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An Afterburner at the ILC: The Collider Viewpoint *

Tor O. Raubenheimer
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

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INTRODUCTION

The "Afterburner" is a concept introduced in Ref. 1 to use a plasma wakefield accelerator (PWFA) to double the energy of the Stanford Linear Collider (SLC). The SLC operated from 1987 until 1998 with a center-of-mass (cms) energy equal to 92 GeV. The SLC afterburner was considered in the 2003 SLAC Scenarios Study(2) as a route to finding a low mass Higgs but it was determined to be too difficult to revitalize the SLC and the probability of a successful physics study was deemed unlikely.

In this paper, we consider the issues associated with applying the afterburner concept to the next-generation linear collider, referred to as ILC. The international high-energy physics community has endorsed the ILC as the next large scale accelerator project. The collider would be designed to have an initial cms energy of 500 GeV in Phase I which could be upgraded to 1 TeV in Phase II. The peak luminosity of the collider should be in excess of 2×10^{34} $cm^{-2}s^{-1}$. More detailed parameters for the linear collider as determined by the International Linear Collider Steering Committee are described in Ref. 3. The desired completion date for the collider would be in the middle of the next decade and the cost is expected to be many billions of dollars; additional information about the ILC can be found at Ref. 4.

An afterburner might provide a very attractive upgrade path for the ILC under a number of scenarios. First, an afterburner could be used to upgrade the Phase II ILC from a cms energy of 1 TeV to ~2 TeV using with little capital cost and little increase in ac power consumption. The timescale for such an upgrade would likely be after 2020 and the physics motivation would be driven by results from the Large Hadron Collider (LHC) at CERN and the ILC. Second, the afterburner might be used to upgrade the Phase I ILC if there are few available resources but a strong desire to reach ~1 TeV cms energy. The afterburner could be expected to be much riskier than the planned Phase II upgrade but would likely be much cheaper. The timescale for

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this upgrade would be ~2018 and it would be driven by results from the LHC and the ILC. Third, the afterburner could be considered as the Phase II upgrade for the ILC and the additional expense and infrastructure needed to support to nominal Phase II upgrade could be reduced. This would reduce the total project cost by ~10% but would make the upgrade to 1 TeV much riskier. A decision would likely be needed late in this decade, i.e. ~2009.

In the next two sections, we will introduce the afterburner concept and the normal and superconducting versions of the ILC[†] and then we will describe possible configurations for an afterburner focusing on the requirements from the collider viewpoint. In particular, attention will be given to issues that will degrade the performance of the particle detector at the IP of the collider. Finally, we will discuss some of the outstanding questions.

SUMMARY OF THE SLC AFTERBURNER

As stated, the afterburner was introduced in Ref. 1 as a proposal to double the energy of the Stanford Linear Collider (SLC). The basic concept is illustrated in Figure 1. The basic concept was to replace the SLC final focus systems with short plasma wakefield accelerators (PWFA) operating in the "blow-out" regime. In concept, the gradient on the electron side could be ~8 GeV per meter while that on the positron side would be lower due to additional difficulties creating a PWFA channel for the positron beam. The accelerator plasma density would be the order of 10^{22} m^{-3} and the matched beam sizes are ~1 μm.

