A high-luminosity superconducting twin e^+e^- linear collider with energy recovery

V. I. Telnov a,b

^a Budker Institute of Nuclear Physics, Novosibirsk, Russia
^b Novosibirsk State University, Novosibirsk, Russia

E-mail: telnov@inp.nsk.su

ABSTRACT: Superconducting niobium cavity technology (used for ILC) makes it possible to build a linear collider with energy recovery (ERLC). To avoid parasitic collisions inside the linacs a twin LC is proposed. In this article, we consider the principle scheme of the collider and its energy consumption, and also estimate the achievable luminosity, which is limited by collision effects. With a duty cycle of 1/3, a luminosity of about 5×10^{35} cm⁻²s⁻¹ is possible, which is almost two orders of magnitude higher than at the ILC, where the beams are used only once.

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1 Introduction

Linear e^+e^- colliders (LC) have been actively developed since the 1970s as a way to reach higher energies. Their main advantage over storage rings is the absence of synchrotron radiation during acceleration, which makes it possible to achieve much higher energies. Their main weak point is the one-pass use of beams. At storage rings, the same beams are used many millions of times, whereas in LC they are sent to beam dumps after a single collision. This inefficient use of electricity results in a low collision rate and therefore a lower luminosity.

There were many LC projects in the 1990s (VLEPP, NLC, JLC, CLIC, TESLA, etc.) [1]; since 2004 only two remain: ILC [2] and CLIC [3]. The ILC is based on superconducting (SC) Nb technology (in the footsteps of the TESLA), while the CLIC uses Cu cavities and operates at room temperature. Both colliders work in pulse mode; their beam structures are given in Table 1. The difference is only in the length of bunch trains: for the ILC it is 4150 times longer. The luminosities and wall plug powers are very similar. In fact, the use of superconducting technology gives the ILC no advantage. Moreover, the accelerating gradient in the ILC is 2–3 times lower. The only benefit of superconducting cavities is the larger distance between bunches, which is good for detectors.

The main advantage of the superconducting technology is the feasibility of energy recovery, where the beam, after passing the interaction point (IP), is decelerated in the

	ILC	CLIC
$2E_0, \text{GeV}$	250	250
bunches/train, n_b	1312	354
bunch spacing, ns/m	554/165	0.5/0.15
train length, $\mu {\rm s}/{\rm km}$	720/220	0.177/0.053
rep. rate, Hz	5	50
collision rate, kHz	6.56	17.7
power (wall plug), MW	128	225
luminosity, $10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$	0.75	1.37

Table 1. Pulse structure of the ILC and CLIC.

opposing linac and thus returns its energy to the accelerator. This opportunity was noticed originally and discussed in the very first publications on linear colliders by M. Tigner [4], A. Skrinsky [5], U. Amaldi [6]. The LC scheme with energy recovery considered by H. Gerke and K. Steffen in 1979 [7] is shown in Fig. 1. This scheme provides not only energy recovery but also multiple use of the same electron and positron beams. One of the problems with multiple use of beams is a large energy spread that appears due to beamstrahlung at the IP. After beam deceleration, the relative energy spread becomes too large for injection to the damping rings. In order to reduce it, authors have foreseen "de(bunchers)" (bunch compressors and decompressors) that change the energy spread and the bunch length while keeping $\sigma_E \sigma_z$ constant.

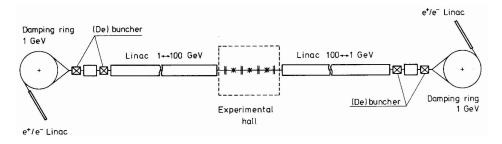


Figure 1. Gerke–Steffan's scheme of a linear collider with energy recovery [7]

However, the Gerke-Steffen scheme has as few deficiencies:

- the quality factor of SC cavities at that time was $Q_0 \sim 2 \times 10^9$, which was not enough for the continuous operation mode. Removal of the heat from cryogenic structures requires a lot of energy due to Carnot efficiency; therefore, a duty cycle of 1/30 was adopted.
- in order to exclude parasitic bunch collisions inside the linac, only one bunch is present at any one moment at each half linac, which limits the collision rate to of f = 30 kHz (for a total LC length of 10 km). With a duty cycle of 1/30, the average rate would be a mere 1 kHz.

