Suggested ILC Beam Parameter Range Rev. 2/28/05
Tor Raubenheimer

The machine parameters and the luminosity goals of the ILC were discussed at the 1st ILC Workshop. In particular, Nick Walker noted that the TESLA machine parameters had been chosen to achieve a high peak luminosity but with a high disruption parameter which left little room for operational optimization (http://lcdev.kek.jp/ILCWS/Talks/14wg1-2-walker-ilckek.pdf). Changes to ease operational constraints would likely cause the peak luminosity to decrease. It was suggested that a wiser approach would be to define an operating plane where a number of different machine configurations achieve the same peak luminosity. The specifications for the different subsystems would be determined by the most difficult parameters in the operating plane thereby ensuring some level of operational flexibility.

In this note, such an operating range is defined. This range is meant to provide a guideline so that the ILC Working Groups can consider what will be difficult and what will not. Many of the modifications required to support such an operating range would be inexpensive however some would have a large impact. This must be understood. It is expected that the Working Groups will provide feedback so that the range can be further refined – a Discussion Board at: http://www-project.slac.stanford.edu/ilc/acceldev/beamparameters.html has been created for the discussion of the beam parameters.

The overall parameters for the ILC are listed in the ILC Scope document from the ILCSC, which can be found at: http://www.fnal.gov/directorate/icfa/LC_parameters.pdf. This specifies three integrated luminosity goals:

1) 500 fb^{-1} at 500 GeV after the 1st 4 years of physics operation and
2) 500 fb^{-1} at 500 GeV in the following two to three years or
3) 1000 fb^{-1} at 1 TeV in the following four years

As the design work evolves, it will likely be necessary to review these requirements with the physics community.

To relate the integrated luminosity to the peak luminosity, a model for the integrated luminosity is needed. Such a model is described on p. 207 of the US LC Technology Options Study (USTOS): http: //www.slac.stanford.edu/xorg/accelops/. Assuming 9 months of accelerator operation each year with 1.5 months dedicated to startup and 75% hardware availability with additional fractions allocated to Machine Development, MPS trips, and a reduction of the peak luminosity due to tuning, this model estimates an integrated luminosity that is roughly equal to 1.1×10^7 seconds times the peak luminosity. Thus a peak luminosity of 2×10^{34} $cm^{-2}s^{-1}$ would integrate to 220 fb^{-1} in one year. This model is similar to the JLab experience described by Andrew Hutton in Appendix A.

A model for the luminosity evolution after construction is completed was presented at Snowmass 2001. Assuming that during the first four years of physics operation the collider integrates 25%, 50%, 75%, and 100% of the design luminosity, then a peak luminosity of 2×10^{34} $cm^{-2}s^{-1}$ will provide the specified 500 fb^{-1} with a 10% margin. Although such a schedule is aggressive, it may be possible since the ILC Scope document states that there would be a full year of commissioning after the construction project completion but before the physics running and there will likely be many years of commissioning the injector and more than one year of commissioning the main linacs during the construction project itself.

The specification of the peak luminosity then allows the definition of a nominal parameter set which is very similar to that in the TESLA TDR and the USTOS. The most contentious choice in a parameter set will likely be the initial accelerator gradient. The gradients that have been discussed range from 18 MV/m to 45 MV/m. The TDR listed an initial gradient of 23.4 MV/m while the USTOS report specified 28 MV/m and both specified 35 MV/m for the upgrade to higher energy. Thoughts on the gradient status were described in the WG5 summary at the 1st ILC Workshop (http://lcdev.kek.jp/ILCWS/Talks/15ple-5-WG5%20Summary_WG5_final.pdf). At this time, a gradient of 25 MV/m achieved using BCP is thought to be in hand. A gradient of 35 MV/m still requires essential work. It is thought that 35 MV/m will be achieved using electro-polishing (EP) by the time of the ILC TDR however it was clear that many members of the WG5 felt that a gradient of 35 MV/m would allow little operating margin with the TESLA-type cavities.

