

REVISITING THE COLD ILC PARAMETERS*

Hasan Padamsee, Cornell University, Ithaca, New York, 14853, USA

Abstract

Discussions are currently underway to re-examine the parameters of the cold ILC. Using the TESLA parameters MathCad program developed in 1991 [1], I examined several variations to explore consequences to the capital and operating costs of the linac (cryomodules, RF & refrigerator only). The cost coefficients were chosen to match the distribution of the above items in the TESLA TDR at a gradient of 25 MV/m. One parameter to vary is the gradient from 25 to 50 MV/m coupled with a realistic Q (which falls with gradient) as well as with an optimistic Q (held constant at 10^{10}). Other parameters to vary are: number of bunches, bunch spacing, and repetition rate to decrease costs and separately to decrease the damping ring size.

COSTS VS. GRADIENT

Among many parameters of the final collider, cost is obviously a very important one, but not as simple to characterize since the cost coefficients for the ILC components are still open to study and improvement. Nevertheless, it is necessary to gauge the impact of a particular change by considering its impact on cost. To include costs, I updated the Mathcad based parameters program [1] to use the approximate cost coefficients from the TESLA TDR. Here the overall costs of the main sub-systems such as linac, RF, and refrigeration are clear and repeated here in Table 1 as a useful starting calibration point. Note that I did not include the tunnel cost in the evaluations because (most likely) the length of the tunnel will NOT change with the choice of the gradient for the 500 GeV ILC. Rather the tunnel length will be fixed for one TeV energy at 35 MV/m design gradient. Certainly the overall length of the tunnel for one TeV can be shorter for gradients above 35 MV/m. But given the long road to gradients > 35 MV/m, it is more likely that if gradients higher than 35 MV/m are realized the impact will be on the final energy of the upgrade, rather than the length of the tunnel installed for the ILC.

Two aspects of the cost are important, the capital and the total AC power cost over the running period of the ILC. To evaluate the electricity cost I used a rate of 0.1\$/kWh and an effective continuous operation time of 5 years, 365 days per year at 24 hours per day.

Table 1: Linac cost breakdown (arbitrary units) for 500 GeV Collider at 25 MV/m (similar to TDR)

Linac	RF	Cryo	Capital Cost	Total Cost	AC Power
1	0.6	0.16	1.76	2.2	100 MW

Starting gradient from 25 to 50 MV/m

Cold technology has been making steady progress in gradients. At the time the TDR was written, gradients of 25 MV/m with Qs of 10^{10} were nearby. By the time of the cold technology decision, the one TeV upgrade path pushed gradient demonstrations at the 35 MV/m level although at somewhat lower Q values. Much more work is still needed to improve the reliability of 35 MV/m in cryomodules. Nevertheless the question arises as to whether one should already plan on using gradients higher than 25 MV/m for the 500 GeV collider in order to reduce capital cost, since the modules installed would have to demonstrate 35 MV/m capability anyway to be suitable for the upgrade. The decision of the best gradient will depend on how much cost reduction can be realized by using gradients higher than 25 MV/m, and the corresponding technical implications and risks. There have also been suggestions to consider gradients above 35 MV/m via improved structure geometries or materials.

In the *Cost vs. Gradient* cases studied, I made no change to the TDR beam parameters and therefore there is no effect on the luminosity and backgrounds. Figure 1 shows the *Q vs. Gradient* behavior assumed for the realistic case. As the gradient rises, the number of active meters for 500 GeV falls proportionally. The peak RF power (or the number of klystrons) remains constant since the peak beam power remains constant. But the average RF power rises because the Q_{ext} rises to match the beam power, and so does the rf pulse length. The cryopower and the AC power associated with the refrigerator also rise, but slower than the average RF power because as the dynamic heat load rises with gradient, the static heat load falls with decreasing length. Recall that the dynamic heat load for a pulsed machine is not as overwhelming at the duty factor of about one per cent. For example, the dynamic (9 kW at 2K) and the overall static (10 kW) heat load start out as nearly the same at 25 MV/m. At 35 MV/m the dynamic load rises to 20 kW and the static falls to 7 kW. (For simplicity, I assumed an overall static heat load of 0.5 W/m at 2 K to include the 5 - 8 K static components.)

To address the main question of cost reduction with gradient, Fig. 2 shows two sets of curves for capital and total (capital plus operating) costs. The upper pair of curves is for total costs and lower pair is for capital costs. In each case, costs are examined for two scenarios involving *Q vs Eacc*. In one case (called realistic) the Q drops as in Fig.1, and in the second case (called optimistic) the Q stays constant at 10^{10} with gradient. For the realistic case there is a shallow minimum between 30 — 45 MV/m in the total cost.

