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# Future prospects of accelerator science for particle physics

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ABSTRACT

Future advances in understanding fundamental questions of nature require revolutionary developments in accelerator science to allow several orders of magnitude enhancements in terms of energy, intensity, faster timing, and higher resolution [1]. The challenges of the 21st century (energy, power, environment, resources, cost, and space) also play a significant role in the development of accelerator tools. In this overview article, we consider several recent developments and ideas that may become steps in addressing the challenges and which may find their way into designs of accelerator tools of the future.

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## 1. Introduction

Accelerators are powerful tools that help to answer the fundamental questions of matter and reveal the origins of the Universe and the nature of Life. However, opening new horizons in science requires not evolution, but revolution—the challenge has been set for three orders of magnitude enhancements of the accelerator tools in terms of energy, intensity, faster timing and higher resolution [1]. Addressing this challenge requires focusing on technologies which, yesterday, may have been considered as dreams, while tomorrow may result not only in breakthroughs in understanding the fundamental questions, but may also produce a variety of technological applications. The specific challenges of the 21st century (energy, power, environment, resources, cost, and space) are the major factors affecting the development of accelerator science and the accelerator tools. In this article, we overview several approaches, primarily related to linear colliders, which may become steps in addressing the challenges and which may find their way into designs of accelerator tools of the future.

## 2. Linear collider power

In this section we will discuss parameter optimization of linear collider, focusing in particular on its beam power. While the first approach, the ILC low power option, may be well developed to be considered for ILC baseline design, the second idea, the beam and energy recycling is very conceptual.

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### 2.1. Low power parameters for ILC

The International linear collider (ILC) [2] is designed to operate at the energy of 500 GeV in the Center of Mass with peak luminosity of 2E34 $cm^{-2} s^{-1}$, has projected site length of about 31 km, beam power of 11 MW per beam and wall plug power consumption of about 230 MW.

The ILC low power option, aimed to achieve practically the same luminosity with reduced beam power, would give potential cost reduction due to reduced cryogenic system, smaller diameter damping rings, and would in other words reduce what can be called the "carbon footprint" of ILC. The ILC Reference Design Report (RDR) included a "low power" parameter set [2], but it was not favored by the detectors, because of larger number of $e^+e^-$ pairs and higher number of hits of those pairs in the first layers of the vertex detector [3]. Moreover, the RDR low *P* option assumed using 0.2 mm long bunch, requiring a two stage bunch compressor, while a single stage bunch compressor, if it were feasible, would be a cost saving design option.

The physics performance of the low power parameter set may be improved by using a "travelling focus" [4]. In this regime, the bunch is lengthened but the hour-glass effect can be overcome due to additional focusing by the opposite bunch. The matched focusing condition is provided by a dynamic shift of the focal point to coincide with the head of the opposite bunch.

The suggested parameter set for a new low power option is shown in Table 1 in comparison with the nominal and RDR low power set. Since analytical predictions are unreliable in a high disruption regime, the beam–beam simulation code Guinea-Pig [5] was used (referred as GP in Table 1). The travelling focus may be used with a flat longitudinal density distribution however a Gaussian distribution works almost as well. This is the case used in Table 1. To maintain the luminosity, stronger focusing at the IP is used for both of the low power sets.

**Table 1**
Parameters considered for new low power set.

| Parameters | Nominal RDR | Low *P* RDR | New low *P* |
|---|---|---|---|
| *E* CM (GeV) | 500 | 500 | 500 |
| $N$ | 2.0E+10 | 2.0E+10 | 2.0E+10 |
| $n_b$ | 2625 | 1320 | 1320 |
| $F$ (Hz) | 5 | 5 | 5 |
| $P_b$ (MW) | 10.5 | 5.3 | 5.3 |
| $\gamma\varepsilon_X$ (m) | 1.0E−05 | 1.0E−05 | 1.0E−05 |
| $\gamma\varepsilon_Y$ (m) | 4.0E−08 | 3.6E−08 | 3.6E−08 |
| $\beta_x$ (m) | 2.0E−02 | 1.1E−02 | 1.1E−02 |
| $\beta_y$ (m) | 4.0E−04 | 2.0E−04 | 2.0E−04 |
| Trav. focus | No | No | Yes |
| $\sigma_x$ (nm) | 639 | 474 | 474 |
| $\sigma_y$ (nm) | 5.7 | 3.8 | 3.8 |
| $\sigma_z$ (μm) | 300 | 200 | 300 |
| GP dE/E | 0.023 | 0.045 | 0.036 |
| GP $L$ (cm$^{-2}$ s$^{-1}$) | 2.0E+34 | 1.9E+34 | 1.9E+34 |
| GP $L$ in 1% | 1.5E+34 | 1.1E+34 | 1.2E+34 |