In choosing the gradient and the average current in the linac we considered four issues:

1) a 10 MW maximum klystron output with 15% overhead for feedback and 6% for rf distribution losses;
2) a cryomodule with 8, 10, or 12 cavities installed;
3) a linac bunch spacing that is consistent with a sub-harmonic bunching frequency of either 217 MHz (1/6 of the linac frequency) or 325 MHz (1/4 of the linac frequency) as well as being consistent with having twice as many bunches with exactly ½ the spacing – this would support a longitudinal separation of the IP's;
4) an injector system that does not require a major upgrade in average current or emittances for the 1 TeV upgrade.

Three possible examples that meet these requirements are:

1) a gradient of 40 MV/m with a 10 MW klystron feeding 16 cavities and a beam current 11.8 mA and a bunch spacing of 352 buckets;
2) a gradient of 35 MV/m with a 10 MW klystron feeding 20 cavities and a beam current of 10.4 mA and a bunch spacing of 384 buckets;
3) a gradient of 30 MV/m with a 10 MW klystron feeding 24 cavities and a beam current of 10.8 mA and a bunch spacing of 400 buckets.

These three options have different linac lengths, AC power consumptions, and capital costs. Using the US Options cost model, it appears that the capital cost of the cases with 40 and 35 MV/m are comparable but reducing the gradient to 30 MV/m would cost roughly 150M$ more. The 1 TeV site length would be roughly 8 km longer at 30 MV/m than at 35 MV/m and 13 km longer than at 40 MV/m. However the linac AC power consumption at 500 GeV for 30 MV/m would be 15 MW less than at 35 MV/m and about 40 MW less than at 40 MV/m. Possible linac parameters for these cases are listed in Table 1.

To describe an operating plane, we will assume 30 MV/m and a Q0 of 1.5×10^{10} for the initial configuration. This gradient choice has a few advantages:

1) It is close to the cost minimum for the collider although not at the cost minimum; the cost minimum is estimated to be at a gradient of 35 to 40 MV/m.
2) The Q0 of 1.5×10^{10} is similar to what has been achieved in some of the EP cavities and seems fairly robust at 30 MV/m.
3) The 30 MV/m provides operating margin for the TESLA-style cavities and is very close to the 28 MV/m specified for the TESLA XFEL.

There are also a number of disadvantages of the 30 MV/m choice, probably the most important of which is the increased cost and the longer site length compared to a higher gradient. This choice should be reviewed in the future but fortunately the gradient choice does not have a very big impact on the rest of the beam parameters.

In addition, we will assume the same gradient for the energy upgrade to 1 TeV. The choice of keeping the same initial and final gradient also has advantages and disadvantages.

1) It simplifies the injector systems. There would be no reason to modify injector system to support an energy upgrade and, if a dog-bone damping ring is chosen, the damping rings can be separated longitudinally in the tunnel from the main linacs during the initial years where learning to operate the damping rings will likely be difficult.
2) It provides a straightforward upgrade path in that no modifications are needed to the installed hardware. If improved hardware were available for the upgrade, it would allow for beam energies in excess of 1 TeV.

However, keeping the same gradient for the upgrade will likely require greater installation in the tunnel during the upgrade and may also require restarting cryomodule production which could increase the total project cost of the 1 TeV collider. In addition, starting with a lower initial gradient but installing cavities that can support higher gradients allows for increased energy reach by trading luminosity versus beam energy. The trade-offs between these different approaches needs further review.

For the 400 bucket spacing in the main linacs, the damping rings could be configured to operate with a 485 MHz rf system. In this case, a bunch spacing of 10 rf buckets and extracting every 15th bunch would yield the desired linac bunch spacing. For the ½ bunch spacing, simply reducing the bunch spacing to 5 rf buckets would work. Other bunch linac spacings can also be configured however the timing could be simplified by adopting a 650 MHz damping ring rf frequency as suggested by Andy Wolski. This would likely provide greater flexibility in the operating choices.

Given the gradient choice, the operating range is defined with five parameter sets: Nominal, Low Charge, Large Spot, Low Beam Power, and High Luminosity. The Nominal set is quite close to the parameters in the TESLA TDR and the US Options report. The only differences are:

1) a larger $\gamma\varepsilon y$ similar to that in the USTOS report to account for dilutions in regions other than the main linacs;
2) slightly larger βx to decrease the horizontal angular divergence which, combined with the larger $\gamma\varepsilon y$, leads to a luminosity of 2×10^{34} cm^{-2}s^{-1};

3) a slight increase in the average beam current to improve the efficiency at 30 MV/m with a corresponding decrease in the bunch spacing (the spacing is chosen to be easily divided by two as may be desired by the beam delivery systems);
4) the higher gradient of 30 MV/m which increases the AC power to 104 MW.

