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ILC Running Scenarios

LCC Parameter Group

Abstract

We need some running scenarios...

1 Introduction

The ILC requirements document "Parameters for the Linear Collider" [1] describes a 500 GeV machine with the possibility of extending the energy up to 1 TeV. The ILC design given in the Technical Design Report (TDR) realizes this machine. Following the discovery of the Higgs boson at the LHC, the Japan Association of High Energy Physicists (JAHEP) recommended that the ILC physics studies "shall start with a precision study of the Higgs boson and then evolve into studies of the top quark, dark matter particles, and the Higgs self-couplings, by upgrading the accelerator. A more specific scenario is as follows:

- A Higgs factory with a centre of mass energy of approximately 250 GeV shall be constructed as the first phase.
- The machine shall be upgraded in stages up to a centre of mass energy of ∼500 GeV which is the baseline energy of the overall project.
- Technical extendibility to a 1 TeV region shall be preserved."

A multiple staged energy implementation, while technically feasible, will require several stop-start cycles with associated complications: thus the LCC Directorate has interpreted the JAHEP statement to mean a project with a first stage of 250 GeV. A pause in installation would then ensue to allow for a period of commissioning (∼1 year) and physics operation of approximately 4 years after which time a single shutdown of ∼1 year would be used to complete the project to 500 GeV.

This is consistent with the TDR physics goal of 250 fb^{-1} of integrated luminosity at 250 GeV using the nominal TDR peak luminosity of 7.5×10^{33} $\text{cm}^{-2}\text{s}^{-1}$ and assuming a yearly luminosity progression of 10%, 30%, and 60% of peak as proposed in the requirements document.

However, this represents a significantly different construction scenario from that described in the TDR with impact on the overall schedule and the associated sub-system planning. The TDR specifies construction at the start of the full 500 GeV project. The impacts of this different construction scenario were addressed by Dugan, Harrison, List and Walker in their note [2] "Implications of an Energy-Phased approach to the realization of the ILC." The note was intended to outline for planning purposes, the major changes to the TDR arising from this phased energy approach.

Following this initial consideration given to the machine construction issues, a study has been conducted to understand the physics implications of the staging choices. An ILC Parameters Joint Working Group was created by the LCC Directorate with the following charge:

> The ILC parameter working group reports to the LCC Directorate. It consists of members from both the ILC accelerator and the physics & detector groups where each team selects a co-convener for this working group.

> This working group prepares information on ILC machine parameters and staging scenarios as well as potential upgrade paths in a form readily usable by the LCC. In doing so, the WG will take into account technical machine constraints and physics and detector needs regarding the fundamental ILC machine parameters such as energy, luminosity, crossing angles, etc.
>
> The first task for the working group is to prepare multiple scenarios for staging up to about 500 GeV. The report should contain the pros and cons of each scenario as well as luminosities needed at each energy to produce corresponding physics results.

In order to quantify the impact of various options of running on the physics output, and particularly on its evolution with time, ten operating scenarios were initially considered. Operating scenarios must be distinguished from the staging scenarios. Staging refers to the installed energy capability of the collider. Operating specifies the collision energy. In other words, operations may be conducted at a lower energy than the full capability of the collider once a staging upgrade has been implemented. The ten initial scenarios were reduced to three, which are described in the remainder of this document.

The principal physics motivations for operations in the 250-500 GeV range are [3]:

- 250 GeV.

  precision Higgs couplings

- 350 GeV.

  top quark mass and couplings

  precision W couplings

  precision Higgs couplings

- 500 GeV.

  precision search for Z′

  Higgs couplings to top

  Higgs self-coupling

  search for supersymmetry

  search for extended Higgs states

These physics motivations have driven the design of the staging scenarios.

2 Total integrated luminosity and polarisation splitting

The total integrated luminosities collected at various center-of-mass energies will determine the ultimative physics reach of the ILC. At the moment, it is not yet clear what the best combination of dataset sizes will be. We propose the examples listed in table 1 for studying this issue. In particular, the scenarios "C1-X" serve to illustrate different balancing between $\sqrt{s} = 250$, 350, and 500 GeV. Scenarios A1 and B1 will be discussed in the next section and are listed here only for completeness.

	$\int \mathcal{L}dt$ [fb^{-1}]				
$\sqrt{s}$	A1	B1	C1-250	C1-350	C1-500
250 GeV	2000	2000	2000	500	500
350 GeV	200	200	200	1700	200
500 GeV	3000	3000	3500	3500	5500
	For each of the above scenarios				
1 TeV	5000				
90 GeV	100				
160 GeV	500				

Table 1: Total target integrated luminosities per center-of-mass energy.

The ultimate physics reach further depends on the assumed beam polarisations. Concerning the absolute values, the highest achievable degree of polarisation is desirable, in particular for the positron beam. A sharing between the four possible sign combinations is proposed in table 2. It should be noted that one can only profit from the full cancellation of experimental systematic uncertainties between these samples if they are accumulated simultaneously by continuously flipping the beam helicities at the corresponding frequencies.

At $\sqrt{s} = 250$ and 350 GeV, it is expected that the main interest will be on reactions mediated by s-channel exchange of a Z boson or a photon. Thus 90% of the data is collected in the unlike-sign combinations, preferring left-handed electrons over right-handed. Only a minimal amount of 10% for control of systematics on the like-sign configurations.

At higher $\sqrt{s}$, the picture changes because new physics is more likely to enter the game. For example Dark Matter with axial-vector couplings would profit significantly from like-sign data-taking, but also the determination of the chiral properties of new particles requires a more balanced sharing between beam helicity configurations. Also indirect searches eg. via the electroweak couplings of the top quark prefer right-handed electrons over left-handed ones. Thus, a splitting of 40%,40%,10%,10% is proposed here. At the Z pole, we assume the same splitting as at the high energies, since one of the main observables will be the left-right asymmetry.