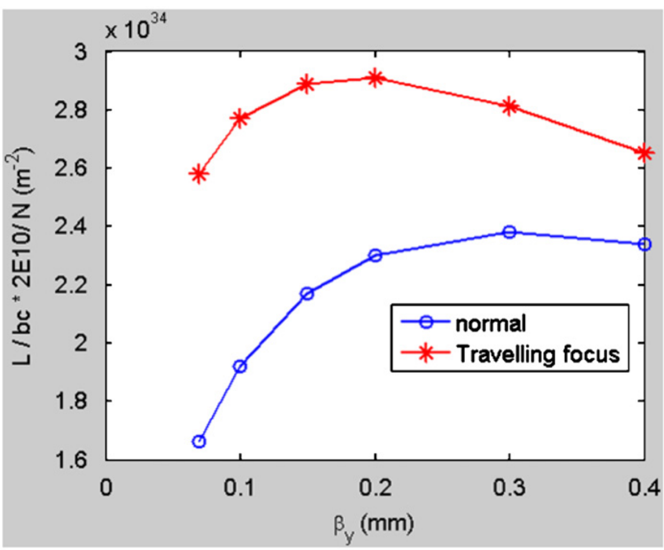


**Fig. 1.** Hour-glass and travelling focus. Luminosity per bunch crossing versus the vertical beta-function.

The hour-glass effect for normal and for travelling focus conditions is shown in Fig. 1 for a beam with 300 μm length. With the travelling focus, the luminosity continues to increase with decreasing beta function, until about half the nominal beta-function.

The new low power parameters have lower beamstrahlung energy spread compared to the RDR low *P* set, but it is still somewhat higher than in the nominal case. The luminosity in the 1% peak, an important criterion for physics performance, is somewhat higher than in the RDR low *P*, but still reduced in comparison with the nominal case.

In the travelling focus regime the beam–beam force keeps the beams focused on each other. For optimal focusing, one is in a regime of higher disruption, which causes higher sensitivity to any beam offset. Thus, operation of the intratrain feedback and intratrain luminosity optimization is more challenging.

One of the important criteria for detector performance is the number and distribution of $e^+e^-$ beam–beam pairs in $\Theta$-$P_t$ coordinates, in particular the location of the edge of the distribution. For the new low *P* parameters, the edge was found to be about the same as nominal. However, the total number of pairs is about twice as large for low *P*.

The travelling focus can be created in two ways. The first way is to have a small uncompensated chromaticity and a coherent *E*–*z* energy shift along the bunch. The second way to create a travelling focus is to use a transverse deflecting cavity giving a *z*–*x* correlation in one of the FF sextupoles and thus a *z*-correlated focusing. The cavity would be located about 100 m upstream of the final doublet, at the $\pi/2$ betatron phase from the FD. The needed strength of the travelling focus cavity can be compared to the strength of the normal crab cavity (which is located just upstream of the FD) and it can be shown that the needed strength of the travelling focus transverse cavity is about 20% of the nominal crab cavity.

### 2.2. Energy recycling in a linear collider

While the low power parameter set may be considered for a new baseline of the ILC, what is described next is a still very preliminary—an idea of energy recycling in a linear collider. If such a possibility would found to be feasible, it may help to reduce the linear collider power consumption and thus contribute to cost reduction, aligning the design with the energy conservation and environmental friendly approaches of the 21st century.

The considered approach is to decelerate the beam, after collision, in the same linac, recover major part of RF energy, dump the beam at low energy of a few GeV, and possibly, recycle the positrons.