The other parameter sets define the operating range. The Low Charge case assumes ½ the single bunch charge with twice as many bunches having slightly lower IP beam emittances, smaller IP beta functions, and shorter bunch lengths. The resulting IP disruption is roughly half that of the nominal parameters and the bunch spacing in the main linac is exactly half that in the nominal parameter set to be consistent with IP's separated longitudinally. To accommodate such a set of parameters, the spacing in the damping rings must be halved, the bunch length must be further shortened, and the BDS must be designed to operate over a range of beta*. Such a set of parameters may be desired to reduce space charge effects in the damping rings, wakefield effects in the main linacs, or IP disruption effects. Such an operational scenario is similar to that found for the SLC where the operational single bunch charge was roughly ½ of the design.

The Large Spot case assumes larger emittances and a longer bunch length yielding a vertical spot size that is twice the size of the Low Charge parameters but with a disruption that is almost three times higher. This may be the most difficult parameter set for the BDS because of the larger angular IP beam sizes.

The Low Beam Power case might be chosen if there are limitations to the average beam power, the linac bunch spacing or the damping rings. Here, the number of bunches is reduced by more than a factor of two and the linac spacing is increased by 50%. The luminosity is recovered by focusing the beam to smaller spot sizes and allowing a large IP disruption parameter and a large beamstrahlung. It may be possible to reduce the linac AC power consumption in this case however it is likely that such a reduction would not really be possible and instead the linac would operate less efficiently.

Another parameter set that might be considered is a High Rate option which probably has the largest hardware impact in that the luminosity is achieved by operating the collider at 10 Hz with a shorter bunch train. This would increase the required AC power significantly and would require large margins on the AC distribution, the modulator charging supplies, and the cooling and cryogenic systems.

Another high rate set of parameters might be considered when operating at lower cms energy as might be desired to study a low mass Higgs or the Top. In such a case, the luminosity might be increased by increasing the repetition rate to maintain a constant average power. Parameters for these low energy cases need to be developed in the future. It would be useful to understand the hardware implications of operating at higher repetition rates when keeping the average ac power consumption constant (if possible).

Finally, the High Luminosity case takes the most difficult of all the parameters and combines them. In such a case, the peak luminosity might reach 4.9×10^{34} $cm^{-2}s^{-1}$ at 500 GeV but the beamstrahlung power will be two to three times higher than the nominal case. It probably makes sense to design the beamstrahlung dumps for much higher than nominal power to allow for scenarios such as this with increased luminosity but this implies that the beamstrahlung dump should be designed for multi-megawatt photon beams.

Emittance dilution budgets are not explicitly listed for the different parameter sets as these will need to be balanced using detailed calculations between the Low Emittance Transport sub-systems (BC, Linac, and BDS). In all cases, it was assumed that the baseline damping rings are designed to produce normalized emittances of $\gamma\varepsilon_x=8\text{x}10^{-6}$ m-rad and $\gamma\varepsilon_y=2\text{x}10^{-8}$ m-rad however this also will need further consideration as the damping ring designs evolve.

Lists of the primary suggested beam parameters for 500 GeV and 1 TeV are in Tables 2 and 3. The parameters are based on an assumed gradient of 30 MV/m but parameters for other gradients could be very similar with the main difference being the average current. In summary, the main issues that are implied by these parameters are:

1) 5640 bunches in the damping rings,
2) bunch lengths that vary from 500 to 150 μm,
3) main linac bunch spacing varying between 200 and 600 buckets,
4) emittance preservation which is probably most difficult with either the Low Charge or the Low Beam Power parameters,
5) the range in final focus beta* and beamstrahlung power.

Finally, these parameters are meant to provide a guideline so that the ILC Working Groups can understand what will be difficult and what will not and suggest modifications. Many of the choices such as the gradient will need to be revisited with further understanding of the hardware and operational limitations. In addition, many of the modifications required to support such an operating range would be inexpensive however some would have a large impact. These impacts need to be understood so that the range can be further refined.