- electron and positron bunches cannot be focused by the same final focusing systems (no one had noticed this obstacle), so this scheme could work (which is not obvious) only in one direction of the beams.
- the estimated luminosity was $L = 3.6 \times 10^{31}$ cm⁻²s⁻¹, which is too low to be of interest.

Since the 1980s, LC energy recovery schemes have no longer been considered. This is because the collision rate at a single-pass LC is similar to that at an ERL collider (as discussed above), and the luminosity per collision can be much higher at a single-pass LC due to the larger permissible disruption of the beams.

For many years, linear colliders have been considered as the obvious next large HEP project after the LHC. People expected very rich new physics to emerge in the energy range covered by LCs ($2E_0 = 100-3000$ GeV). Unfortunately, the LHC has found only the Higgs boson. Physicists are therefore in doubt about linear colliders. It is only absolutely clear that we need an e^+e^- Higgs factory at the energy $2E_0 = 250$ GeV. But after the discovery of the light Higgs boson, the FCC-ee and CEPC circular 100 km e^+e^- colliders came into play, promising an order of magnitude higher luminosity at this energy, followed by the 2×100 GeV proton collider in the same tunnel. This is the reason that a decision on the ILC has not yet been made, although it was expected shortly after the publication of the TDR in 2013.

Below, we revisit the concept of an energy-recovery LC and show that the above problems can be overcome. In addition, significant progress has been made on SC cavities over the past three decades. The quality factor has been increased by more than an order of magnitude. The emphasis will be on the Higgs boson energy. The result is intriguing and can change the course of the game.

2 Superconducting twin linear collider with energy recovery

The first question is why it is necessary to exclude parasitic beam collisions inside the linacs. At first glance, the transverse beam sizes in linacs are much larger than at the IP, so the loss of particles due to such collisions appears to be insignificant. The reason lies in the instability of the beams. If we want to use beams multiple times, the instability criteria are the same as in storage rings and are determined by the vertical tune shift (or the beam-beam parameter) [8]

$$\xi_y = \frac{N r_e \beta_y}{2\pi \gamma \sigma_x \sigma_y} \lesssim 0.1, \quad \sigma_i = \sqrt{\epsilon_{n,i} \beta_i / \gamma}.$$
(2.1)

The ratio of the beam-beam parameters in the linac and at the IP is

$$\frac{\xi}{\xi^*} = \frac{\sqrt{\beta_y/\beta_x}}{\sqrt{\beta_y^*/\beta_x^*}} \gg 1,$$
(2.2)

because in the linac $\beta_x \sim \beta_y$, while at the IP $\beta_x^* \gg \beta_y^*$. Note that this result is independent of the energy at which parasitic collisions occur.

To solve this problem we propose a twin linear collider in which the beams are accelerated and then decelerated down to $E \approx 5$ GeV in separate parallel linacs with coupled RF systems, see Fig. 2. RF power is always divided equally among the linacs. RF energy comes to the beams both from an external RF source and from the decelerating beam. These can be either two separate SC linacs connected by RF couplers at the ends of multi-cell cavities (9-cell TESLA cavity), or one linac consisting of twin (dual) cavities with axes for two beams. Such cavities have been designed and tested for XFELs [9–12].

Twin LC with energy recovery

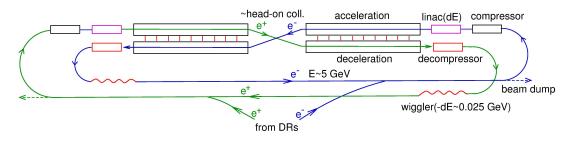


Figure 2. The layout of the SC twin linear collider.