The main challenge of beam recycling in a linear collider is that the beam collision creates a noticeable (a few percents) energy spread and also disrupts the beam emittance. For the beam recycling to be feasible, the IP beam parameters must be modified in such a way that the beamstrahlung energy spread would be reduced to about one tenth of a percent, allowing decelerating the beam down to a few GeV. Since the initial $\varepsilon_y$ is so small, its increase practically does not matter, and therefore a large disruption parameter $D_y$ is less of a concern—this gives an additional flexibility for optimization of the IP parameters.

The considered approach for reduction of the beamstrahlung energy spread is to use lower charge, larger number of bunches, smaller emittance and also to consider travelling focus that allow longer $\sigma_z$ and smaller energy spread. The aimed luminosity is 1E34 cm$^{-2}$ s$^{-1}$ which is somewhat lower than the peak ILC luminosity, however all this luminosity will be in the sharp peak, due to low beamstrahlung and thus comparable with ILC nominal parameter case which has ~1.5E34 in the 1% peak of luminosity spectrum.

A particular parameter set that may illustrate conceptual feasibility of beam and/or energy recovery for linear collider is shown in Table 2. The E-recycle set has ten times smaller energy spread after collision as seen in Table 2 and Fig. 2 shows that about 92% of the disrupted beam has an energy offset less that a percent. Thus, 92% of the beam could be decelerated down to about 10 GeV, where dumped (or possibly recovered). Despite the large disruption, the emittance of the disrupted beam does not limit its deceleration – Fig. 3 shows that the beam is contained in *x* within 200mm*mrad (and much smaller in y).

After collisions, the beams, following the 14 mrad crossing angle trajectory, would enter a separate beamline to go around the Beam Delivery System, and be brought back to the ends of the opposite linac. Collimation of about 8% of the beam may be done on the way. This beamline, going around the BDS, could also create $\lambda_{RF}/2$ of path difference, if needed for the beam to RF time matching. If the beam is decelerated in the same accelerating structures, the train structure with mini-trains and gaps can be arranged to avoid collisions of accelerating and decelerating bunches in the linac. The length of mini-trains needs to be equal

**Table 2**
Parameter set for energy recycle in linear collider.

| Parameters | Nom. RDR | E-recycle |
|---|---|---|
| E CM (GeV) | 500 | 500 |
| $N$ | 2.0E+10 | 5.0E+09 |
| $n_b$ | 2625 | 11000 |
| $T_{sep}$ (ns) | 369.2 | 90.0 |
| $I_{ave}$ in train (A) | 0.0087 | 0.0089 |
| $f_{rep}$(Hz) | 5 | 5 |
| $P_b$ (MW) | 10.5 | 11.0 |
| $\gamma\varepsilon_X$ (m) | 1.0E−05 | 4.0E−06 |
| $\gamma\varepsilon_Y$ (m) | 4.0E−08 | 2.0E−08 |
| $\beta_{x/y}$ (mm) | 20/0.4 | 20/0.4 |
| $\sigma_{x/y}$ (nm) | 639/5.7 | 404/4.0 |
| $\sigma_z$ (mm) | 0.3 | 0.6 |
| $D_y$ | 19.0 | 21.2 |
| $U_{ave}$ | 0.047 | 0.009 |
| $\delta_B$ | 0.023 | 0.002 |
| $P_{beamstrahlung}$ (MW) | 0.24 | 0.024 |
| $n_{gamma}$ | 1.29 | 0.53 |
| $H_d$ | 1.70 | 1.53 |
| Geom $L$ (cm$^{-2}$s$^{-1}$) | 1.14E+34 | 6.69E+33 |
| $L$ (cm$^{-2}$s$^{-1}$) | 1.95E+34 | 1.02E+34 |