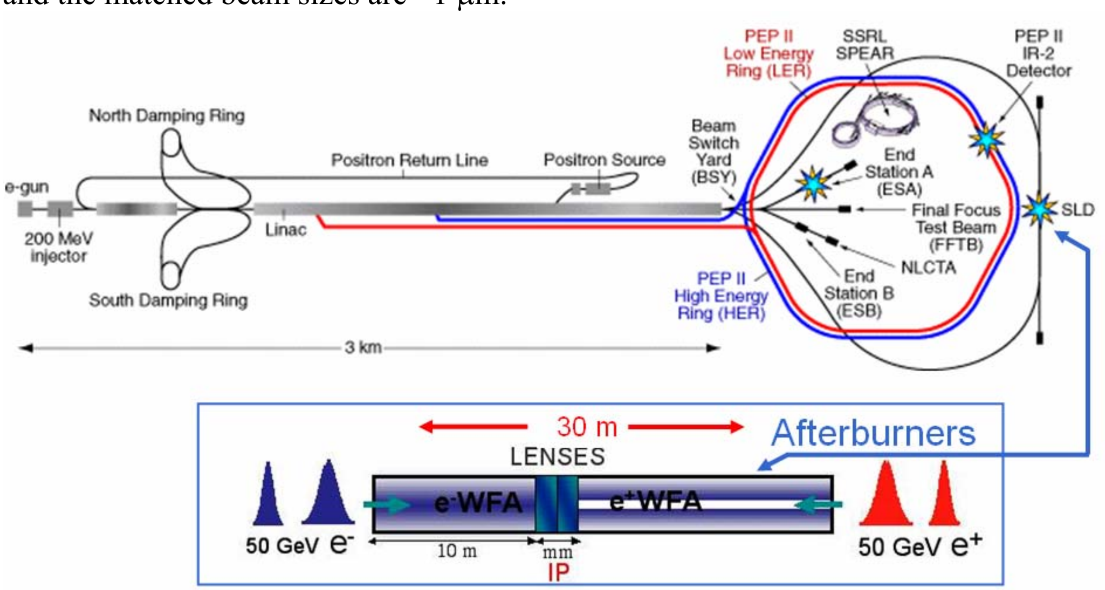

FIGURE 1. Schematic of the SLC Afterburner (from Tom Katsouleas).

To drive the PWFA, it was thought to accelerate a pair of micro-bunches on both the electron and the positron sides to ~50 GeV. In both the electron and positron

[†] At the time of completion of this paper, the International Technology Review Panel had chosen the superconducting technology for the ILC however during the study both options were considered and are thus reported here.

cases, the leading bunch would excite the plasma wave and would have a charge of $\sim 3\times 10^{10}$ $e^{\pm}$ with a bunch length of ~60 μm. This bunch would be decelerated while exciting the plasma and was not thought to contribute to the luminosity. The luminosity production bunches would trail the drive bunches by ~200 μm and would have a charge of roughly 1×10^{10} $e^{\pm}$ with a bunch length that is half that of the drive bunch.

Because of the large induced energy spread in the production bunches, the focusing might be most easily performed with a short plasma lens at the exit of the plasma accelerator. Only a few millimeters of plasma at a density of $\sim 10^{24}$ m^{-3} would be needed to decrease the beam size by an order of magnitude.

ILC LAYOUT AND PARAMETERS

The International Linear Collider is a proposal for a second generation linear collider with an initial cms energy of 500 GeV. Two technologies have been proposed: one with normal conducting rf cavities and one with superconducting rf cavities. Parameters and designs for the two options as developed by the US Linear Collider Steering Group are described in Ref. 5. At the time of the completion of this paper, the International Technology Review Panel(6) had chosen the superconducting technology for the ILC however both options will be described in this paper.

Parameters for the two options as developed in Ref. 5 are listed in Table 1 and a schematic of the US Cold design is shown in Figure 2. The linear colliders consist of fairly complex injector systems to generate the low emittance beams, bunch compressors and spin rotators to shorten the bunch length and orient the beam polarization, long linacs to accelerate the beams, and beam delivery systems to collimate the beam tails and focus the beams down to the small spots necessary to produce the luminosity at either of the two interaction regions (IRs).

Table 1. Parameters for the US Warm and US Cold LC from Ref. 5.

	Stage I		Stage II	
	US Warm	US Cold	US Warm	US Cold
CMS Energy (GeV)	500	500	1000	1000
Luminosity (10^{33})	21	26	31	38
Repetition Rate (Hz)	120	5	120	5
Bunch Charge (10^{10})	0.75	2	0.75	2
Bunches/RF Pulse	192	2820	192	2820
Bunch Separation (ns)	1.4	337	1.4	337
Eff. Gradient (MV/m)	52	28	52	35
Injected $\gamma\varepsilon_x$ / $\gamma\varepsilon_y$ (10^{-8})	300 / 2	800 / 2	300 / 2	800 / 2
$\gamma\varepsilon_x$ at IP (10^{-8} m-rad)	360	960	360	960
$\gamma\varepsilon_y$ at IP (10^{-8} m-rad)	4	4	4	4
β_x / β_y at IP (mm)	8 / 0.11	15 / 0.4	13 / 0.11	24 / 0.4
σ_x / σ_y at IP (nm)	243 / 3.0	543 / 5.7	219 / 2.1	489 / 4.0
σ_z at IP (μm)	110	300	110	300

Pinch Enhancement	1.46	1.77	1.41	1.68
Beamstrahlung δ_B (%)	4.6	3.0	8.2	5.9
Photons per e+/e-	1.2	1.5	1.2	1.6
Two Linac Length (km)	13.4	27	26.8	42.5