Table 3 shows as example case the resulting absolute luminosities per center-of-mass energy and helicity configuration for the scenario C1-250.

For all center-of-mass energies, further discoveries at the LHC could lead to modifications of the ideal sharing between helicity fractions.

	fraction with $\mathrm{sgn}(P(e^-), P(e^+)) =$			
	(-,+)	(+,-)	(-,-)	(+,+)
$\sqrt{s}$	[%]	[%]	[%]	[%]
250 GeV	67.5	22.5	5	5
350 GeV	67.5	22.5	5	5
500 GeV	40	40	10	10
1 TeV	40	40	10	10
90 GeV	40	40	10	10
160 GeV	67.5	22.5	5	5

Table 2: Relative sharing between beam helicity configurations proposed for the various center-of-mass energies.

	integrated luminosity with $\mathrm{sgn}(P(e^-), P(e^+)) =$			
	(-,+)	(+,-)	(-,-)	(+,+)
$\sqrt{s}$	[fb^{-1}]	[fb^{-1}]	[fb^{-1}]	[fb^{-1}]
250 GeV	1350	450	100	100
350 GeV	135	45	10	10
500 GeV	1400	1400	350	350
1 TeV	3200	3200	800	800
90 GeV	40	40	10	10
160 GeV	340	110	25	25

Table 3: Integrated luminosities per beam helicity configuration resulting from the fractions in table 2 in scenario C1-250.

3 Running Scenarios

The total integrated luminosities presented in the previous section can be collected at different stages of the machine in a different periods of time. We will give here a few examples of running scenarios. In this we apply the following guidelines/restrictions:

- There are two main parameters to vary:
  - the integrated luminosity to be collected at $\sqrt{s} = 250$ GeV with an inital staged 250GeV machine. We will consider 3 cases in the tables below: A) 250 fb^{-1}, B) 500 fb^{-1}, C) 100 fb^{-1}, which corresponds to A) 4.1, B) 6.4, C) 2.8 years of running of the inital 250 GeV staged machine before upgrading it to 500 GeV, including ramp-up.

  - the final amount of luminosity per energy. In order to limit the amount of cases, we only study this variation for the case of scenario C by varying the operation energy for the second half of running time after the luminosity upgrade.

- All scenarios assume that an integrated luminosity of at least $200\,\mathrm{fb}^{-1}$ will be collected at the top threshold near $\sqrt{s} = 350\,\mathrm{GeV}$. We assume that this will be done with the 500 GeV machine operated at a reduced gradient. We arbitrarily put this before the first data-taking at $\sqrt{s} = 500\,\mathrm{GeV}$ when calculating the ramp-up times. However it should be noted that one would maybe prefer a precision measurement like the top threshold scan with a better run-in machine. We leave this decision open at this point since it does not influence the total running time or the installation scheme.

- All scenarios are limited to about equal total operation times near 25 years, before a 1 TeV upgrade.

- We include both a possible luminosity upgrade and an energy upgrade in order to give a complete picture of the longterm potential of the ILC. However the exact details of the longterm program will depend on future developments at previous stages of the ILC, at the LHC and possibly other scientific results. Thus we do not speculate here about all the possible variations of the more long-term program, in particular the 1TeV runs. However we note that in principle also part of the 500 GeV datasets could be accumulated with the 1 TeV machine, then at 10 Hz and thus doubling the instantaneous luminosity.

- It should be noted explicitely that further discoveries, in particular at ILC-500, will change the details and might add the neccessity to run at additional intermediate energies, either for scanning production thresholds of new particles, or for disentangling several states close by in mass (eg. in SUSY measure the $\tilde{\tau}$ mixing angle in $\tilde{\tau}_1\tilde{\tau}_2$ mixed production below the $\tilde{\tau}_2\tilde{\tau}_2$ pair production threshold).

- At each $\sqrt{s}$, the total integrated luminosities given below should be understood to be split up between the four possible beam helicity configurations as specified in section 2.

- We do not list here physics running at the Z-pole or at the WW-threshold. However we note that their physics program should be done at some point, where the timing will depend on the outcome of an inital running at $\sqrt{s} = 500\,\mathrm{GeV}$.

- We don't list either runtime on the Z-pole for calibration. This will be needed at least twice per year for detector calibration (eg of the momentum scale of the tracking detectors). Here, more precise specifications from the experiments are needed to assess systematically the amount of data needed for which level of calibration precision.

- The details about the time lines for these scenarios including ramp-up and upgrade-installation times will be presented in section 4.

3.1 Running Scenarios

Here we present more details on the five running scenarios which end up in the final integrated luminosities as given in section 2. The total running times are all near 25 years, achieving different total luminosities depending on the time of the upgrades and the choices of energy steps. The assumptions on the ramp-up times and efficiencies will explained in section 4, the time development of some physics results discussed in section 5.

	Stage	250	500			500 LumiUP			
Scenario	$\sqrt{s}$ [GeV]	250	350	500	250	500	250	350	500
A1	$\int \mathcal{L}dt$ [fb^{-1}]	250	200	1000	750	2000	1000	-	-
	time [years]	4.1	2.7	3.5	4.2	4.9	3.1	-	-
B1	$\int \mathcal{L}dt$ [fb^{-1}]	500	200	1000	500	2000	1000	-	-
	time [years]	6.2	2.7	3.5	3.1	4.9	3.1	-	-
C1-250	$\int \mathcal{L}dt$ [fb^{-1}]	100	200	1000	400	2500	1500	-	-
	time [years]	2.8	3.3	3.5	2.7	5.8	4.2	-	-
C1-350	$\int \mathcal{L}dt$ [fb^{-1}]	100	200	1000	400	2500	-	1500	-
	time [years]	2.8	3.3	3.5	2.7	5.8	-	4.4	-
C1-500	$\int \mathcal{L}dt$ [fb^{-1}]	100	200	1000	400	2500	-	-	2000
	time [years]	2.8	3.3	3.5	2.7	5.8	-	-	3.5

Table 4: Four running scenarios with the same final integrated luminosities and real time required for each run including ramp up. Not included: installation, calibration and physics runs at Z pole and WW-threshold, 1 TeV, new physics thresholds.