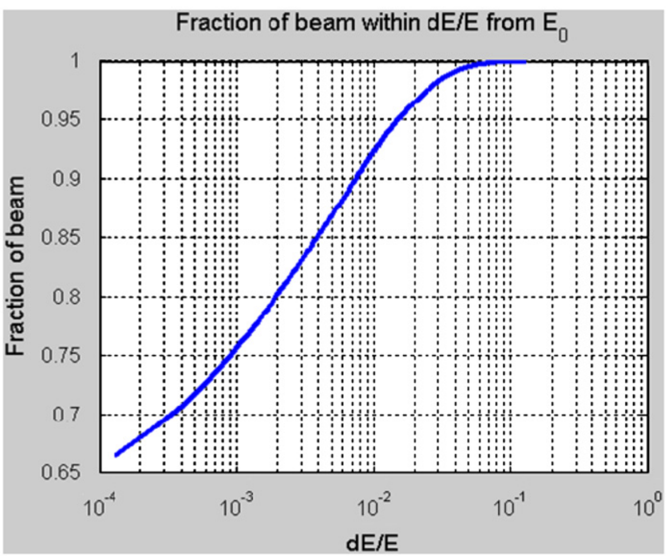


**Fig. 2.** Cumulative distribution of disrupted beam for an energy recycle parameter set.

to the full length of the beam delivery and the gap between mini-trains equal to twice the linac length to the extraction point plus the BDS length. However this arrangement of the train lengthens the pulse and the cryogenic losses. A cleaner possibility may be to use a cryomodule with dual aperture (like LHC magnets) with independent accelerating and decelerating structures.

## 3. Beam collimation and focusing

The beam delivery system of linear collider includes several sub-systems that are necessary for diagnostics, tuning, collimation, focusing the beams and their extraction after collision. Collimation system is one of the primary sub-systems that define the length and performance of beam delivery. The Machine Detector Interface design challenge is associated with the need to satisfy the often conflicting requirements of the machine and detector, while ensuring efficient push-pull operation.

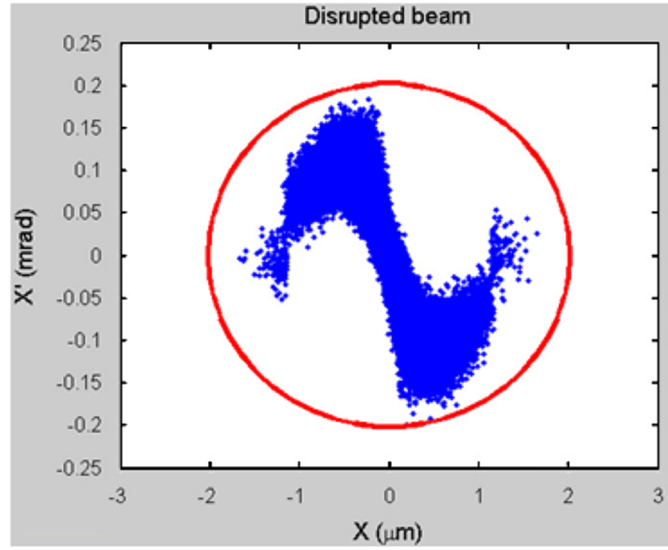


**Fig. 3.** $X$–$X'$ for disrupted beam of E-recycle set. The red circle corresponds to 200 mm*mrad emittance.

### 3.1. Crystal collimation in linear colliders

The collimation system of ILC Beam Delivery System includes the betatron and energy collimation sections. For ILC, the BDS length is 2.2 km per side and the collimation sections occupy almost a kilometre per side of that length. Collimation in ILC is arranged by spoiler-absorber pairs where a thin spoiler placed close to the beam and spreads the beam halo, which is then absorbed at thick absorber placed at large apertures with respect to the beam center. Since the spoiler is placed very close to the beam, the wakefield-caused perturbations it produces on the beam are of a concern. The damage threshold for the spoilers defines the needed beam size, and thus the beta-functions at the spoilers which in turn define the required length of the collimation section.

A question may be asked if a spoiler can be replaced by more "invisible", in terms of wakefields or damage, crystal. The effects of the beams in bent crystals include channeling, de-channeling, volume capture and finally the volume reflection (VR). The latter is of particular interest due to its large angular acceptance (equal to the bending angle of the crystal) and large probability of reflection (about 90% or more of incident particles get reflected). The VR radiation has been recently studied and it was, in particular, shown [6] that volume reflection of 200 GeV electrons or positrons sent onto 0.6 mm Si crystal with 10 meters radius of curvature produces the radiation spectrum peaked at about 30 GeV of the photon energy. It is remarkable that VR radiation spectrum is very similar for both positrons and electrons which make this phenomenon to be a good candidate for collimation system of linear collider, conceptually visualized in Fig. 4.