The collider would operate at an energy $2E_0 \approx 250$ GeV in a semi-continuous mode with a duty cycle: collisions for a few seconds (depending on the heat capacity of liquid He system), then a break to cool the cavities. In one cycle, the beams make about 10–30 thousand revolutions.

During collisions, beams get an additional energy spread that is damped by wigglers installed in the return pass at the energy $E \approx 5$ GeV. The relative energy loss in wigglers is about $\delta E/E \sim 1/200$. We require that the steady-state equilibrium energy spread at the IP due to beamstrahlung is $\sigma_E/E_0 \sim 0.2\%$, the same as at the ILC and CLIC before the beam collision. Such a spread would be sufficient for beam focusing.

When the beam is decelerated down to 5 GeV, its relative energy spread increases by $E_0/E \sim 25$ times to $\sigma_E/E \sim 5\%$. To make it acceptable for travel without losses in the arcs, its energy spread is reduced by 10–15 times with the help of the bunch (de)compressor; then, the relative energy spread in the arcs will be less than 0.5%. The beam lifetime will be determined by the tails in beamstrahlung radiation. This loss should not exceed 1-2% after 10000 revolutions. The IP energy spread, beam instability and beam losses determine the IP beam parameters, and hence the luminosity.

An important question is the injection and removal of the beams. When the collider is full, the distance between bunches is 1.5–3 meters; they are accelerated and decelerated due to the exchange of energy between the beams. External RF power is required only for energy stabilization and compensation for radiation and high order mode (HOM) losses. During the injection/removal of the beams, normal energy exchange does not occur until the bunches fill the entire orbit, so the external RF system must work at full power. However, at the ILC, the power of the RF system is only sufficient to accelerate beams with a bunch distance of 100–150 m. In our case, with energy recovery, we need a much shorter inter bunch distance. To solve this problem, one must first inject the bunches with a large interval and then (at subsequent revolutions) add bunches between the bunches already circulating. Removal of beams is done in reverse order.

3 Requirements on beam parameters at the IP

Energy spread in beam collisions

During the beam collisions, the particles emit synchrotron radiation (beamstrahlung), which contributes to the energy spread of the beam. The increase of the beam energy spread in a single collision $(n_{\gamma} < 1)$ [13–15]

$$\Delta \sigma_E^2 = n_\gamma \langle \epsilon_\gamma^2 \rangle = \frac{\langle \epsilon_\gamma^2 \rangle}{\langle \epsilon_\gamma \rangle^2} \frac{(n_\gamma \langle \epsilon_\gamma \rangle)^2}{n_\gamma} \approx \frac{5.5 \, (\Delta E)^2}{n_\gamma},\tag{3.1}$$

$$\frac{\Delta E}{E_0} \approx \frac{0.84 r_e^3 N^2 \gamma}{\sigma_z \sigma_x^2}, \ n_\gamma \approx 2.16 \frac{\alpha r_e^2 N}{\sigma_x}, \tag{3.2}$$

where ΔE is the average energy loss, n_{γ} is the average number of photons per collision $(n_{\gamma} \ll 1 \text{ under our conditions}), \alpha = e^2/\hbar c \approx 1/137, r_e = e^2/mc^2$. Here, we neglect the energy spread due to the inhomogeneity of the Gaussian beam $(\sigma_E \approx 0.54\Delta E)$, which is much smaller. As a result, we get

$$\frac{\Delta \sigma_E^2}{E_0^2} \approx 1.8 \frac{N^3 r_e^5 \gamma^2}{\alpha \sigma_x^3 \sigma_z^2}.$$
(3.3)

