ILC possibilities at Z and W

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Introduction

In the following note, we will review the possibilities and associated issues with running the ILC at 90 GeV and 160 GeV centre of mass for physics, based on the published TDR machine, extended where necessary.

The quoted performance figures are the result of simple scaling of the published TDR parameters, and should be taken as tentative, subject to further detailed studies and simulations (when resources are available).

Gamma scaling at its limitations

Figure 1 shows the published TDR baseline luminosity parameters (200—500 GeV) for both the analytical (dashed line) and GUINEA PIG simulated results (solid line), the latter also including the effect of the waist shift optimisation, resulting in slightly higher values for the higher E_{cm} operating points. The analytical values also include an extension to 90 GeV and 160 GeV, essentially assuming the luminosity scales as γ (constant IP beta functions). Table 1 gives the corresponding analytical values for the low-energy running points.

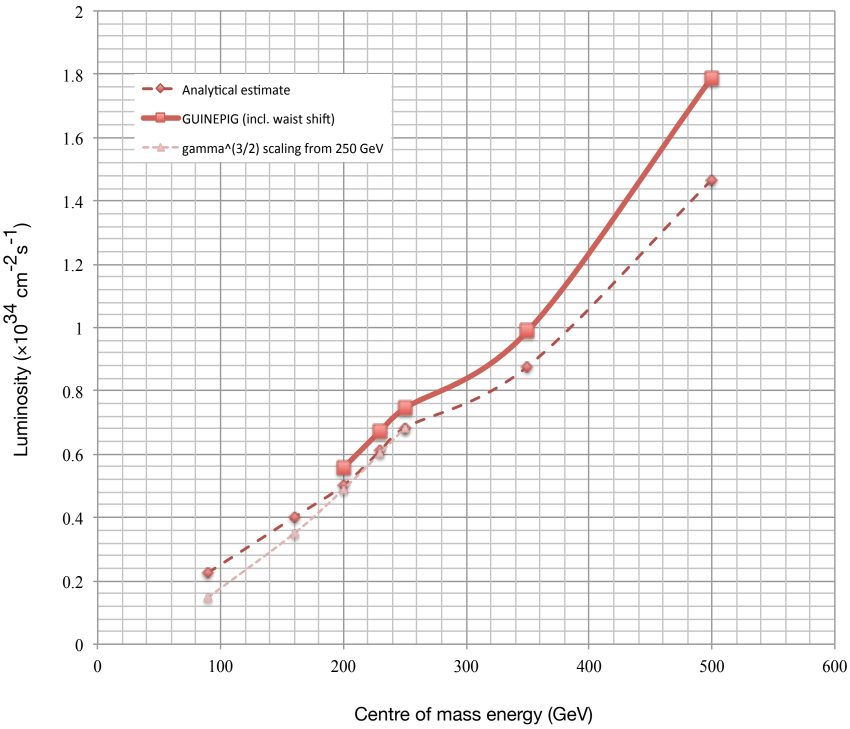

Figure 1: ILC luminosity parameters versus centre of mass energy. Data points are the published numbers, with the exception of the 90 GeV and 160 GeV analytical points. The $\gamma^{3/2}$ scaling (from the 250 GeV luminosity) is also shown.

Table 1: Low-energy centre of mass parameters assuming constant IP beta functions and the TDR beam parameters.