3.2 Total running time and total integrated luminosities

Table 5 summarizes the run times of the scenarios defined in table 4. The comparison of scenarios A1, B1 and C1-250 shows that longer initial running at a staged 250 GeV machine leads to an overall longer time in order to accumulate the same final integrated luminosity. This is expected since a staged 250 GeV machine provides significantly lower instantaneous luminosity than the 500 GeV baseline machine operated at $\sqrt{s} = 250$ GeV. In particular C1-250 is shorter than A1 and B1 but still delivers 500 fb^{-1} more than these two scenarios at 500 GeV.

4 Timelines of the running scenarios

The timelines for integrated luminosity have been estimated and are shown in the plots below under the following assumptions:

		total run time *before*	
	500 GeV	Lumi upgrade	TeV upgrade
Scenario	[years]	[years]	[years]
A1	4.1	16.0	25.5
B1	6.2	17.1	26.6
C1-250	2.8	13.8	25.3
C1-350	2.8	13.8	25.5
C1-500	2.8	13.8	24.6

Table 5: Cummulated running times for the five scenarios, including ramp-up and installation of upgrades. Not included: calibration and physics runs at Z pole and WW-threshold, 1 TeV, new physics thresholds.

Basic assumptions

- All plots are presented in calendar years (not Snowmass years)
- A full calendar year is assumed to represent eight months running at an efficiency of 75% (the RDR assumption). This corresponds approximately to $Y = 1.6 \times 10^7$ seconds of integrated running. (This is significantly higher than a Snowmass year of 10^7 seconds.)
- t = 0 (start of Year 1) is the start of running for physics. Year 0 ($-1 \leq t < 0$), directly after construction, is assumed to be for machine commissioning only (not shown in the plots).
- If the peak instantaneous luminosity is L, then the nominal integrated luminosity for a fully-operational calendar year is $L_{int} = L \times Y$. For any given calendar year during a period of ramp-up, the integrated luminosity for that year is $f \times L_{int}$, where f is the ramp fraction associated with the year ($f \leq 1$).