Crystal survivability is an essential question for consideration of crystal based collimation system. Recent experiments at SLAC devoted to studies of excitation of solid materials by ultra-short bunches have shown a new effect that may be relevant for design of the linear collider collimation system [7]. In this experiment, magnetized samples were placed under the 30 GeV beam with 100fs to 5ps duration, and switching of the original magnetization due to field of the short bunch was studied. Typically, a localized damage was observed in the center of demagnetization pattern, due to the beam. The size of the damage was ten to thirty microns, close to the transverse size of the beam. In this study the new effect was observed: while there was damage of a sample observed for 4ps beam, this damage disappeared for a shorter 140fs beam. A possible explanation of damage disappearance suggested in [7] is that for short bunches the field gradient exceeds 2.5 V over 0.25 nm (typical distance between atoms) so that potential wells around each atom shift, and conduction zones do not overlap any more. Therefore, potential gradient leads to breakup of conduction path, there will be no current and correspondingly no heat transfer and no damage. (The energy still goes into the material, but is probably dissipated via emission of terahertz photons).

Summarizing discussion on new collimation approaches, one can conclude that the Volume Reflection Radiation may be a phenomenon suitable for arranging collimation in linear collider; that with short bunches, the damage threshold is moved out; that there is plausible explanation of the phenomena although further theoretical and experimental studies may be needed, and that this effect may allow the LC collimation system to become shorter (or to have higher safety margin). Detailed studies would require further design studies as well as experiments at facilities like FACET (see below).

### 3.2. Simplified machine detector interface

The ILC approach to stability of beam collision is based on a possibility to apply intratrain feedback within the 1ms long train, which allow avoiding any active mechanical stabilization of Final Doublet and allow to tolerate FD jitter of the order of hundred nm. The kicker of the intratrain feedback in ILC is located between QD0 and QF1, about 10 m from IP.

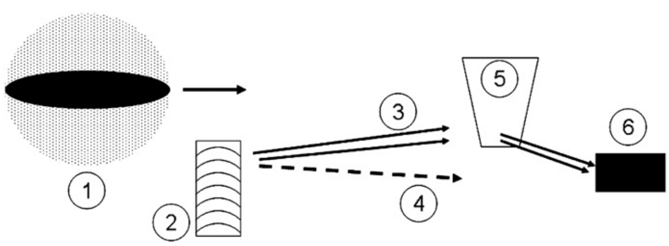


**Fig. 4.** Concept of linear collider collimation system based on volume reflection radiation phenomenon. Here (1) is beam core and beam halo, (2) is bent crystal producing volume reflection, (3) are particles from beam halo that lost about 10–20% of their energy due to volume reflection radiation, (4) photons produced during volume reflection, (5) bending magnets, which separate halo particles that lost significant part of their energy during volume reflection, and (6) absorber of halo particles and photons.

For CLIC [8], with 1 nm beam size and 150 ns long train, one has to use all possible means to provide stability of beam collisions. The trip-around time of the intratrain feedback has to be minimized and thus the kicker and BPM of the intratrain feedback need to be located as close to the IP as possible. Assuming that the kicker and BPM are placed at 2 m from IP, the irreducible delay will be equal to 12 ns. Electronic latency may give another 13 ns [9], giving 25 ns latency in total, allowing about six iterations of intratrain feedback.

Placing the feedback kicker, BPM and the electronics (which may require shielding) inside of detector may require some increase of $L^*$, so it is likely that FD will be partly outside of the detector. Stability of the latter is important—it was observed at SLD that stability of its superconducting triplets was about 30 nm, while stability of the floor was about a nanometer in the same frequency range. While SLD was not designed to be stable, this comparison is indicative—the tunnel floor is likely to be much more stable than the detector. It gives another reason to consider removing FD from the detector entirely, by increasing $L^*$ to about 8 m, and placing FD on a more stable tunnel floor.

For 3 TeV CM CLIC, in order to reduce synchrotron radiation effect from FD on the beam size (Oide limit), one may need to lengthen the FD quads, especially QF1. It may be then practical to split such long quads to independent pieces, reducing stability requirements as $1/N^{0.5}$ (for those frequencies where they will move independently). This will further ease the challenge of FD stability.

Taking all this into account, the CLIC IR with doubled $L^*$ may look as shown in Fig. 5, which would have the following advantages: (a) reduced feedback latency—several iteration of intratrain feedback over 150 ns train; (b) FD placed on tunnel floor, which is ~ten times more stable than detector—easier for stabilization; (c) design is not limited by the sizes of stabilization system or interferometer hardware; (d) push–pull design is greatly simplified; (e) easier FD design and no need for antisolenoid; (f) reduced overall risk and increased feasibility; (g) shorter $L^*$ may still be consider for an upgrade.