Centre-of-mass energy	$\boldsymbol{E_{cm}}$	**GeV**	**90**	**160**
Beam energy	E_{beam}	GeV	45	80
Collision rate	f_{rep}	Hz	5	5
Number of bunches	n_b		1312	1312
Electron bunch population	N_-	$\times 10^{10}$	2.0	2.0
Positron bunch population	N_+	$\times 10^{10}$	2.0	2.0
Bunch separation	Δt_b	ns	554	554
Bunch separation $\times f_{\mathrm{RF}}$	$\Delta t_b f_{\mathrm{RF}}$		720	720
Pulse current	I_{beam}	mA	5.8	5.8
RMS bunch length	σ_z	mm	0.3	0.3
Electron RMS energy spread	$\Delta p/p$	%	0.42	0.24
Positron RMS energy spread	$\Delta p/p$	%	0.42	0.24
Electron polarisation	P_-	%	80	80
Positron polarisation	P_+	%	31	31
Horizontal emittance	$\gamma\varepsilon_x$	µm	10	10
Vertical emittance	$\gamma\varepsilon_y$	nm	35	35
IP horizontal beta function	$\beta_x{}^*$	mm	16.0	16.0
IP vertical beta function	$\beta_y{}^*$	mm	0.34	0.34
IP RMS horizontal beam size	$\sigma_x{}^*$	nm	1348	1011
IP RMS veritcal beam size	$\sigma_y{}^*$	nm	11.6	8.7
IP RMS horizontal divergence	$\theta_x{}^*$	µrad	84.2	63.2
IP RMS vertical divergence	$\theta_y{}^*$	µrad	34.2	25.6
Horizontal distruption parameter	D_x		0.2	0.2
Vertical disruption parameter	D_y		24.3	24.3
Horizontal enhancement factor	H_{Dx}		1.0	1.0
Vertical enhancement factor	H_{Dy}		4.5	4.5
Total enhancement factor	H_D		1.7	1.7
Geometric luminosity	L_{geom}	$\times 10^{34}$ cm^{-2}s^{-1}	0.13	0.24
Luminosity	$\boldsymbol{L}$	**$\times 10^{34}$ cm^{-2}s^{-1}**	**0.23**	**0.40**
Average beamstrahlung parameter	Y_{av}		0.004	0.009
Maximum beamstrahlung parameter	Y_{max}		0.009	0.022
Average number of photons / particle	n_γ		0.65	0.85
Average energy loss	δE_{BS}	%	0.11	0.34

The simple γ scaling ($L \propto \gamma$) gives approximately 2×10^{33} cm^{-2}s^{-1} and 4×10^{33} cm^{-2}s^{-1} for 90 GeV and 160 GeV respectively. However, these values are likely to be optimistic due to the following issues.

IP beam divergence and collimation depth

The assumption of constant beta functions at the IP result in the IP beam divergence scaling as $1/\sqrt{\gamma}$. This has implication of machine-related (beam halo) backgrounds in the detector, as well as the impact of collimator wakefields in the collimation system of the beam delivery system. A more conservative approach is to hold the beam divergence constant, which would lead to a $L \propto \gamma^{3/2}$ scaling if we only consider the horizontal plane (in general the more demanding for backgrounds), or $L \propto \gamma^2$ if the divergence of both planes is held constant. Figure 1 also shows the $L \propto \gamma^{3/2}$ scaling from the 250 GeV TDR luminosity, which results in luminosity estimates of 1.5×10^{34} cm^{-2}s^{-1} and 3.5×10^{34} cm^{-2}s^{-1} for 90 GeV and 160 GeV respectively. $L \propto \gamma^2$ results in $\sim1\times10^{33}$ cm^{-2}s^{-1} and $\sim3\times10^{33}$ cm^{-2}s^{-1} (90 GeV and 160 GeV respectively).

It should be noted that the TDR solution for $E_{cm} \leq 250$ GeV already assumes an effective “shorter” FD solution that enables the collimation depth (and hence divergence) to be increased. A similar reconfiguration of the final focus system for 90 GeV or 160 GeV may also be possible (or even mandatory), although in this case it may ultimately require the FD to be physically replaced by a different solution.

Emittance preservation in the main linacs and BDS.