After the collision the bunch decelerates and then stretches during the bunch decompression where its $\Delta \sigma_E$ and σ_E decrease proportionally. Due to SR radiation in damping wigglers at the energy $E \sim 5$ GeV, where particles lose the energy δE in one pass, an equilibrium energy spread is achieved [8]:

$$\frac{\Delta \sigma_E^2}{\sigma_E^2} = 2 \frac{\delta E}{E}.$$
(3.4)

Substitution of (3.3) into (3.4) gives the equilibrium energy spread at the IP

$$\left(\frac{\sigma_E}{E_0}\right)^2 \approx 0.9 \frac{N^3 r_e^5 \gamma^2}{\alpha \sigma_x^3 \sigma_z^2 (\delta E/E)}.$$
(3.5)

For the desired damping rate and energy spread σ_E/E_0 , we obtain the requirements for the beam parameters at the IP

$$\frac{N^3}{\sigma_x^3 \sigma_z^2} < \frac{8 \times 10^{-3}}{r_e^5 \gamma^2} \left(\frac{\sigma_E}{E_0}\right)^2 \frac{\delta E}{E}.$$
(3.6)

Beam instability

Our linear collider behaves as a cyclic storage ring, so there is a second limitation on the beam parameters at the IP, due to the tune shift. For flat beams and head-on collisions, it is

$$\xi_y = \frac{Nr_e \sigma_z}{2\pi \gamma \sigma_x \sigma_y} \lesssim 0.1 \quad (\text{for } \beta_y \approx \sigma_z).$$
(3.7)

At the ILC, the beams collide at a crossing angle of $\theta_c \approx 15$ mrad, which makes it easier to remove highly disrupted beams. In the ILC case, you should use the crab-crossing scheme (tilt of the bunches by $\theta_c/2$) to preserve the luminosity. In the case of our cyclic LC, beam disruption is small and beams can be removed through the aperture of the opposing final quadrupole; therefore we assume nearly head-on collisions with a small crossing angle to facilitate the separation of the beams.

We do not consider collisions at a large crossing angle ("crab-waist" scheme) because it would provide no benefit when beamstrahlung is important or the beams are short.

Beam lifetime

The beam lifetime at high-energy e^+e^- storage rings is determined by the emission of high-energy beamstrahlung photons [16]. An electron (positron) is lost when its energy loss is greater than ηE_0 , where η is the energy acceptance. In our case, the bunches are decelerated by a factor of 125/5=25 and then expanded by a factor of ~ 15; therefore, the energy acceptance in the 5 GeV arc should be approximately 25/15=1.67 greater than the maximum acceptable relative energy loss at the IP. If we take the energy acceptance in arcs at 5 GeV equal to 3%, then at the IP it should be $\eta = 0.03/1.67 = 0.018$.

The formulas for calculating the beam lifetime are given in the Ref. [17]. For the lifetime of the beam to correspond to $n_{\rm col}$ collisions in the collider with energy acceptance η , it is necessary to have

$$\frac{N}{\sigma_x \sigma_z} < \frac{3.6 \times 10^{-3} \eta}{\gamma r_e^2 \ln\left(7 \times 10^{-7} \eta \sigma_z n_{\rm col} / \gamma r_e\right)} \tag{3.8}$$

or

$$n_{\rm col} = 1.43 \times 10^6 \frac{\gamma r_e}{\eta \sigma_z} \exp\left(\frac{0.0036 \,\eta \sigma_x \sigma_z}{N \gamma r_e^2}\right) \tag{3.9}$$

Below, we will show that in the case of operation with a duty cycle, the duration of the active phase can be around 1 to 3 s. During this time, 7.5 to 22.5 thousand beam collisions take places. To have a beam loss at the level of 1%, the beam lifetime must correspond to $n_{\rm col} \sim 10^6$ (a lifetime of about 2 minutes).