Table 1. Selected linac parameters versus gradient.

500 GeV Linac Parameters versus Gradient

	TESLA	**USSC**	**30 MV/m**	**35 MV/m**	**40 MV/m**
E_cms (GeV)	**500**	**500**	500	500	500
N	**2.00E+10**	**2.00E+10**	2.00E+10	2.00E+10	2.00E+10
Nb	**2820**	**2820**	2820	2820	2820
T_sep (ns)	**336.9**	**336.9**	307.7	295.4	270.8
Buckets @ 1.3 GHz	**438**	**438**	400	384	352
I_ave (A)	**0.0095**	**0.0095**	0.0104	0.0108	0.0118
Gradient	**23.40**	**28.00**	30.00	35.00	40.00
Cavities / 10 MW klys	**36.00**	**30.00**	24.00	20.00	16.00
Q0	**1.00E+10**	**1.00E+10**	1.50E+10	1.00E+10	7.00E+09
Qext	**2.50E+06**	**2.99E+06**	2.93E+06	3.28E+06	3.44E+06
Tfill (us)	**420.0**	**502.7**	491.9	550.9	577.1
Trf (ms)	**1.37**	**1.45**	1.36	1.38	1.34
F_rep (Hz)	**5**	**5**	5	5	5
Linac overhead	**0**	**5%**	5%	5%	5%
Total # of cavities	**20592**	**18096**	16656	14240	12480
Total # of klystrons	**572**	**603**	694	712	780
Active two linac length (km)	**21.6**	**18.7**	17.3	14.8	12.9
Total two linac length (km)	**30.0**	**27.0**	23.5	20.1	17.9
Pb (W)	**1.13E+07**	**1.13E+07**	1.13E+07	1.13E+07	1.13E+07
Pac (linacs) (W)	**9.40E+07**	**1.05E+08**	1.04E+02	1.21E+02	1.42E+02

Table 2. Beam and IP parameters for 500 GeV cms.

500 GeV Beam and IP Parameters

	TESLA	**USSC**	**Nominal**	**Low Q**	**Large Y**	**Low P**	**High Lum**
E_cms (GeV)	**500**	**500**	500	500	500	500	500
N	**2.00E+10**	**2.00E+10**	2.00E+10	1.00E+10	2.00E+10	2.00E+10	2.00E+10
Nb	**2820**	**2820**	2820	5640	2820	1330	2820
T_sep (ns)	**336.9**	**336.9**	307.7	153.8	307.7	461.5	307.7
Buckets @ 1.3 GHz	**438**	**438**	400	200	400	600	400
I_ave (A)	**0.0095**	**0.0095**	0.0104	0.0104	0.0104	0.0069	0.0104
Gradient	**23.40**	**28.00**	30.00	30.00	30.00	30.00	30.00
IP Parameters							
gamepsX (m-rad)	**1.00E-05**	**9.60E-06**	1.00E-05	1.00E-05	1.20E-05	1.00E-05	1.00E-05
gamepsY (m-rad)	**3.00E-08**	**4.00E-08**	4.00E-08	3.00E-08	8.00E-08	3.50E-08	3.00E-08
BetaX	**1.50E-02**	**1.50E-02**	2.10E-02	1.20E-02	1.00E-02	1.00E-02	1.00E-02
BetaY	**4.00E-04**	**4.00E-04**	4.00E-04	2.00E-04	4.00E-04	2.00E-04	2.00E-04
SigX	**5.54E-07**	**5.43E-07**	6.55E-07	4.95E-07	4.95E-07	4.52E-07	4.52E-07
SigY	**5.0E-09**	**5.7E-09**	5.7E-09	3.5E-09	8.1E-09	3.8E-09	3.5E-09
SigZ	**3.00E-04**	**3.00E-04**	3.00E-04	1.50E-04	5.00E-04	2.00E-04	1.50E-04
Dx	**2.26E-01**	**2.35E-01**	1.62E-01	7.08E-02	4.68E-01	2.26E-01	1.70E-01
Dy	**2.53E+01**	**2.23E+01**	1.85E+01	1.00E+01	2.86E+01	2.70E+01	2.19E+01
U_ave	**0.054**	**0.055**	0.046	0.061	0.036	0.100	0.133
delta_B	**0.030**	**0.031**	0.022	0.018	0.024	0.057	0.070
P_Beamstrahlung (W)	**3.35E+05**	**3.47E+05**	2.48E+05	2.05E+05	2.67E+05	3.06E+05	7.90E+05
N_gamma	**1.477**	**1.504**	1.257	0.823	1.664	1.756	1.725
Hd_x	**1.061**	**1.069**	1.022	1.002	1.465	1.061	1.026
Hd_y	**5.317**	**5.071**	4.727	3.764	3.211	4.142	5.037
Hd	**1.80E+00**	**1.78E+00**	1.70E+00	1.56E+00	1.79E+00	1.65E+00	1.74E+00
Geometric Luminosity	**1.64E+38**	**1.45E+38**	1.20E+38	1.29E+38	1.12E+38	1.24E+38	2.83E+38
Luminosity ($m^{-2}s^{-1}$)	**2.94E+38**	**2.57E+38**	2.03E+38	2.01E+38	2.00E+38	2.05E+38	4.92E+38
Coherent pairs/bc	**7.14E-35**	**4.65E-34**	7.71E-43	4.29E-31	3.19E-56	3.31E-15	2.21E-09
Inc. Pairs/bc	**4.14E+05**	**3.66E+05**	2.59E+05	8.37E+04	3.50E+05	6.12E+05	6.37E+05