Increasing $L^*$ will in principle leads to some reduction of luminosity, due to larger chromaticity and potentially larger aberrations. Another potential limitation is tightening of the collimation depth with longer $L^*$, and corresponding increase of jitter amplification and emittance growth due to collimation wakefields. However, if the collimation depth is limited by extraction apertures, and not by the vertex detector, then the increase of $L^*$ may be done simultaneously with increase of extraction apertures, without tightening of the collimation depth. In such assumptions, analysis for ILC parameters predicted slow decrease of luminosity with increase of $L^*$. For CLIC case the analysis should be repeated.

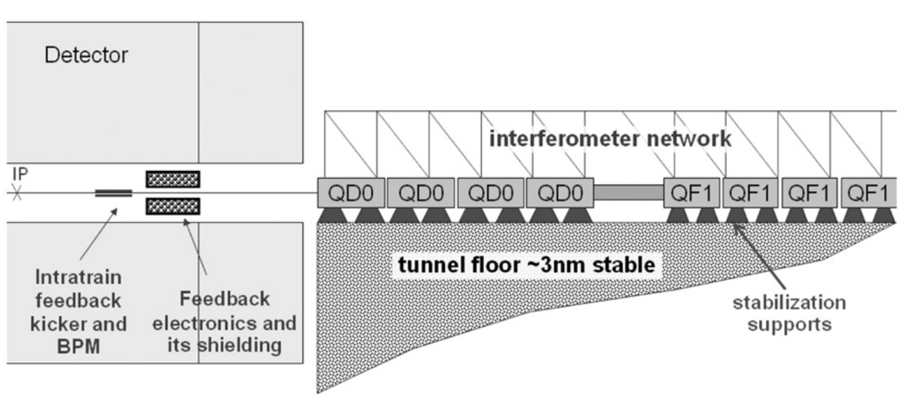


**Fig. 5.** Concept of machine detector interface for linear collider where doubling the distance between IP and first quadrupole allow removing the final doublet outside of detector, simplifying design of push-pull system, and easing stability requirements for the final lenses.

In order to further test the feasibility of such proposal, a tentative version of final focus system with $L^*=8$ m was looked at. A tentative conclusion is that a BDS with $L^*=8$ m may be feasible for CLIC, even for 3 TeV CM. Luminosity (in 1% peak) is close to 80% of the nominal 2E34 (although not including 20% margin to account for errors). Further optimization may be possible.

## 4. Staging of a linear collider

The main motivation for considering staging approach to realization of a linear collider is to get to the physics earlier and for smaller cost. Staging may allow flexible approach to the upgrade path to higher energy that may be adjusted depending on physics results and accelerator technology progress. Therefore, staging approach should be accompanied by pro-active development of advanced methods that may form the basis for future upgrades.

Recently, different staging scenarios for start-up of the International Linear Collider have been considered within the framework of the Global Design Effort (GDE). In particular, in [10] it was suggested to consider the first stage if ILC to be a low energy photon collider, a Higgs factory. A panel commissioned by GDE prepared a report [11] where the physics reach as well as the configurations of the BDS and IP and parameters for the staged ILC were evaluated. In particular, the first stage features a single Damping Ring and a very short BDS (0.3 km per side) without a dedicated collimation system. The photon driver—an FEL photon source [12] or laser can be placed in the BDS tunnel near the IP or in the IR hall. Through several stages, the initial configuration can be brought to the nominal 500 GeV CM $e^+e^-$ state.

One of the essential advantages of the staging approach is that it may allow modifying the energy upgrade path depending on the physics outcome and can take best advantage of emerging technologies, such as the one described in the next section.

## 5. Concept of PWFA linear collider

Plasma wake-field acceleration (PWFA) has demonstrated acceleration gradients above 50 GeV/m [13]. Simulations have shown high (30% or more) energy transfer efficiency from the drive bunch to the witness bunch. This may open the opportunity for a linear collider that could be compact, efficient and more cost effective that the one built with present microwave technologies ([14] and refs therein).