Thus, we have a third constraint (3.8) on beam parameters due to the beam lifetime. Note that the beam energy spread at the IP gives the constraint (3.6) on a slightly different combination: $N/(\sigma_x \sigma_z^{2/3})$. Which of the two restrictions is more important? Direct comparison shows that for our choice: $\delta E/E = 1/200$, $\sigma_E/E_0 = 0.002$, E = 125 GeV, 3% acceptance in 5 GeV arcs and $\sigma_z \sim 0.03$ mm (explained later), $n_{\rm col} = 10^6$, these two constraints coincide quite unexpectedly.

Further on, we will use beam parameters obtained from the beam energy spread at the IP and the instability condition, (3.6) and (3.7), assuming that the beam lifetime is under control. This is sufficient for the discussed set of parameters; for other conditions, one can simply check the lifetime using the formula (3.9).

4 Beam parameters and luminosity

For four unknown beam parameters at the IP: $N, \sigma_x, \sigma_y, \sigma_z$ we have two restrictions, (3.6) and (3.7), and one relationship: $\sigma_y \approx \sqrt{\epsilon_{ny}\sigma_z/\gamma}$. Collision effects for flat beams depend on the combination N/σ_x ; therefore, taking N as a free parameter, we find beam sizes

$$\sigma_z \approx 19.2 \frac{\xi^{6/7} \epsilon_{ny}^{3/7} r_e^{4/7} \gamma}{(\sigma_E/E_0)^{4/7} (\delta E/E)^{2/7}},$$
(4.1)

$$\sigma_x \approx 0.7 \frac{N r_e^{9/7}}{\xi^{4/7} \epsilon_{ny}^{2/7} (\sigma_E / E_0)^{2/7} (\delta E / E)^{1/7}},\tag{4.2}$$

$$\sigma_y = 4.4 \frac{\xi^{3/7} \epsilon_{ny}^{5/7} r_e^{2/7}}{(\sigma_E/E_0)^{2/7} (\delta E/E)^{1/7}}.$$
(4.3)

As expected, $\sigma_x \propto N$. It is interesting that σ_x and σ_y do not depend on the energy. Finally, we get the luminosity

$$L \approx \frac{N^2 f}{4\pi \sigma_x \sigma_y} = 2.6 \times 10^{-2} \frac{N f \xi^{1/7}}{\epsilon_{ny}^{3/7} r_e^{11/7}} \left(\frac{\sigma_E}{E_0}\right)^{4/7} \left(\frac{\delta E}{E}\right)^{2/7}.$$
 (4.4)

For $\sigma_E/E_0 = 2 \times 10^{-3}$, $\delta E/E = 0.5 \times 10^{-2}$, $\xi = 0.1$, $\epsilon_{ny} = 3 \cdot 10^{-8}$ m (as at the ILC), we have

$$\sigma_x \approx 9\left(\frac{N}{10^{10}}\right) \ \mu \text{m}, \quad \sigma_z \approx 0.3 \frac{E[\text{GeV}]}{125} \ \text{mm}, \quad \sigma_y = 6.1 \ \text{nm}.$$
 (4.5)

$$L \approx 4.35 \times 10^{36} \frac{(N/10^{10})}{d[\mathrm{m}]} \approx 9 \times 10^{36} I[\mathrm{A}] \mathrm{cm}^{-2} \mathrm{s}^{-1},$$
 (4.6)

where d = c/f is the distance between the bunches. Please note, this luminosity is for continuous operation (100% duty cycle). For example,

$$N = 10^{10}, d = 3 \,\mathrm{m} \,(I = 0.16 \,\mathrm{A}) \Rightarrow L = 1.45 \times 10^{36} \,\mathrm{cm}^{-2} \mathrm{s}^{-1}.$$
(4.7)

In this example, the power radiated in damping wigglers by both beams is $P_{\rm SR} = 8$ MW. For comparison, at FCC-ee(250) $L = 8.5 \times 10^{34}$ at $P_{\rm SR} = 100$ MW. As one cansee, the SR power at the energy recovery linear collider is 215 times smaller for the same luminosity.