Table 3. Beam and IP parameters for 1 TeV cms.

1 TeV Beam and IP Parameters

	TESLA	USCS	Nominal	Low Q	Large Y	Low P	High Lum
E_cms (GeV)	**800**	**1000**	1000	1000	1000	1000	1000
N	**1.40E+10**	**2.00E+10**	2.00E+10	1.00E+10	2.00E+10	2.00E+10	2.00E+10
Nb	**4886**	**2820**	2820	5640	2820	1330	2820
T_sep (ns)	**175.4**	**336.9**	307.7	153.8	307.7	461.5	307.7
Buckets @ 1.3 GHz	**228**	**438**	400	200	400	600	400
I_ave (A)	**0.0128**	**0.0095**	0.0104	0.0104	0.0104	0.0069	0.0104
Gradient	**35.00**	**35.00**	30.00	30.00	30.00	30.00	30.00
IP Parameters							
gamepsX (m-rad)	**8.00E-06**	**9.60E-06**	1.00E-05	1.00E-05	1.20E-05	1.00E-05	1.00E-05
gamepsY (m-rad)	**1.50E-08**	**4.00E-08**	4.00E-08	3.00E-08	8.00E-08	3.50E-08	3.00E-08
BetaX	**1.50E-02**	**2.44E-02**	3.00E-02	1.50E-02	1.10E-02	1.20E-02	1.00E-02
BetaY	**4.00E-04**	**4.00E-04**	3.00E-04	2.00E-04	6.00E-04	2.00E-04	2.00E-04
SigX	**3.92E-07**	**4.89E-07**	5.54E-07	3.92E-07	3.67E-07	3.50E-07	3.20E-07
SigY	**2.8E-09**	**4.0E-09**	3.5E-09	2.5E-09	7.0E-09	2.7E-09	2.5E-09
SigZ	**3.00E-04**	**3.00E-04**	3.00E-04	1.50E-04	6.00E-04	2.00E-04	1.50E-04
Dx	**1.98E-01**	**1.45E-01**	1.13E-01	5.67E-02	5.09E-01	1.89E-01	1.70E-01
Dy	**2.80E+01**	**1.75E+01**	1.79E+01	8.96E+00	2.67E+01	2.47E+01	2.19E+01
U_ave	**0.086**	**0.123**	0.109	0.154	0.081	0.257	0.376
delta_B	**0.042**	**0.061**	0.050	0.044	0.060	0.134	0.178
P_Beamstrahlung (W)	**7.33E+05**	**1.38E+06**	9.02E+05	8.03E+05	1.09E+06	1.15E+06	3.21E+06
N_gamma	**1.433**	**1.601**	1.429	0.987	2.163	2.109	2.220
Hd	**1.80E+00**	**1.68E+00**	1.52E+00	1.54E+00	2.02E+00	1.61E+00	1.74E+00
Geometric Luminosity	**2.81E+38**	**2.27E+38**	1.85E+38	1.85E+38	1.40E+38	1.81E+38	4.54E+38
Luminosity ($m^{-2}s^{-1}$)	**5.07E+38**	**3.81E+38**	2.82E+38	2.84E+38	2.81E+38	2.92E+38	7.88E+38
Coherent pairs/bc	**3.15E-19**	**6.80E-11**	1.92E-13	8.39E-08	2.03E-20	9.91E-01	8.18E+02
Inc. Pairs/bc	**4.66E+05**	**5.01E+05**	4.32E+05	1.50E+05	6.67E+05	1.10E+06	1.36E+06