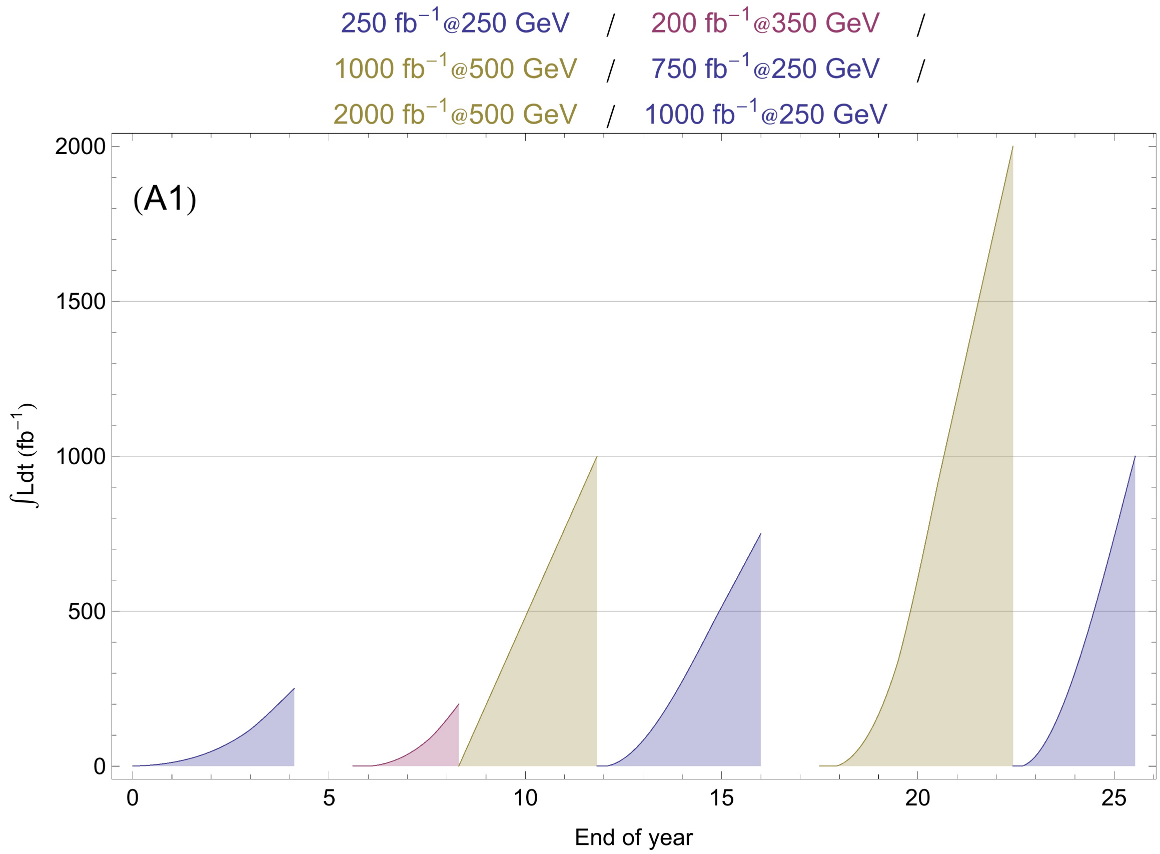
Ramp-up assumptions

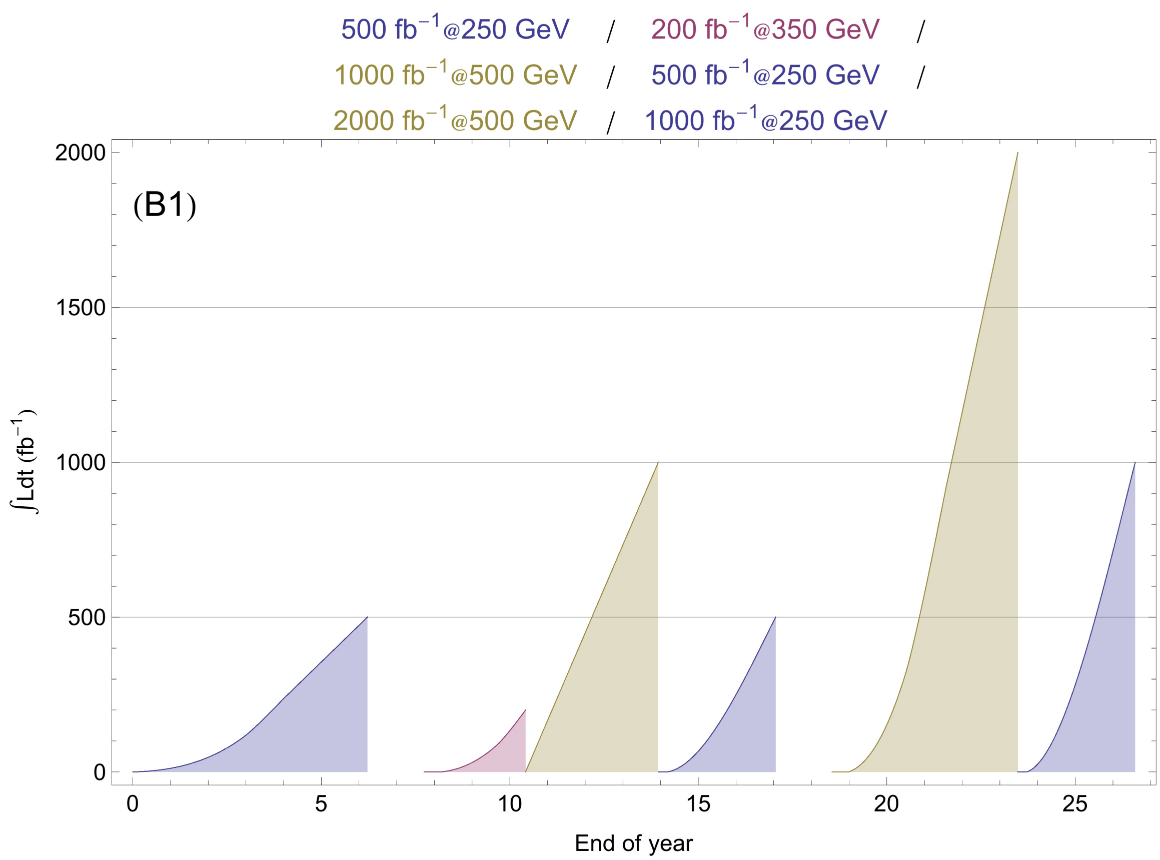
- A ramp-up of luminosity performance is in general assumed after: (a) initial construction and after 'year 0' commissioning; (b) after a downtime for an accelerator upgrade (energy to 500 GeV or luminosity); (c) a change in operational mode which may require some learning curve (e.g. going to 10-Hz collisions).
- A ramp is defined as a set of ramp factors f, one factor for each consecutive integral calendar year at the beginning of a specific run.
- For the initial physics run after construction and year 0 commissioning, the RDR ramp of 10%, 30%, 60% and 100% over the first four calendar years is always assumed (all scenarios).