5 High-order mode losses (HOM)

When particles are accelerated in linear accelerators, they take energy $\Delta E = e\mathcal{E}_0 \Delta z$ from the cavity due to the destructive interference of the RF field in the cavity \mathcal{E}_0 and the wave \mathcal{E}_r radiated by the bunch into the cavity. When the particles are decelerated ($\Delta E = -e\mathcal{E}_0 \Delta z$), they return their energy back to the cavity due to constructive interference between the RF field and the radiated field. However, such a picture with an ideal energy exchange is valid only for the fundamental cavity mode. High radiation modes (longitudinal wake fields \propto bunch charge) lead to energy losses during both acceleration and deceleration. For this reason, the energy recovery efficiency is not 100%. When the beam passes through a single diaphragm with a radius of a, the energy loss can be easily estimated as the energy of the beam field at r > a. However, for a long linear accelerator with multiple apertures, the picture is more complex. In this case, according to R. Palmer [18], the energy loss by one electron per unit length

$$-\frac{dE}{dz} \approx \frac{2e^2N}{a^2}.$$
(5.1)

It is noteworthy than the energy losses do not depend on the distance between the diaphragms and on the bunch length. This simple formula is supported by detailed numerical calculations. There is a dependence on the bunch length, but very weak. For TESLA–ILC accelerating structures (a = 3.5 cm), a numerical calculation [19] gives the energy losses in the wakefield for $\sigma_z = 400 \ \mu m$ (the energy loss in the cryomodule is divided by the active length of accelerating cavities)

$$-\frac{dE}{dz} \approx 22 \left(\frac{N}{10^{10}}\right) \frac{\text{keV}}{\text{m}}.$$
(5.2)

For bunch lengths $\sigma_z = 0.25$ –1 mm, the coefficient varies within the range 24.2–17.6. The formula (5.1) gives 23.5. So, for TESLA cavities and $N = 10^{10}$, these HOM losses are ~0.1% of the accelerating gradient $G \sim 20$ –30 MeV/m. Taking into account that these losses occur both during acceleration and deceleration, we find that the energy recovery efficiency is ~ 99.8%.

For 2E = 250 GeV, G = 20 MeV/m, the active collider length is L = 12.5 km. The total power of HOM energy losses (twin collider, both beams)

$$P_{\text{HOM}} = \frac{265}{d[\text{m}]} \left(\frac{N}{10^{10}}\right)^2 \text{ MW.}$$
 (5.3)

For $N = 10^{10}$ and d = 3 m $P_{\text{HOM}} = 88.3$ MW, which is a lot. Recall that the power of synchrotron radiation in damping wigglers is only 8 MW. Keep in mind that these numbers are for continuous operation.

What happens with the HOM energy generated by the beam inside the linear accelerator? This energy is two orders of magnitude greater than the RF energy dissipated due to the residual resistivity of the cavities (see the next section). Fortunately, most of this energy can be extracted from the SC cavities in two ways: a) using HOM couplers which dissipate the energy at room temperature; b) with the help of special HOM absorbers located between the cavities. The latter are maintained at an intermediate temperature around 50–80 K where refrigeration systems operate at much higher efficiencies. However, some small part of the HOM energy is dissipated in the walls of SC cavities.

This HOM problem in high-current ERL linacs is well-known. Possible solutions: larger iris radius and fewer cells per cavity makes HOM removal easier; a larger aperture radius also decreases $P_{\text{HOM}} \propto 1/a^2$. So, there is a problem, and very serious one. Perhaps, for this task, it is necessary to slightly modify the TESLA cavities. If it is not enough, one can reduce the number of particles in the bunch: the HOM power is proportional to N^2 , while $L \propto N$.

At the TESLA–ILC this problem is absent (much easier) due to the much larger distance between bunches.