Appendix A –
Andrew Hutton

ILC Integrated Luminosity from JLab Experience

Andrew Hutton

Accelerator Availability

The availability of CEBAF for Physics at JLab is defined as the fraction of the time that the beam meets the Users' experimental needs. It is described surprisingly well by the following formula:

> 85% for single Hall operation
>
> 80% for two Hall operation
>
> 75% for three Hall operation
>
> 10% reduction in availability for the first three months of operating a new capability (e.g. strained cathode, Ti-Sapphire laser, different rep rate, etc.)

The accelerator is "Down Hard" for 12-15% of the time. This covers component failures, loss of power, anything that prevents beam in the machine. Note that this time includes recovery time from the failure (which in the case of the Central Helium Liquefier can be long time). The additional downtime is due to tuning, optimization, and special conditions in one Hall that are incompatible with the program in other Halls (calibrations, Mott measurements, etc.).

> **From CEBAF experience, assume accelerator availability for Physics is 80%**

Experiment Availability

Over many years the experiment availability has exceeded 85%.

> **From CEBAF experience, assume experiment availability is 85%**

Simultaneous availability

We assume no correlations between accelerator and experiment availabilities.

> **From CEBAF experience, assume simultaneous availability is 80% x 85% = 68%**

Operating weeks per year

We operate the accelerator for roughly 40 weeks a year, the remaining 12 weeks are spent on two six-week maintenance periods. In general, we schedule 30 weeks (168 hours per week) a year of operations for Physics. The remaining 10 weeks include planned changes in the accelerator or experiment configuration, machine development time, short maintenance periods, etc. This is probably close to what will be required in the first few years of ILC.

From CEBAF experience, assume 30 weeks operation for Physics

Delivered Hours of Physics

From CEBAF experience, assume 30 x 168 x 68% = 3,400 Hours = 1.2 x 10^7 seconds

CEBAF experience provides a 20% safety factor compared to the nominal "Snowmass year" of 10^7 seconds.

ILC Integrated luminosity

Integrated luminosity assumes a design luminosity of 2 x 10^{34} cm^{-2} s^{-1} and a "Snowmass year".

ILC Integrated luminosity = 2 x 10^{34} x 10^7 cm^{-2} per year = 200 fb^{-1} per year

The Physics community required 500 fb^{-1} in four years with a ramp up over the first few years as shown in the Table.

Year	-2	-1	0	1	2	3	4
Luminosity	Commissioning	Commissioning	Detector testing	0.4 x 10^{34} cm^{-2} s^{-1}	1.0 x 10^{34} cm^{-2} s^{-1}	1.6 x 10^{34} cm^{-2} s^{-1}	2.0 x 10^{34} cm^{-2} s^{-1}
Integrated Luminosity	-	-	-	40 fb^{-1}	100 fb^{-1}	160 fb^{-1}	200 fb^{-1}
Total Luminosity	-	-	-	40 fb^{-1}	140 fb^{-1}	300 fb^{-1}	500 fb^{-1}

Conclusion

A luminosity goal of 2 x 10^{34} cm^{-2} s^{-1} and a "Snowmass year" is consistent with the ILC Physics requirements.

A "Snowmass year" is consistent with CEBAF experience and includes both experiment and machine availabilities, including time lost to configuration changes, that are to be expected.