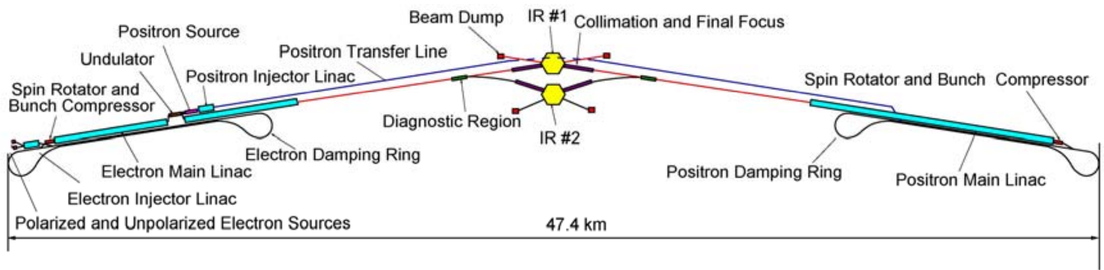

FIGURE 2. Schematic of the US Cold LC layout from Ref. 5.

The beam delivery system is roughly 1.8 km per side. The beamlines contain the post-linac emittance diagnostics, linac beam dumps, a beam switchyard to direct the beams to one of the two IRs, and the final focus with an integrated collimation system. Both the Warm and Cold designs have crossing angles of 20 to 30 mrad at the two IPs which will likely be necessary to extract the highly disrupted beams. Assuming average gradients >1 GeV per meter, the final focus beamlines contain plenty of space for a plasma wakefield accelerator to accelerate the beams by another 500 GeV per side to reach cms energies of 2 TeV.

To achieve the desired luminosity with a manageable efficiency and ac power consumption, the both the Warm and Cold designs operate with long trains of bunches. At a cms energy of 1 TeV, the average beam power is 10 ~ 20 MW per beam. For the PWFA, this may prove to be one of the largest difficulties because a large fraction of this energy is lost to the plasma leading to an energy deposition at the level of 100 kW/m. Maintaining uniform plasma density under such conditions may prove difficult.

POSSIBLE AFTERBURNER CONFIGURATIONS

To evaluate the feasibility of an Afterburner for the ILC, we developed a parameter set by scaling from the parameters of the SLC Afterburner(1). In particular, each bunch in the bunch train consists of two micro-bunches having a charge ratio of 3:1 and a total charge equal to that of the nominal LC parameters. The achievable gradient was scaled as N / σ_z^2 from the SLC afterburner parameters which estimated a gradient of 8 GeV/m assuming a charge of 3×10^{10} e^- and a bunch length of 63 μm(1).

The three major differences between the concept suggested here and the original SLC design that will be discussed are the required multi-bunch operation, the drive beam generation, and an insertion between the final focus and the PWFA that will almost certainly be needed to minimize backgrounds and provide feedback control on the beam pointing to ensure collisions at the IP. Indeed, if a suitable conventional transport line/final focus could be designed, it would be most advantageous to place the PWFA at the end on the rf linac rather than closer to the IP.

Afterburner Beam Parameters

The parameters for the Afterburners where chosen with a goal of achieving a luminosity, at a cms energy of 2 TeV, in excess of 1×10^{34} $cm^{-2}s^{-1}$ which is probably the minimum value of interest. There are three terms that determine the luminosity: the bunch charge, the spot sizes, and the number of bunches per rf pulse. To achieve any reasonable luminosity without excessive ac power requirements, all designs will need to operate with multi-bunch trains. For this design iteration, we simply assumed the nominal train structure for the linear colliders.

Thus, in the case of the US Warm design, it was assumed that the collider would operate with a 2.8 ns bunch spacing which is double the nominal case of 1.4 ns(7). The larger bunch spacing allows a higher bunch charge of 1.5×10^{10} so the average loading is the same as nominal and the number of bunches is halved. The drive bunch length was assumed to be 66 μm and the production bunch length was assumed to be 33 μm which is 1/3 the nominal bunch length of 110 μm. The micro-bunch separation was chosen to be 200 μm so that the effect of the longitudinal wakefield in the X-band linacs could be easily compensated by running off-crest. The scaling then suggests a gradient of roughly 3 GeV/m with a plasma density of $\sim2\times10^{22}$ m^{-3}.

In the case of the US Cold design, the nominal US Cold parameters were assumed for the bunch charge however, to achieve reasonable gradients, the bunch length of the drive and production bunches were assumed to be 100 μm and 50 μm. In this case, the production bunch length is 1/6 the nominal bunch length. The micro-bunch separation was again assumed to be 200 μm where the overlap between the two micro-bunches was becoming large. In this case, the scaling suggests a gradient of 4 GeV/m with a plasma density of $\sim2\times10^{22}$ m^{-3}.