6 RF losses in cavities

One of the main problems of SC linear accelerators operating in a continuous mode is heat removal from the low-temperature SC cavities. Energy dissipation in one (multi-cell) cavity

$$P_{\rm diss} = \frac{V_{\rm acc}^2}{(R/Q)/Q_0},$$
 (6.1)

where $V_{\rm acc}$ is the operating voltage, R/Q is the fundamental mode shunt impedance, and Q_0 is the cavity quality factor. The 1.3 GHz TESLA–ILC cavity has R/Q = 1036 Ohm and the length $L_c = 1.04$ m. For the accelerating gradient G = 20 MeV/m and $Q_0 = 3 \times 10^{10}$, the thermal power $P_{\rm diss} = 13.5$ W/m, or 680 W/GeV. Taking into account some residual HOM losses, we assume $P_{\rm diss} \approx 1$ kW/GeV. Such a continuous-mode SC linac is currently being developed for the XFEL LCLS-II at SLAC [20, 21].

The overall heat transfer efficiency from temperature $T_2 \approx 1.8$ K to room temperature $T_1 \sim 300$ K is $\eta = \varepsilon T_2/(T_1 - T_2) \approx 0.3 \times 1.8/300 = 1/550$. The required refrigeration power for the twin 250 GeV collider is $P_{\text{refr}} = 2 \times 250 \text{ GeV} \times 550 \times 1 \text{ kW/GeV} \approx 275 \text{ MW}$.

In recent years, great progress has been made both in increasing the maximum accelerating voltage and in increasing the quality factor Q_0 . In the ILC project, it is assumed $Q_0 = 10^{10}$ and G = 31.5 MeV/m. For continuous operation, it is advantageous to work at $G \approx 20$ MeV/m, where $Q_0 \sim 3 \times 10^{10}$ is within reach now. Moreover, N-doping and other surface treatment technologies have already resulted in $Q_0 \sim 5 \times 10^{10}$ at T = 2 K and $Q_0 \sim (3-4) \times 10^{11}$ at T < 1.5 K [22, 23]. According to a leading expert [24], one can hope for a reliable $Q_0 = 8 \times 10^{10}$ at T = 1.8 K.

Currently, we can take $Q_0 \sim 3 \times 10^{10}$ and a duty cycle DC = 1/3, which corresponds to $P_{\text{refr}} = 92$ MW. With $Q = 6 \times 10^{10}$, it is possible to work in the continuous mode with $P_{\text{refr}} \sim 135-150$ MW. This is a very important goal: the continuous mode is much better than the pulsed duty cycle.

7 Choice of parameters

<u>Duty cycle.</u> The value DC = 1/3 seems reasonable, with refrigeration power about 100 MW. Duration of continuous operation is determined by the heat capacity of the liquid He that surrounds the cavity and can be estimated as

$$\Delta t = \frac{c_p m \Delta T}{P_{diss}} \sim 12.5 \,\mathrm{s},\tag{7.1}$$

where $c_p(\text{He}) = 2 \text{ J/g}$ at T=1.8 K, *m* is the mass of liquid He per one TESLA cavity (we take 0.02 m³ or 2.5 kg), $P_{\text{diss}} \sim 20 \text{ W}$, $\Delta T \sim 0.05 \text{ K}$. At 1.5 K, $c_p \approx 1 \text{ J/g}$. So, we can safely choose the work duration $\Delta t = 2$ s, the break 4 s, the cycle duration 6 s.

<u>Distance between bunches d.</u> The luminosity $L \propto 1/d$. Possible problems: bunch separation at the IP, $P_{\text{HOM}} \propto 1/d$, the long range transverse wake fields can lead to a beam instability. We assume d = 1.5 m.