A concept for a PWFA-based Linear Collider is outlined in Fig. 6 and detailed description can be found in [15] and in references therein.

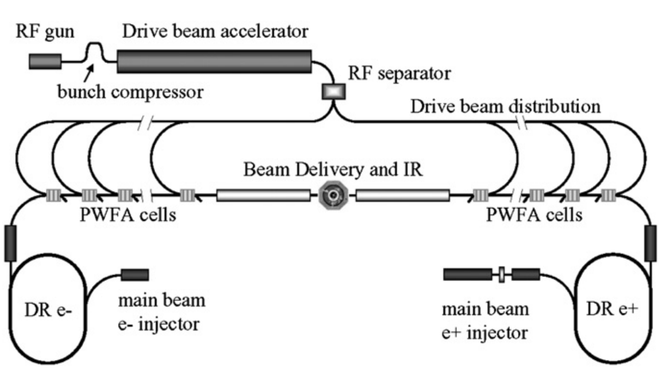


**Fig. 6.** Concept for a multi-stage PWFA-based linear collider.

This PWFA-LC design uses a conventional 25 GeV electron drive beam accelerator, to produce trains of drive bunches distributed in counter-propagating directions to 20 PWFA cells for both the electron and the positron arms of the collider to reach energy of 500 GeV for each beam. Each cell provides 25 GeV of energy to the main beam in about a meter of plasma. The drive beam system is very similar to the CLIC drive beam concept which is being tested at the CTF3 test facility [16].

The main beam bunch train consists of 125 bunches, each separated by 4 ns. The drive beam train consists of 20 mini-trains each with 250 bunches separated by 2 ns. An RF separator splits the drive beam before it is sent to the distribution system. There are 100 ns gaps between each mini-train in the drive beam train, to accommodate the kicker rise time. To allow for the counter-propagation distribution of the drive beam, the distance between PWFA cells must be equal to half of the distance between mini-trains, i.e. 600 ns/2 or about 90 m.

The main beam bunch charge is 1E10 particles with a Gaussian distribution. A plasma density of 1E17 cm-3 and a drive bunch charge of 2.9E10 were chosen to achieve power transfer efficiency from the drive beam to the main beam of 35% with a gradient of roughly 25 GV/m. The drive beam bunch length is 30 $\mu$m while the main beam bunch length is 10 $\mu$m and the drive-main beam bunch separation is 115 $\mu$m. The separation between the two bunches must be approximately equal to the plasma wavelength.

The parameters and luminosity at the interaction point (IP) were optimized for the high beamstrahlung regime. The luminosity within 1% of the nominal CM energy is 1.3E34 $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which is similar to that in the ILC. The relative energy loss due to beamstrahlung is about $\delta_B=30\%$. The main beam emittances are typical for TeV collider designs, and the β-functions at the IP are $\beta x/y=10/0.2$ mm.

The drive beam accelerator is a heavily loaded linac that achieves a high efficiency of power transfer to the beam by using a high peak current and a low gradient. The drive beam distribution system consists of kickers with a 100 ns rise time that distribute drive beam mini-trains into return arcs followed by dogleg magnetic combiners. These combiners use the difference in energy of the drive and main beams to merge the two before the PWFA cells. Similar doglegs are installed at the exit of the cells for beam separation. The combiners also focus the beam to the matched β-functions at the entrance of PWFA cell.

Further plans for development of the concept include both theoretical design study and experimental investigations, at the FACET facility.

## 6. FACET

Facility for Advanced Accelerator Experimental Tests (FACET) will use unique properties of SLAC $e^+$ and $e^-$ beams (ultra-short, high charge, high energy) to provide a unique facility for accelerator research and in particular for studies of various issues associated with plasma-wakefield acceleration [15]. Two electron bunches formed by notch collimator will allow study energy doubling, high efficiency acceleration, emittance preservation. "Sailboat" dual chicane will give unique opportunity to study acceleration of positrons by an electron bunch. The facility will also give unique science opportunities to study variety of applications such as plasma beam source, plasma lens for compact focusing, bent crystal for beam collimation or photon source, dielectric wakefield acceleration, energy-doubling for existing facilities such as FEL's, generation of THz radiation for materials studies.

## 7. Summary

In this article, several ideas and strategies were overviewed some of which may become steps in addressing the challenges of accelerator science.


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