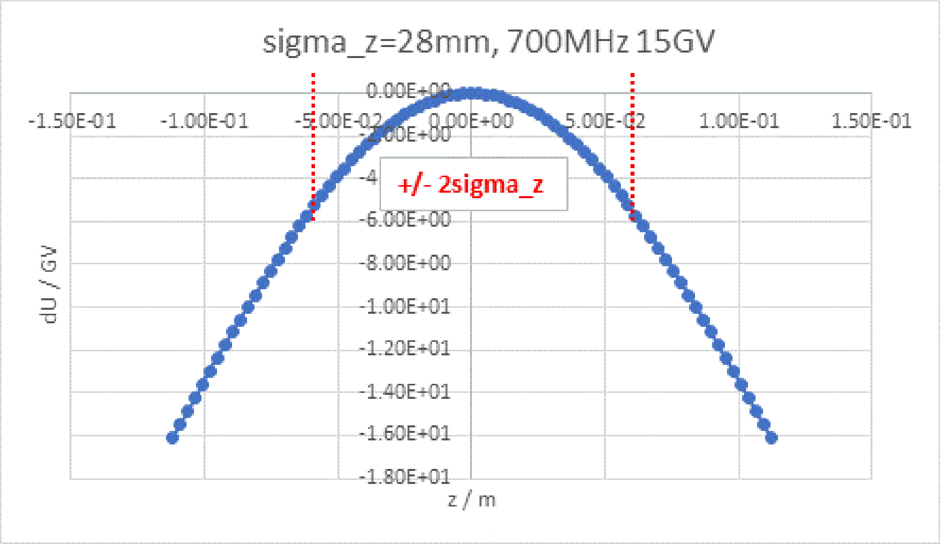
2.2.3: Bunch Length

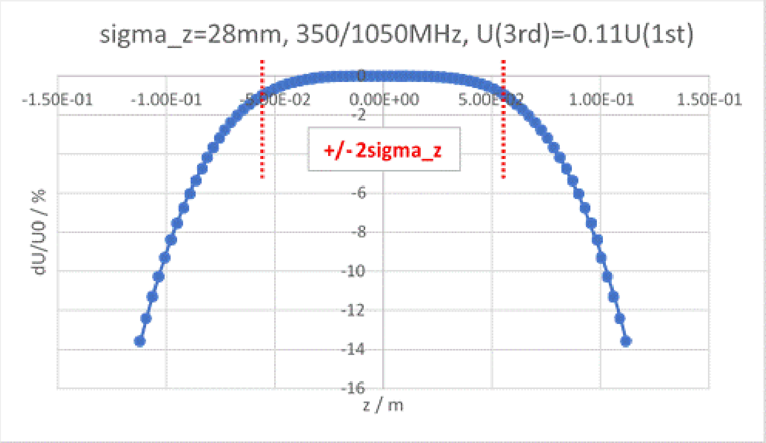
Peter, Reinhard

Lengthening of the bunch in order to reduce beamsstrahlung becomes a potential problem for the RF system due to the non-linearity of the RF-potential. A low-frequency system is advantageous in this context and an improvement of the RF field flatness can be achieved by adding a higher harmonic system with a voltage opposite to the main ERL RF. For the example of a 350MHz 1st harmonic system the situation is depicted in the figure below. Assuming that the FFS requires an energy deviation from the on-crest particle of not more than 1% for the core of the beam (+/- $2\sigma_z$) in order to avoid an increase of the beam size at the IP (this could be more relaxed with a wide-band FFS), the maximum tolerable bunch length is 10mm. When adding a 3rd harmonic system with 11% of the voltage of the 1st harmonic system, a bunch length up to 28mm would be tolerable (see 2nd figure below). Note that in that case also the 1st harmonic voltage has to be increased by 11% to maintain the full beam energy.



The energy spread in the bunch caused by the RF curvature on the accelerating branch of the ERL is completely removed on the de-accelerating branch so that it does not contribute to the issue of large energy spread of the beam at the damping ring energy.