The number of particles per bunch N. On the one hand, the luminosity is proportional to N, the accelerator can easily accelerate $N = 2 \times 10^{10}$; however the HOM energy losses are proportional to N^2 and an increase of N can lead to a problem with the heat removal. For DC = 1/3 and d = 1.5 m, $P_{\text{HOM}} \approx 59 (N/10^{10})^2$ MW, which should be compensated by RF system. In order for this HOM power to be several times smaller than the refrigeration power, we assume $N = 0.5 \times 10^{10}$; then, $P_{\text{HOM}} \approx 15$ MW.

For the parameters chosen, $L \approx 5 \times 10^{35}$ cm⁻²s⁻¹.

8 Power consumption

- Beam generation. The number of circulating bunches $n_b = 2 \times (40 \text{ km/1.5 m}) = \frac{53 \times 10^4}{53 \times 10^4}$ (both beams). If bunches are prepared once every 6 s (see previous section), the average power for beam generation (with the efficiency $\varepsilon = 10\%$) will be less than 2.5 MW.
- Radiation in wigglers. $P_{\rm SR} \approx 8 \,\mathrm{MW} \times \mathrm{DC}/\varepsilon = 5.3 \,\mathrm{MW}$ at $\varepsilon = 50 \,\%$.
- High-mode energy losses: $P_{\text{HOM}} = 15 \text{ MW}/\varepsilon = 30 \text{ MW}$ at $\varepsilon = 50 \%$.
- Refrigeration $P_{\rm ref} = 92$ MW.

Total electric power $P_{\text{tot}} \approx 130$ MW, similar to the ILC baseline.

9 Summary of parameters

Below are the preliminary parameters of the Superconducting Linear Collider with the Energy Recovery (ERLC). Beam emittances are chosen very similar to the ILC, just as a wish. The ERLC and ILC consist of the same elements: linear accelerators, arcs, compressors, but in the ILC the bunch passes this pass once, while in the ERLC it is about 10 thousand times (the damping time corresponds to about 400 revolution). A quick glance at the issues revealed no unsolvable problems.

10 Conclusion

At present, the design of the superconducting ILC is quite similar to that of any roomtemperature LC: the beams are used only once and superconductivity adds very little value (a slight increase in efficiency, larger distances between bunches, and a lower peak klystron power). This scheme was laid down 40 years ago. Since then, great progress has been made in SC cavities, $Q = 3 \times 10^{10}$ has become a reality and $Q \sim 6 \times 10^{10}$ seems possible.

In this article, I propose a way to overcome the main obstacle faced by linear colliders with energy recovery: parasitic collisions in linacs. The proposed scheme of a twin linear collider opens the way to an energy-recovery LC with a luminosity at $2E_0 = 250$ GeV almost two orders of magnitude higher than at the ILC and significantly higher than at the FCC. It is worth considering these ideas carefully before starting the construction of the ILC.

	unit	ERLC	ILC
Energy $2E_0$	GeV	250	250
Luminosity \mathcal{L}_{tot}	$10^{34}{\rm cm}^{-2}{\rm s}^{-1}$	48	0.75
Duty cycle		1/3	n/a
Accel. gradient, G	MV/m	20	31.5
Cavity quality, Q	10^{10}	3	1
Length $L_{\rm act}/L_{\rm tot}$	km	12.5/22	8/20
P (wall)	MW	~ 130	128
N per bunch	10^{10}	0.5	2
Bunch distance	m	1.5	166
Rep. rate, f	Hz	2×10^8	6560
Norm. emit., $\epsilon_{x,n}$	$10^{-6} {\rm m}$	20	10
Norm. emit., $\epsilon_{y,n}$	$10^{-6} {\rm m}$	0.035	0.035
β_x^* at IP	cm	25	1.3
β_y at IP	cm	0.03	0.04
σ_x at IP	$\mu { m m}$	4.5	0.73
σ_y at IP	nm	6.1	7.7
σ_z at IP	cm	0.03	0.03
σ_E/E_0 at IP	%	0.2	~ 1

Table 2. Parameters of e^+e^- linear colliders ERLC and ILC.

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