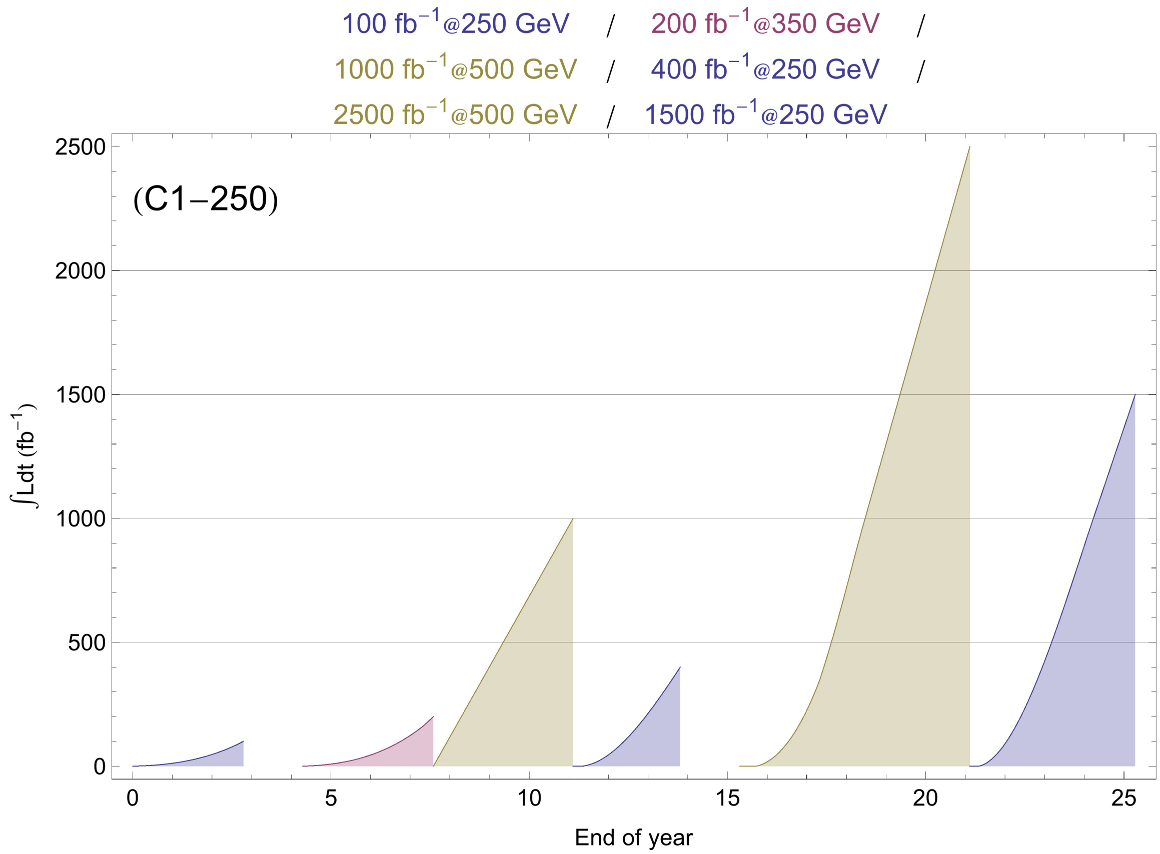
- In general, the ramp after the shutdowns for installation of the remaining linacs (500 GeV machine) or luminosity upgrade is assumed slightly shorter (10%, 50%, 100%) with no year 0.
- Going up in centre of mass energy from 350 GeV to 500 GeV is assumed to have no ramp associated with it, since there is no modification (shutdown) to the machine. This assumption is rather optimistic, but one assumes that during 350 GeV physics running, machine development time has been spent to 'check out' 500 GeV operations.
- Going to 10-Hz operation at 50% gradient does assume a ramp however (25%, 75%, 100%), since 10-Hz affects the entire machine including the damping rings and sources etc.