Preserving the small vertical emittance in general becomes more demanding at lower beam energies. Chromatic emittance growth scales quadratically with the beam energy spread ($\delta = \Delta E/E$). Since the energy spread scales inversely proportional to the beam energy, the chromatic emittance growth scales as $1/\gamma^2$. Similarly emittance growth due to transverse wakefields also scales as $1/\gamma^2$. In the beam delivery system, the larger emittance increases sensitivity to higher-order geometric aberrations in the Final Focus System ($\propto 1/\gamma^{3/2}$ for third-order aberrations). All of these effects will combine to further dilute the luminosity at these lower beam energies (or result in more demanding tolerances). Quantification of these effects requires further beam dynamics studies, but the effects should not be more than 10—30%.

Positron production

Polarised positron production

By far the most demanding challenge for low-energy operation is the production of polarised positrons, using the baseline undulator-based scheme. The source as described in the TDR effectively ‘turns off’ at an electron beam energy of 100-125 GeV (200-250 GeV CM). For the 147 m undulator in the TDR, the positron yield (e^+ per e^-) is ~1 at a beam energy of 125 GeV . Since publication of the TDR, simulations have shown that the desired yield of 1.5 can be regained at 125 GeV beam energy by increasing the undulator length to ~230 m (the length currently reserved for the upgrade to higher polarisations). Nonetheless, the yield rapidly decreases below this energy, to the point that there is no practical solution for physics operation below ~230 GeV.

The solution proposed in the TDR was the so-called 10-Hz production mode, whereby the electron main linac was pulsed at 10-Hz, with alternative pulses used to accelerate a beam at 150 GeV for positron production and $E_{cm}/2$ for collisions respectively. Simulations made of the main linac transport with realistic misalignments showed that the higher-energy e+ production beam of 150 GeV could be successfully accelerated and transported along a linac tuned for 100 GeV beam (200 GeV CM operation). However, the production beam was several millimetres off axis at the entrance to the undulator, requiring a pulsed magnet correction system to correct the beam trajectory. Furthermore, a pulsed extraction system after the undulator was required to remove this unwanted beam to a high-powered beam dump. While considered conceptually feasible, the exact design details of this solution have never been worked out in any detail.

For the recent focus on 250 GeV CM operation by the Joint Parameters Working Group, the longer undulator solution has always been considered more attractive. We should note that implicit adoption of this solution allowed us to consider increased repetition rate (10 Hz) for high luminosity running. Using the 10-Hz production scheme would limit collisions to 5 Hz.

For 90 GeV and 160 GeV operation, it is quite likely that 10-Hz production scheme will prove intractable, since the e^+ production beam is (for 90 GeV CM operation) a factor of three larger in energy. This remains to be studied.

A possible solution is to reconfigure the electron linac as shown schematically in Figure 2:

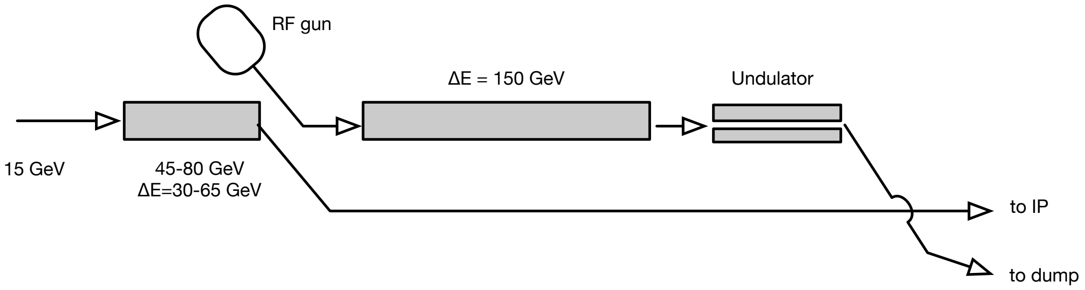

Figure 2: "Giga Z" configuration for polarised positron production.

The concept is to segment the main linac into a short linac for physics beam acceleration, and then use the remaining linac for positron production. Assuming a total of 150 GeV is required for positron production, this would leave ~98 GeV for physics (assuming only a few GeV need to be removed to provide sufficient space between the linac segments). The exact length of warm insert required is likely to be defined by the length of the ~100 GeV beam transport chicane.