Table 2. Possible afterburner parameters for the US Warm and US Cold LC.

	2 TeV		2 TeV	
	US Warm	Afterburner	US Cold	Afterburner
CMS Energy (GeV)	1000	2000	1000	2000
Two Linac Length (km)	26.8	0.33	42.4	0.25
Repetition Rate (Hz)	120	120	5	5
Bunch Charge (10^{10})	1.5	1.1 / 0.4	2.0	1.5 / 0.5
Bunches/RF Pulse	96		2820	
Bunch Separation	2.8 ns	0.67 ps	337 ns	0.67 ps
Beam Power (MW)	14	28	23	45
Eff. Gradient (MV/m)	52	3000	35	4000
Plasma density (m^{-3})		2.0×10^{22}		2.0×10^{22}
$\gamma\varepsilon_x$ at IP (10^{-8} m-rad)	360	360	960	960
$\gamma\varepsilon_y$ at IP (10^{-8} m-rad)	4	4	4	4
Plasma Lens Reduction		10		11
σ_x / σ_y at IP (nm)	219 / 2.1	37 / 3.9	489 / 4.0	60 / 3.9
σ_z at IP (μm)	110	33	300	50
Pinch Enhancement	1.46	1.1	1.7	1.2

Beamstrahlung δ_B (%)	8.2	42	5.9	36
Photons per e+/e-	1.2	2.0	1.6	1.9
Luminosity (10^{33})	31	10	38	14

At high energy, the beam-beam forces disrupt the outgoing beams and generate large quantities of beamstrahlung. The usual remedies for minimizing the beam-beam effects are to collider very flat beams having ~100:1 horizontal to vertical aspect ratios and to keep the bunch charge relatively low. The large aspect is actually relatively straightforward in that it takes advantage of two features: first, the low emittance beams are generated in damping rings where flat beams are naturally generated, and, second, the quadrupole magnet focusing is naturally asymmetric and naturally yields a tighter focus in one plane compared to the other.

Unfortunately, because of the energy spectrum coming from the PWFA which is expected to be ~10%, a conventional final focus will likely be difficult to implement (although a conventional FFS still warrants investigation). Instead, the SLC Afterburner assumed that a plasma lens could be used to demagnify the beams by a factor of ~10. Assuming a matched input beam, a plasma lens of roughly 4 cm in length with a plasma density of $\sim 2\times 10^{24}$ m^{-3} would demagnify a 1 TeV beam by a factor of 10 in both planes which, given the bunch train discussed above, would be sufficient to provide a luminosity of $\sim 1\times 10^{34}$ $cm^{-2}s^{-1}$.

Beam Generation

In both cases, it was assumed that the linear collider damping ring complex would be used to generate the low charge production bunches. The damping rings generate "flat" beams with vertical emittances that are less than 1% of the horizontal. The lower bunch charge should make the damping rings easier to operate although the shorter compressed bunch length will complicate the design of the bunch compressors. In particular, the single-stage bunch compressor in the US Cold design will need to be upgraded to a two-stage compressor like that in the US Warm design. This would entail some fairly significant modification to the present design. In the US Warm case, the modifications would including adding another 1 GeV of X-band acceleration and reducing the strength of the compressor chicane which should be relatively straightforward provided there is adequate space. There are concerns about emittance dilution due to Coherent Synchrotron Radiation which will need to be investigated although simple scaling from the US Warm and Cold parameters suggest that the impact will be relatively small.

Two options were considered for the drive bunch generation. First, they could be generated and merged with the drive bunches at relatively low energy after the final bunch compression and co-accelerated in the main linacs along with the production bunches. This would allow a single PWFA stage and it allows for reasonable IP parameters with relatively low production bunch charge – this is useful at high energy where the IP beam-beam forces can create a mess. Advantages of this approach are that it optimally uses the main linac and requires a relatively small addition to the injector system. The primary disadvantages of this approach is the difficulty in separating the drive beam from the production beam close to the IP and the difficulty in creating the drive bunches for the positron beam which most likely must be positrons because they are co-accelerated adjacent to the production positron bunches.

Second, it might be possible to generate a series of low energy drive beams. In this case, the production bunches would be accelerated in the main linac and the drive bunches might be generated in a long train in a scheme similar to the CLIC drive beam although the timing is more difficult to arrange than in CLIC. One advantage of this scheme is that electrons could be used for both drive beams. In addition, this approach has the significant advantage that it would be simple to separate the drive beam from the high energy production beam which will reduce background sources at the IP. However, the PWFA would need to be staged which will greatly increase the complexity. Furthermore, to minimize the ac power consumption, the collider would need to operated at lower repetition rate and likely the luminosity would be lower for the same ac power consumption.