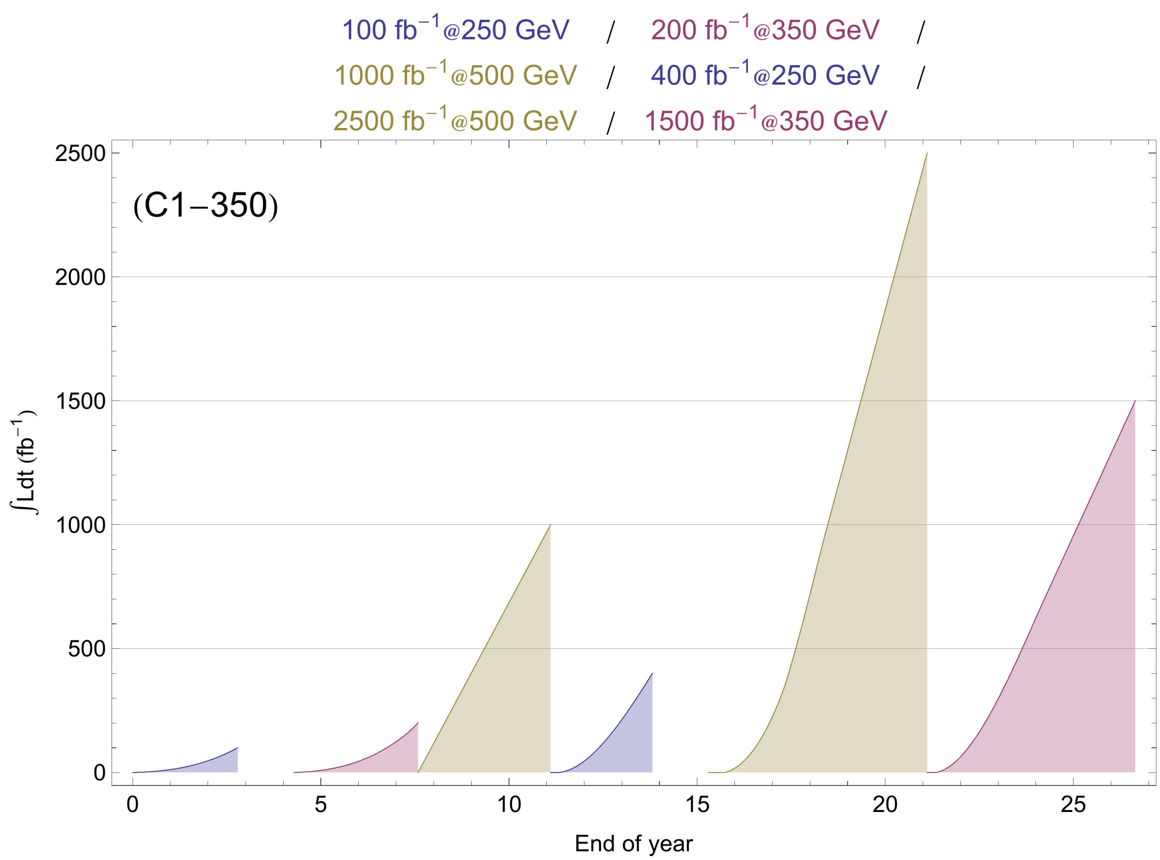
Shutdowns

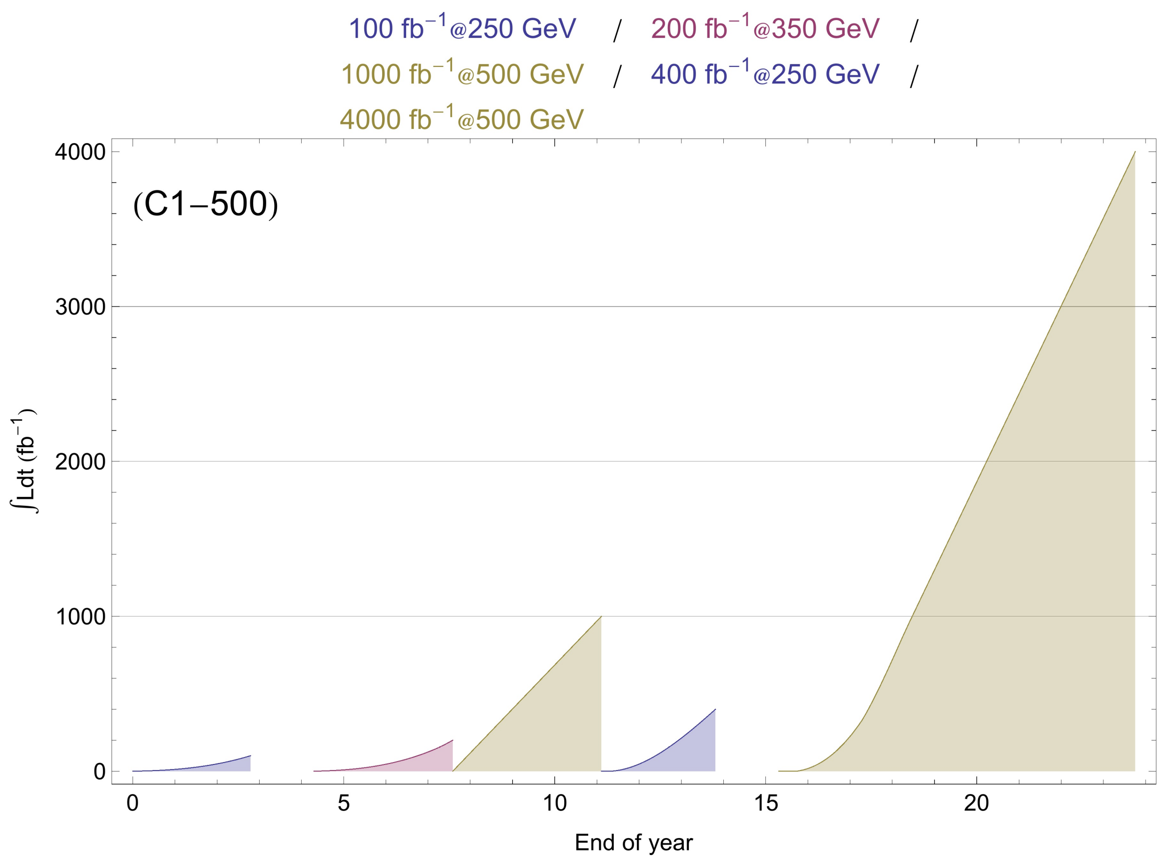
- Two major 18 month shutdowns are assumed for (a) installation of the remaining linac for the 500 GeV machine, and (b) the luminosity upgrade.
- In both cases, the down-times may be on the optimistic side, but would appear to be roughly consistent with the TDR construction installation rates, assuming that the same level of manpower is available, and that all the necessary components for installation are (mostly) available at the time the shutdown starts.
- The first shutdown is to install the remainder of the main linacs to increase the energy capacity from the initial phase 250 GeV cm to 500 GeV cm. This includes removal of the temporary transport lines in the main linac, and subsequent installation of cryomodules, klystrons, modulators, LLRF and associated infrastructure (and possibly cryoplants).
- The second shutdown is for the TDR luminosity upgrade, where the number of bunches per pulse is increased from 1310 to 2620. This requires the installation of an additional 50% of klystrons and modulators, as well as the possible installation of a second positron damping ring. It is assumed that linac and damping ring installation occur in parallel and do not interfere with each other.


250 fb^{-1}@250 GeV / 200 fb^{-1}@350 GeV /
1000 fb^{-1}@500 GeV / 750 fb^{-1}@250 GeV /
2000 fb^{-1}@500 GeV / 1000 fb^{-1}@250 GeV
(A1)
$\int$Ldt (fb^{-1})
End of year


500 fb^{-1}@250 GeV / 200 fb^{-1}@350 GeV /
1000 fb^{-1}@500 GeV / 500 fb^{-1}@250 GeV /
2000 fb^{-1}@500 GeV / 1000 fb^{-1}@250 GeV
(B1)
$\int$Ldt (fb^{-1})
End of year


100 fb^{-1}@250 GeV / 200 fb^{-1}@350 GeV /
1000 fb^{-1}@500 GeV / 400 fb^{-1}@250 GeV /
2500 fb^{-1}@500 GeV / 1500 fb^{-1}@250 GeV
(C1−250)
$\int$Ldt (fb^{-1})
End of year


100 fb^{-1}@250 GeV / 200 fb^{-1}@350 GeV /
1000 fb^{-1}@500 GeV / 400 fb^{-1}@250 GeV /
2500 fb^{-1}@500 GeV / 1500 fb^{-1}@350 GeV
(C1−350)
$\int$Ldt (fb^{-1})
End of year



Summary Tables In the following tables, T and T_{acc} are the run duration and total accumulated time respectively, in calendar years.

A1

	E_{CM}	$\int Ldt$	L_{peak}	Ramp				T	T_{acc}	Comment
				1	2	3	4			
Physics run	250	250	0.75	10	30	60	100	4.1	4.1	TDR nominal operation at 5Hz
Shutdown								1.5	5.6	Upgrade to full 500 GeV machine
Physics run	350	200	1.	10	50	100	100	2.7	8.3	TDR nominal operation at 5Hz
Physics run	500	1000	1.8	100	100	100	100	3.5	11.8	TDR nominal operation at 5Hz
Physics run	250	750	1.5	25	75	100	100	4.2	16.	Operation at 10 Hz
Shutdown								1.5	17.5	Luminosity upgrade
Physics run	500	2000	3.6	10	50	100	100	4.9	22.4	TDR lumi−up at 5Hz
Physics run	250	1000	3.	25	75	100	100	3.1	25.5	TDR lumi−up at 10Hz