The scheme also has advantages for beam dynamics (emittance preservation), since we accelerate the beam at the maximum gradient to 45 GeV (80 GeV) as quickly as possible and then transport it through a relatively low impedance transport line (as compared to the main linac accelerating structures).

Taking the current TDR linac cryogenic segmentation, there is a natural location between the second and third cryo unit in the electron Main Linac (see Fig. 3). Locating a 100—200 m warm insertion at this point would not require any additional 2K bypass. However, the impact of an additional serviceable electron source at this point (for the e^+ production beam) on the CFS housing requires careful study, as does the possibility of adding an additional long low-emittance transport line in the Main Linac tunnel. Furthermore, the 150 GeV e^+ production beam needs to be transported to a beam dump in the BDS, similar to the situation with the 10-Hz production scheme (although without the pulsed extraction). While conceptually feasible, the scheme requires a careful design study to arrive at a practical solution and to address the impact on the CFS.

Clearly removing linac and installing a new electron source and beam transport lines would require a significant shutdown. When considered in this way, a Giga-Z / W programme should only be considered after the main 250—500 GeV programme is complete (possibly before either of the two planned upgrades). It is quite feasible however to include this configuration from 'day one', adding the required tunnel length, and linking the two linac segments via a warm beam line. If all the accelerator hardware is installed, it would in principle be simple to switch between the two modes of operation, albeit at the additional expense of the new accelerator hardware and tunnel length. However, the impact on the BDS may ultimately still require an invasive reconfiguration.

Finally, we should also note that the e^+ production beam will have a much larger longitudinal and transverse emittance in this scheme, being neither damped or longitudinally compressed. The impact on target performance and yield – particularly of the long electron bunch– needs to be checked.

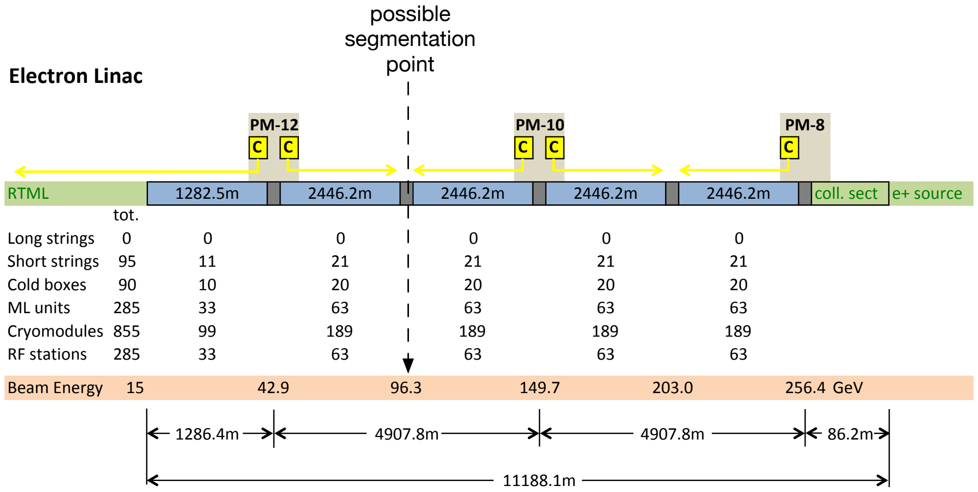

Figure 3: Possible location for the segmentation point for the Giga-Z configuration. The locations between two cryo-units avoids the need for a cryo bypass line.

Unpolarised positron production

The 300-Hz electron-driven positron source being developed by KEK is an independent source and will therefore provide the design positron current independent of the centre-of-mass energy. If polarised positrons are not required for physics, then operation down to the Z-pole becomes relatively straightforward, and would in theory not require any major reconfiguration to the machine, except for the considerations of the final focus (final doublet) mentioned in the previous section. One additional caveat is that it may still be advantageous to include a bypass line to avoid transporting the low-energy beam through the entire linac to avoid excessive emittance growth. Again further simulation work is necessary to quantify these effects.