Interaction Region Issues

In addition to providing the basic high-energy beams, there are a number of issues that need to be addressed to provide useful luminosity for the detector. First, before colliding the beams, the beam halos will need to be collimated to background in the detector – even a single high energy errant electron showering in the detector could impair the performance. The beam tails and backgrounds from the rf linac would be removed by the primary collimation system however removing those from the PWFA which would be placed closer to the IP will likely be more difficult. The primary backgrounds arise from elastic or inelastic scattering off the plasma nuclei. Expression for the scattering rates can be found in many of the studies for the linear colliders – see Ref. 8 for example.

Assuming a Lithium plasma, simple estimates of the halo suggests that roughly 10^{-6} of the beam, i.e. roughly 10^{9} particles per second, will be elastically scattered out to amplitudes of ~40 μm which is beyond the plasma channel in the PWFA. Without some external focusing or collimation, these particles might then continue at large amplitudes and shower in or near the detector. Similar estimates for the inelastic collisions suggest that there would be roughly 10^{11} photons with energies 1 GeV or higher that would be emitted with angles of ~10 μrad. While many of these could pass through the IP, some level of collimation will be required to protect the detector.

Next, as discussed, the present concept is to use a plasma lens to demagnify the beams by a factor of 10 in both planes at the IP. In addition to many questions of implementation, there are three IR related concerns here. First, the lack of a natural focusing axis puts severe constraints on the beam orientation to ensure collisions. An IP beam position feedback will almost certainly be needed to maintain luminosity. Second, there are questions of the plasma lens viability in the presence of a strong solenoidal field as is frequently used in the detector. Third, the plasma lens will generate sources of detector backgrounds very close to the IP and the plasma might damage the vertex detector that surrounds the IP.

Third, because of the rounder beam spots sizes and the higher collision energies, the beam-beam interaction in the Afterburner will be much greater than in the nominal LC designs and thus luminosity spectrum will be degraded and the beam disruption due to the collision will be greater. The beam disruption and resulting outgoing energy spread likely means that a crossing angle will be necessary in both the Warm and Cold designs[‡]. One difficulty associated with a crossing angle is the need for crab-crossing where a transverse rf deflector is used to kick the tail of the beam relative to the head; the ratio of the IP $\sigma_x / \sigma_z \sim 10^{-3}$ and thus there will be significant luminosity loss for crossing angles larger than 1 mrad without crab-crossing.

Finally, the beam properties need to be measured before the collision to provide information for the particle physics detector. This includes the average beam energy and energy spread and the beam polarization.

For all the reasons mentioned above, a plasma-free region close to the IP of up to a few hundred meters in length will likely be needed. It has been assumed that a conventional final focus with the necessary bandwidth would not be possible to implement; the plasma lens provided effective beta functions of ~700 μm in both planes which would be difficult to achieve even without the added bandwidth requirements. However, matching in and out of the PWFA with effective beta functions of roughly 7 cm would be much easier. Thus, it is suggested that a conventional optics insert be developed that would be placed between the PWFA and the plasma lens which will perform the necessary functions for the IR.

CONCLUSIONS

In this paper, we discuss a possible afterburner for the ILC that might double the energy reach to a cms energy of 2 TeV while still attaining a reasonable level of luminosity. Key features of such a device would be a PWFA hundreds of meters long, a short plasma lens to focus the beams at the IP, an insertion region between the two for beam collimation, feedback, and diagnostics, and operation with long bunch trains. The parameters chosen for this study were scaled from those in Ref. 1 and a detailed parameter optimization should be performed and a better understanding of the efficiency of such an accelerator should be attained[(9)].

Of course, there are numerous problems associated with such a concept as the Afterburner. These include plasma physics issues such as maintaining uniform plasma density while depositing ~100 kW/m into the plasma, preventing a hosing instability through hundreds of meters of plasma, and accelerating and focusing the positron beam. They also include issues regarding preservation of the flat beam emittances through the plasma, collimating the extensive beam halo, developing a reasonable IR insertion with the required functionality, and providing the necessary beam stability to reliably log luminosity. Regardless, the concept is very attractive as an upgrade because of the relatively low cost and minimal civil construction.

[‡] A crossing angle is clearly necessary in the Warm design and is likely necessary for the cold design to ensure that the outgoing beam can have a clear exit channel with minimal particle loss.

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