B1

	E_{CM}	$\int Ldt$	L_{peak}	Ramp				T	T_{acc}	Comment
				1	2	3	4			
Physics run	250	500	0.75	10	30	60	100	6.2	6.2	TDR nominal operation at 5Hz
Shutdown								1.5	7.7	Upgrade to full 500 GeV machine
Physics run	350	200	1.	10	50	100	100	2.7	10.4	TDR nominal operation at 5Hz
Physics run	500	1000	1.8	100	100	100	100	3.5	13.9	TDR nominal operation at 5Hz
Physics run	250	500	1.5	25	75	100	100	3.1	17.1	Operation at 10 Hz
Shutdown								1.5	18.6	ScenarioComment
Physics run	500	2000	3.6	10	50	100	100	4.9	23.5	TDR lumi–up at 5Hz
Physics run	250	1000	3.	25	75	100	100	3.1	26.6	TDR lumi–up at 10Hz

C1–250

	E_{CM}	$\int Ldt$	L_{peak}	Ramp				T	T_{acc}	Comment
				1	2	3	4			
Physics run	250	100	0.75	10	30	60	100	2.8	2.8	TDR nominal operation at 5Hz
Shutdown								1.5	4.3	Upgrade to full 500 GeV machine
Physics run	350	200	1.	10	30	60	100	3.3	7.6	TDR nominal operation at 5Hz
Physics run	500	1000	1.8	100	100	100	100	3.5	11.1	TDR nominal operation at 5Hz
Physics run	250	400	1.5	25	75	100	100	2.7	13.8	Operation at 10 Hz
Shutdown								1.5	15.3	Luminosity upgrade
Physics run	500	2500	3.6	10	50	100	100	5.8	21.1	TDR lumi–up at 5Hz
Physics run	250	1500	3.	25	75	100	100	4.2	25.3	TDR lumi–up at 10Hz

C1–350

	E_{CM}	$\int Ldt$	L_{peak}	Ramp				T	T_{acc}	Comment
				1	2	3	4			
Physics run	250	100	0.75	10	30	60	100	2.8	2.8	TDR nominal operation at 5Hz
Shutdown								1.5	4.3	Upgrade to full 500 GeV machine
Physics run	350	200	1.	10	30	60	100	3.3	7.6	TDR nominal operation at 5Hz
Physics run	500	1000	1.8	100	100	100	100	3.5	11.1	TDR nominal operation at 5Hz
Physics run	250	400	1.5	25	75	100	100	2.7	13.8	Operation at 10 Hz
Shutdown								1.5	15.3	Luminosity upgrade
Physics run	500	2500	3.6	10	50	100	100	5.8	21.1	TDR lumi–up at 5Hz
Physics run	350	1500	2.1	25	75	100	100	5.5	26.6	TDR lumi–up at 7Hz

C1–500

	E_{CM}	$\int Ldt$	L_{peak}	Ramp				T	T_{acc}	Comment
				1	2	3	4			
Physics run	250	100	0.75	10	30	60	100	2.8	2.8	TDR nominal operation at 5Hz
Shutdown								1.5	4.3	Upgrade to full 500 GeV machine
Physics run	350	200	1.	10	30	60	100	3.3	7.6	TDR nominal operation at 5Hz
Physics run	500	1000	1.8	100	100	100	100	3.5	11.1	TDR nominal operation at 5Hz
Physics run	250	400	1.5	25	75	100	100	2.7	13.8	Operation at 10 Hz
Shutdown								1.5	15.3	Luminosity upgrade
Physics run	500	4000	3.6	10	50	100	100	8.4	23.8	TDR lumi–up at 5Hz

5 Time Development of Physics Results

In this section we present some examples of how important physics results evolve in time for the five scenarios presented in the document. All plots in this section are still preliminary!

5.1 Higgs coupings to fermions and gauge bosons

The following plots show the current snapshot of available analyses. They are in particular preliminary since most of the analyses at $\sqrt{s} = 350\,\mathrm{GeV}$ are not yet finished. A key question will be how well the HZZ coupling can be extracted at $\sqrt{s} > 250\,\mathrm{GeV}$.

With the currently available analyses, an intial long run at $\sqrt{s} = 250\,\mathrm{GeV}$ benefits mostly the HZZ coupling. Most other couplings are limited by the knowledge of the HWW coupling or by statistics, and thus only reach their full potential once $\sqrt{s} > 250\,\mathrm{GeV}$. However after about $1\,\mathrm{ab}^{-1}$ at $\sqrt{s} = 500\,\mathrm{GeV}$, the HWW coupling becomes limited again by the precision on the HZZ coupling. Thus a further understanding on how well this coupling can be accessed at $\sqrt{s} > 250\,\mathrm{GeV}$ will be crucial in order to determine the ultimately required amount of data at $\sqrt{s} = 250\,\mathrm{GeV}$.

5.2 Higgs Self-Coupling

The measurement of the Higgs Self-Coupling requires at least $\sqrt{s} \geq 450\,\mathrm{GeV}$. A detailled study based on full simulation of the ILD detector concept at $\sqrt{s} = 500\,\mathrm{GeV}$ originally assuming $m_H = 120\,\mathrm{GeV}$ [9] has been updated recently [10] to $m_H = 125\,\mathrm{GeV}$. Preliminary results have been obtained for both unlike-sign helicity configurations of the beams, showing a slight preference for right-handed electrons and left-handed positrons, which suppresses the background much stronger than the signal.

