Perspectives on International Superconducting Linear Colliers (ILC) to the Next Century
Part B: ILC Energy Upgrades to 3 TeV and Beyond

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In Part A of this LOI (submitted to Snowmass Group AF3) we offered comparisons between the different Higgs Factory options in terms of cost, AC power, luminosity, and technological readiness to indicate why the ILC remains the most technologically mature of all possible options ready for an expeditious start. We showed how recent advances in SRF allow the ILC baseline[1] luminosity to be upgraded by a factor of 6, to be competitive with the proposed FCCee[2], but at substantially lower cost. We also discussed in Part A the Top Factory upgrade with estimated costs.

An equally strong physics attraction of ILC is the inherent energy upgradability of the linear collider offering clean e^+e^- physics *to the next century*. Both the ring options, FCCee and CEPC[3] top out at about 380 GeV energy due to synchrotron radiation limits. In this LOI Part B (and following white paper), we show how ILC offers well defined paths to sequential energy upgrades of 0.5 TeV, 1 TeV, 2 TeV and 3TeV with expected SRF cavity performance upgrades to 40, 50 and 60 and 80 MV/m, as well as cost reductions due to large scale implementation. Physics discoveries from 1 TeV may warrant going directly to 3 TeV, which will accelerate the 3 TeV timeline by 10 years. The upgrade path to 3 TeV (competitive with CLIC 3 TeV[4]) is opened by R&D on travelling wave superconducting structures [5] with effective gradients up to 80 MV/m and 25% *R/Q* enhancement. Optimistically the overall gain from TW operation, Low Loss shape, and 50 mm aperture could add up to 60% over the SW TESLA shape. Modelling, optimization and calculations need to confirm these expectations. Finally, a plasma-wakefield accelerator [6] (PWFA) with gradients of many GeV/m would offer dramatically lower capital and operating costs to multi-TeV regime, as physics needs indicate. PWFA technology could well be forthcoming from R&D over the intervening five decades after launch of ILC. We are therefore interested in a detailed discussion of these topics related to ILC energy upgrade potential during the Snowmass process.

High Level Parameters

Table 1 compares the costs, luminosity, AC power, and other parameters for the ILC machines, from 0.25 – 3 TeV. (This Table bypasses the 6xHigh Luminosity ILC250 upgrade phase discussed in Part A.) The cost for the starting Higgs factory (5.5B ILC Units) is consistent with the ILC TDR, amended by Japan [1]. The additional cost for 500 GeV (+2.6B) makes the cost consistent with ILC 500 GeV TDR (in 2012 ILCU) [7]. For the Top Factory, the additional linac is based on a gradient of 40 MV/m at $Q = 2\text{x}10^{10}$. For the 500 GeV upgrade, the additional linac is based on a gradient of 50 MV/m at $Q = 2\text{x}10^{10}$. For the 1TeV and 2 TeV upgrades the gradients for the additional linacs are based on 60 MV/m at $Q = 2\text{x}10^{10}$. As will be discussed in the white paper, these gradient advances are based on proof-of-principle results already in hand for single cell cavities prepared from improved treatments and improved shapes, as well as expected progress from R&D over the intervening decades. Finally, for the 3 TeV upgrade we use a gradient of 80 MV/m for the additional 1 TeV based on an overall 60% reduction in peak surface magnetic field over the Standing Wave TESLA structure due to travelling wave (TW) mode operation [5] advanced shape (e.g. Low Loss shape [8]) and reduced aperture, together with 25% increase in *R/Q* from using an improved shape cavity. Alternatively, if Nb3Sn cavities continue to make progress [9] we can expect 80 MV/m gradients at *Q* values higher than $3\text{x}10^{10}$ and lower cryogenic losses from the use of advanced shape structures. The paper will discuss efforts already started for travelling wave cavity developments which hold the potential for lower peak surface to acceleration field ratios, as well as higher cell-to-cell coupling, and higher *R/Q*s. If advances from TW mode operation are ready in time for the 2 TeV upgrades (2070) the costs for the 2 TeV stage will drop significantly from those shown in Table 1. For all the stages we have assumed additional linac installations without removing already installed lower gradient sections.

For the 1 TeV, 2 TeV and 3 TeV upgrades, we also adopt x2 cost reductions for cryomodules due to large scale production learning curves. For the 3 TeV upgrade we also assumed modest improvements in RF power efficiencies to limit the AC operating power. It is expected that R&D on gradients and *Q*s will continue in parallel to both construction and operation of the machines, such that the extension to the main linacs required for the energy upgrades would benefit from the improved technology and cost saving measures.

The last column in Table 1 compares the ILC 3 TeV upgrade with CLIC 3 TeV showing comparable luminosities, capital costs, and AC operating powers. For comparing the two 3 TeV machines we show that the *total* capital costs (i.e. sum of all the stages) are similar. However, as the white paper will show, the backgrounds at the IP for the ILC 3 TeV are much cleaner than for CLIC 3TeV, and the final energy spread of 16% compared to 35% for CLIC. Similarly, the luminosity for ILC 2 TeV (8.6 $x10^{34}$) is much higher than for CLIC 1.5 TeV (3.7 $x10^{34}$) and again the backgrounds are much lower due to chosen beam parameters.

Timeline to the Next Century

A sensible time scale is based on the completion of the ILC Higgs and Top Factory eras expected to fall roughly between 2030 – 2050, especially if a high luminosity upgrade for the Higgs Factory is included. The 500 GeV ILC energy upgrade would be completed by 2055 with physics till 2060, after which the 1 TeV upgrade installation would be completed by 2065. If LHC or ILC physics results encourage further energy upgrades, these could be installed for 2 TeV by 2075, and 3 TeV by 2085, taking physics discoveries to the dawn of the next century. Alternatively, if the PWFA technology has developed far enough, 2 – 5 TeV energies, or higher, can be reached after 2075 to the next century.

The ILC guarantees a rich, varied and flexible physics program to complement that of the LHC-HL. New physics has been unsatisfactorily absent from LHC so far, and so precision physics from a lepton collider becomes key to Beyond Standard Model physics. The timescales for the upgrades to TeV and beyond would be driven by results from the LHC- HL at CERN, as well as from physics at the ILC and its upgrades.

Table 1 High level parameters for ILC energy upgrades. Costs do not include Detector and Manpower. Detail machine parameters will be presented in the white paper. Detail parameters will be given in the white paper.

		ILC Higgs	ILC Top	ILC 0.5	ILC1	ILC2	ILC3	CLIC
Energy	TeV	0.25	0.38	0.5	1.0	2.0	3.0	3.0
Luminosity	$X10^{34}$	1.35	1.95	1.8	4.3	8.6	6.1	5.9
AC Power	MW	133	158	167	232	547	596	590
Cap Cost	BILCU	5.5	+1.6	+1	+4	+8	+4.5 (24.6 Total)	24.2 Total BCHF
Av. Gradient	MV/m	31.5	34.4	39.0	49.5	55	67.5	72/100
Av. *Q*	10^{10}	1	1.34	1.5	1.75	1.9	2.5	
Av. CM unit cost	M$	1.85	1.85	1.85	1.4	1.15	1.08	
Appr. Year commissioning		2035	2050	2055	2065	2075	2085	2053^

^ As presented to European Strategy Meetings

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