However, the 2nd harmonic system, which is designed to compensate the radiative energy loss, creates a non-linear energy profile which is not compensated. The bunch energy profile for a 700MHz system with a 15 GV voltage is shown in the figure below for a bunch length of 28mm. The energy deviation with respect to the on-crest particle amounts to about -5GV at +/- $2\sigma_z$ which is obviously a serious problem for the damping ring energy and energy acceptance. One could also consider adding a 3rd harmonic system here, but at 2.1GHz it will be very difficult to handle HOM problems and furthermore the energy variation in the tails of the longitudinal bunch distribution becomes too large. Therefore, one can conclude that a bunch length of much more than about 10mm does not seem to be realistically feasible.

2.2.4: Polarisation

Kaoru

Two cases must be considered, namely making use of the Sokolov-Ternov radiative polarization in the damping rings, and the injection and acceleration of pre-polarized beams.

The polarization time of the Sokolov-Ternov effect at 8 GeV is of the order of an hour, very roughly speaking. The cycle time of DR→Arc→IP→Arc→DR is of the order of 10 ms. Therefore, a particle makes ~3x10^5 cycles during a polarization time. So, Sokolov-Ternov polarization does not work if the depolarization in one cycle exceeds

~1/3x10^5 ~ 3 ppm. To estimate the depolarization to this level is not easy but presumably it is not fatal (beam-beam depolarization must be carefully simulated including the downstream FFS). The most difficult problem is the beam loss due to the beamsstrahlung. The polarization life time cannot of course exceed the beam life time. To suppress the beam loss to the level < ppm seems to be very difficult.

The depolarization in one cycle does not impose a tight condition for the case of using pre-polarized beam. The number of particles per second at the IP ranges from 2x10^{16} for Z to 1x10^{15} for 300GeV (6x10^{15} for ttbar). The polarized electron source for ILC is designed to produce 1.3x10^{14} per second. Hence, if the beam loss per cycle is << 1%, the loss can be replenished by a polarized source (top-up injection in DR). Producing polarized positrons is of course hard, but in principle the ILC baseline scheme (undulator with >100GeV electron) can be applied for CERC (but would require more investment).

In the FCC-ee, an accurate energy measurement can be obtained by using polarization: the method uses resonance with the spin tune and the frequency of the depolarizer. However, the spin tune (number of precessions in one cycle IP -> deceleration -> DR -> acceleration -> IP) is not well-defined due to the long stay in the damping ring. Moreover, even if the spin tune is defined, its relation with the beam energy at the IP is not guaranteed. Hence, the beam energy cannot accurately be measured by using polarization.

2.3.1: Cost Estimate

Frank, Reinhard

All cost figures in the following are excluding lab personnel, overheads and site costs. Since details of the design are not known (arc correctors magnets, arc vacuum system (coating?), the presence or not of magnet movers, damping-ring …) and/or likely to evolve, the error bar is high, at least a factor of two for the overall cost.

2.3.1.1 Damping Rings and injectors

A rough cost estimate is based on 1km circumference rings operating at 2GeV beam energy and with 1.3A beam current (365GeV collider case). With a damping time of 2ms (requiring ~150m of 2T damping wigglers), the energy loss per turn amounts to about 3MeV and the RF power to the beam to about 4MW (higher in proportion to the beam current for the lower CM energy options). The estimated cost per ring is 100M$ (+ about 2M$ per MW additional RF power for lower centre-of-mass energy options) and 70M$ for the 1km tunnel (for both rings) including technical infrastructure. Beam sources, pre-accelerators, transfer lines and injection/extraction systems are estimated at 100M$. In total, the DR system is estimated at 370M$. Should it be necessary to increase the damping ring energy (e.g. to 8GeV) to be able to accommodate the large longitudinal emittance of the de-accelerated beam from the ERL, then costs for magnets and RF will be higher, but fewer damping wigglers would be required. Very roughly, a 2x1km 8GeV damping ring system is estimated at 700-800M$.