Possible scope for increasing luminosity at 90 and 160 GeV

In this section we will briefly discuss luminosity upgrade scenarios for low-energy operation. We do not consider any changes to the injector chain (damping rings *etc.*), other than that already foreseen in the TDR.

- **TDR luminosity upgrade**: The TDR proposed to upgrade the luminosity by a factor of two by doubling the number of bunches per RF pulse. This requires adding an additional 50% of klystrons and modulators, as well as a possible second positron damping ring. There are no particular issues with the low-energy running scenarios discussed here, and so the same factor of two can also be assumed at 90 GeV and 160 GeV, resulting in 2—4×10^{33} $\mathrm{cm^{-2}s^{-1}}$ and 6—8×10^{33} $\mathrm{cm^{-2}s^{-1}}$ respectively.
- **Higher repetition rates**: During the recent discussions on 250 GeV CM operation in the Join Parameters Working Group, it was assumed that 10-Hz collisions could be established at 250 GeV CM since the lower required linac gradients provided sufficient overhead for both the average RF AC power and cryo power. This effectively gave another factor of two in the luminosity. However, this is not possible with the Giga-Z scheme, since the positron production linac segment now has to run at full gradient to achieve the required 150 GeV. (In principle, at 45 GeV beam energy, the upstream linac could be run at lower gradient and thus at a higher repetition rate, but this is of no benefit unless positrons can be produced at the same rate.) The non-polarised source (300-Hz electron-driven) already requires a 100 ms damping ring storage time and therefore excludes 10-Hz operation at any E_{CM}, although it may be possible to go to 6 Hz.
- **Pushing Beamstrahlung**: At 90 GeV CM the Beamstrahlung energy spread is of the order of 0.1%. In principle the luminosity can be increased at the expense of higher Beamstrahlung ($L \propto \sqrt{\delta_{BS}}$), by stronger focusing in the horizontal plane. However, this is likely to be constrained by the increase in horizontal beam divergence at the IP as discussed previously.

Summary

The ILC baseline machine can in principle operate at the Z pole and W threshold with luminosities in the ranges of 1—2×10^{33} cm^{-2}s^{-1} and 3—4×10^{33} cm^{-2}s^{-1} respectively. More refined estimates require beam dynamics studies of emittance dilution in the main linacs and BDS, as well as background simulations due to the increase beam divergence and the IP (collimation depth). Such low-energy operation may require an invasive reconfiguration of the beam delivery system –and in particular the final doublet.

Generating polarised positrons using the baseline scheme would require ideally require the main electron linac to be segmented at about the nominal 96 GeV point (Fig. 3), as well as installation of a dedicated electron gun for positron production, and a long low-emittance low-energy beam transport line to the central region. Furthermore, the 150 GeV e^+ production beam will need to be transported to a high-power dump in the central region. This configuration can in principle be made compatible with nominal (high CM operation), but it is assumed that it would more likely be included as an upgrade to the machine for a dedicated "Giga-Z" run at some point.

The 10-Hz positron production scheme briefly described in the TDR may also work at these low energies but is more demanding, both from practical aspects of accelerating and transporting two very different beam energies, as well as for emittance preservation of the lower-energy luminosity pulse.

If unpolarised positrons are sufficient, then the 300-Hz electron-driven source simplifies the scenario and running at low energies for physics becomes more straightforward, although it may turn out that a long low-energy low-emittance transport line is still beneficial.

Irrespective of the scenario, there remains significant design optimisation and simulation work to be done, in particular to ascertain the impact on the CFS.

The factor of two in luminosity from the TDR luminosity upgrade (factor of two in beam power) is in principle directly applicable to the Giga-Z scheme. However, there appears to be no possibility of increasing the repetition rate to further increase the luminosity. Increasing the beam-beam interaction may also prove difficult due to larger beam divergence at the IP (assuming no major re-work of the IR region in undertaken).