Figure 2 shows the time evolution of the precision on the Higgs self-coupling, on the left-hand side assuming the standard 30% as absolute value of the positron polarisation,

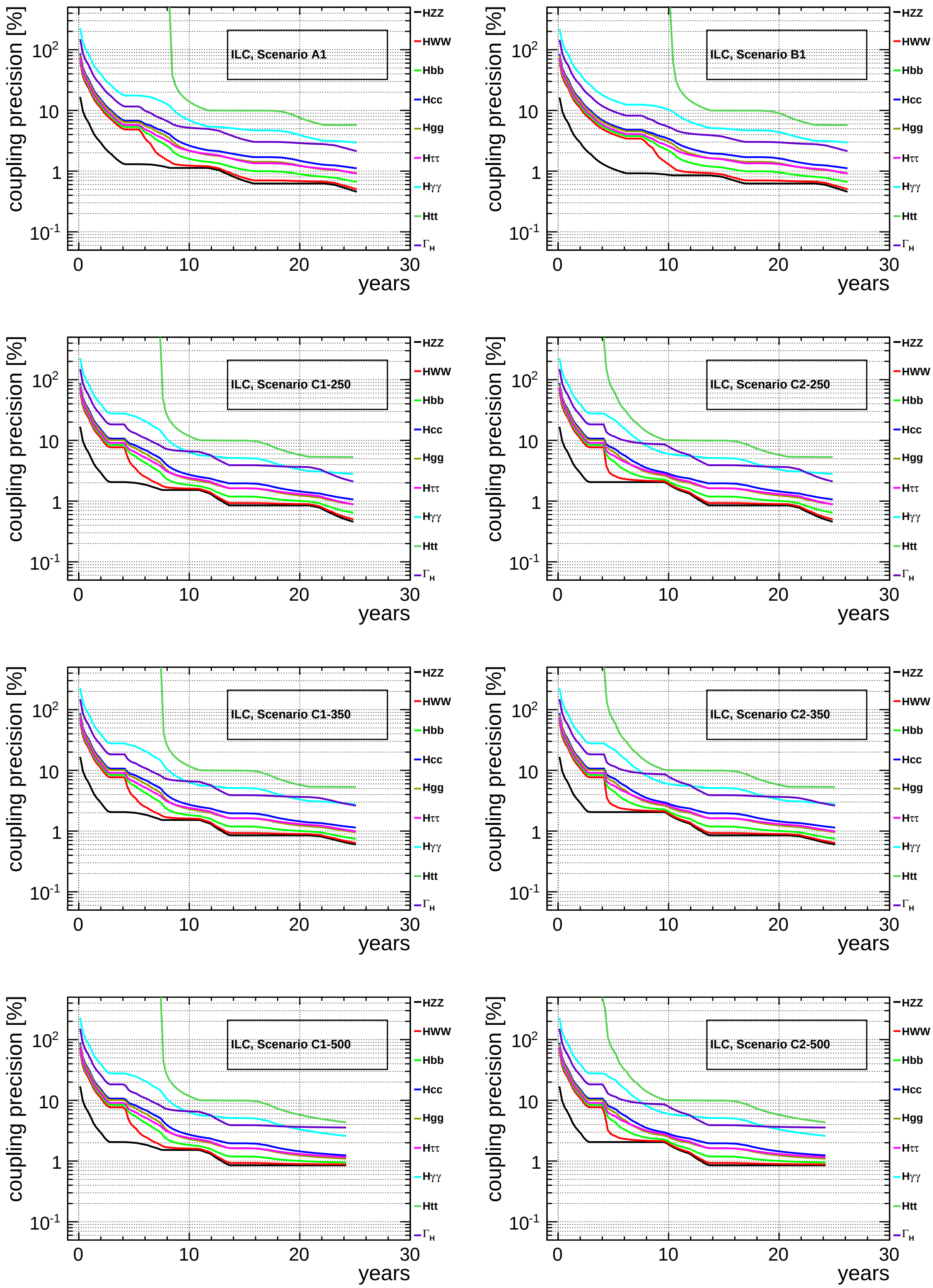


Figure 1: Time evolution of precision on various couplings of the Higgs boson. Scenario C2-X is the same as C1-X, apart from the top threshold run and the first 500 GeV run being switched.

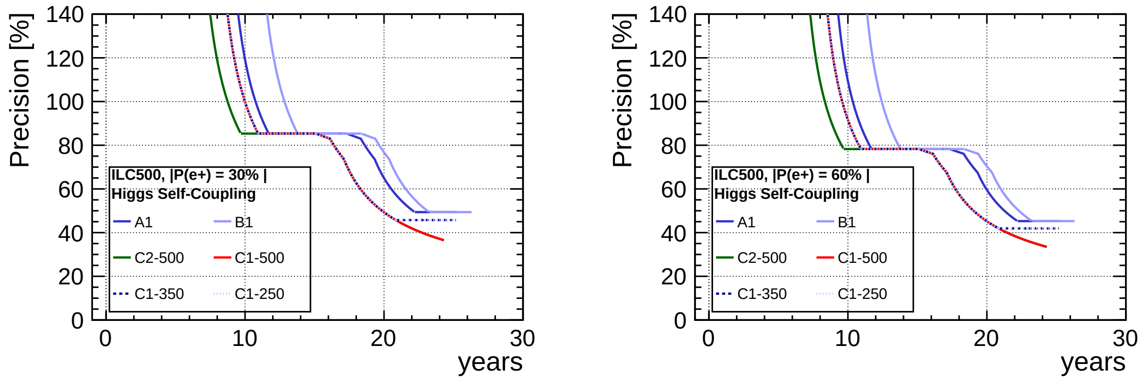


Figure 2: Time-evolution of the precision on the Higgs self-coupling for various running scenarios. Left: $|P(e^+)| = 30\%$, Right: $|P(e^+)| = 60\%$

on the right-hand side assuming $|P(e^+)| = 60\%$. The helicities are chosen according to table 2. Scenario C2-500 is the same as C1-500, apart from the top threshold run and the first 500 GeV run being switched.

6 Additional Parts of the ILC Program

here go additional needs:

- Z-pole for calibration, Z-pole for physics, WW-threshold
- 550 GeV for $t\bar{t}H$
- model-independency of $ZH \to q\bar{q}H$

7 Conclusions

Here will go the conclusions...

Acknowledgement

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