These costs would increase significantly if additional tunnels, possibly at lengths of a few km or even tens of km, are required to connect damping rings and collider tunnels.

2.3.1.2 Collider arc magnet & vacuum system.

Starting from a cost estimate for eRHIC magnets, the proponents estimated that each 100 km arc will cost ~ 125M$, so that 16 arcs would result in a cost of 2B$. However, since eRHIC magnets are stronger than in FCC-ee, the cost will probably be reduced, perhaps by 30% or more [email from V. Litvinenko, dated 11 October 2019]. With a 30% cost reduction the 16 arcs of CERC will cost $1.4B, to be compared with roughly 1.6B$ estimated for 2 FCC-ee arcs (comprising twin-aperture magnets, vacuum, survey and alignment systems).

The unusually low cost of 1.25 k$ per meter per beam line would need to be validated by experts, based on an engineering design for magnets, vacuum system, magnet supports, and any auxiliary components (correctors, movers ...).

2.3.1.3 Collider SRF system and cryogenics

Energy loss from synchrotron radiation (about 15 GeV per beam at 365 GeV c.m.) can be compensated by a higher harmonic RF system.

The fundamental RF system consists of two 23.3 GV linacs. We can estimate the cost from the FCC-ee upgrade from 240 to 365 GeV, which requires 15 GV 800 MHz SRF, incl. cryogenics, at a cost of about 1.5B$. Scaling from 16 GV to 46.5 GV and halving the resulting price (since little RF power will be required) we obtain 2.2B$. A very similar, ~10% higher value is obtained when scaling from the LHeC SRF & cryogenic cost estimate.

In addition, we need to add the cost for 1.3 GV RF linac at higher frequency (8 passes through this linac make up for 10.8 GeV energy loss in the arcs) and here including high RF power. For this we take a fifth of the cost of the 16 GV FCC-ee 800 MHz system, or 0.3B$.

2.3.1.4 Other elements

Several further elements will contribute to the total cost, such as the straight-section and final-focus magnets, the interaction region, transfer & bypass lines, survey and alignment systems for the 16 beam lines and for the final focus, corrector magnet systems, beam diagnostics, accelerator control systems, etc. We assign a cost of 0.5B$ to these remaining items.

2.3.1.5 Total cost estimate for the CERC accelerator at 365 GeV (ttbar machine)

The cost items are summarized in the following table.

Item	very rough cost estimate [B$]
damping rings & injector	0.4 (0.75 for 8 GeV rings)
addt'l SRF straights & transfer tunnels	XX
collider arcs (16 beam lines)	1.4 (with a large error bar of up to a factor of 10)
main RF system & cryogenics (46.5 GV)	2.2
harmonic RF system & cryogenics (1.3 GV)	0.3
Other (straight sections, final focus, IR, survey & alignment, beam diagnostics, controls,…)	0.5
Total	4.8 (5.15) + XX

2.3.2: Staging and Upgradability Oliver

2.3.3: Time Early for Implementation Peter

2.4: Power Consumption Chris

2.5: Comments and Suggestions for improvements All

The ERL is an excellent concept, in principle, to recover the beam energy and to re-cycle it to accelerate subsequent beam in the same accelerator system. However, it is very important to minimize additional power/energy consumption to keep the advantages of this feature and to avoid canceling out the energy saving in the total wall plug-power balance including RF, cryogenics, magnets and general services. It is suggested to confirm the energy balance to be emphasized in addition to the synchrotron radiation reduction. For example, the wall-plug power of the RF and cryogenics for the SRF-ERL should be clearly discussed, as additional balance.

2.6: R&D Required Sergei collects from all

2.7: Recommendations	Andrew

3: CERL – Valery Telnov

The basic concept is described in Chapter 5

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3.5: Comments and Suggestions for improvements	All
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4. Overall Conclusions