* Supported by the National Science Foundation

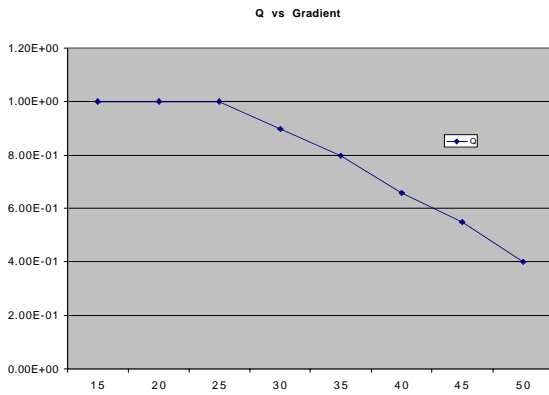


Figure 1: Realistic Q vs Eacc curve used

The linac capital cost drops by 9% upon increasing the gradient from 25 MV/m to 30 MV/m and another 5% at 35 MV/m. Also, the *total* cost (capital plus operating) drops by 6.4% from 25 to 30 MV/m and another 2.9% from 30 to 35 MV/m. Given the higher risks and the smaller incremental capital and total cost benefits from 30 to 35 MV/m, the choice of 30 MV/m may turn out to be quite attractive.

For the optimistic, constant Q case, both capital and operating costs continue to fall slowly with gradient all the way out to 50 MV/m. The total cost drops by 8.7% from 30 MV/m to 45 MV/m. Gradients higher than 35 MV/m are therefore attractive only if the high Q can be maintained.

There are also many technical challenges of gradients higher than 35 MV/m. The Lorentz force detuning increases as the square of the gradient, while the bandwidth decreases as the Qext rises (to match the beam power) from 2.5×10^6 to 5.1×10^6 as the gradient rises from 25 to 50 MV/m. To lower Qext for the higher gradient operation, one could entertain the idea of increasing the peak beam power per cavity either by decreasing the bunch spacing or by increasing the bunch charge. In the first case, the coupler power will rise above 500 kW, and the HOM damping will become more demanding. For the second option, the beamstrahlung and energy spread will intensify.

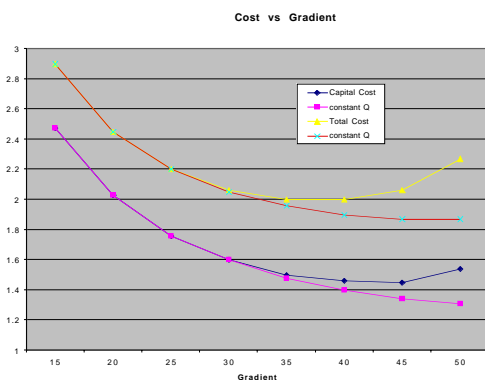


Figure 2: Capital and total costs for two Q vs Eacc cases.

Certainly the choice of 30 MV/m for the 500 GeV collider will improve reliability, considering that cavities would not have to operate near their gradient limit, and that couplers would be operating at lower power (e.g. 285 kW at 30 MV/m). Finally there would be some leeway to increase the energy of the collider (by lowering the current) in case some new discovery (e.g. at LHC) warrants exploration at energies above 500 GeV. As pointed out in the TESLA TDR, a choice near 25 MV/m would allow an energy reach to 700 GeV (at reduced luminosity), if cavities are capable of reaching 35 MV/m.

An important guiding constraint may still be the total AC power for the collider. Fig. 3 shows the AC powers and efficiencies for the realistic Q case and Fig. 4 for the optimistic Q case. For the realistic Q case, the AC power rises rapidly as the gradient rises above 30 MV/m and the accompanying efficiency drops. The other curves of Figs. 3 & 4 show the RF and refrigerator associated AC powers.

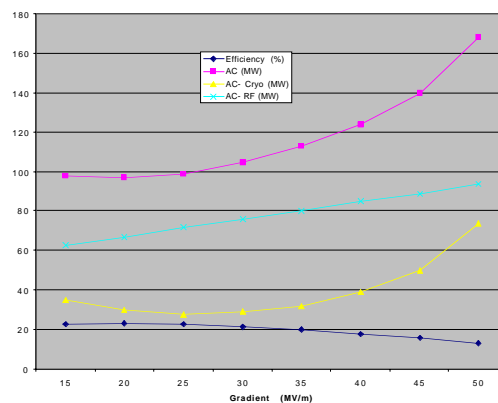


Figure 3: AC powers and efficiency for the realistic case.

At 50 MV/m, the linac AC power has risen from 98 MW to 170 MW and the efficiency has dropped from 23% to 13%. This clearly indicates the importance of maintaining high Q with higher gradients. Clearly the cost benefits of increased gradient can only be realized if the Q is maintained at the high values of 10^{10} , as shown in Fig. 4. Even in the optimistic case, the AC power rises to 130 MW and the efficiency falls to 17.5%. One should keep in mind that the collider AC power is about 50 MW higher in all cases due to the contribution from other sub-systems. It is possible there may be considerable reluctance to move toward a total accelerator facility AC power of 200 MW. High conversion efficiency of AC to beam power has been an important reason to select superconducting technology.

The above trends indicate that for 500 GeV the premium in raising gradients above 30 MV/m becomes marginal. Of course higher gradients along with higher Qs should be pursued to open collider upgrade energies above 1 TeV.

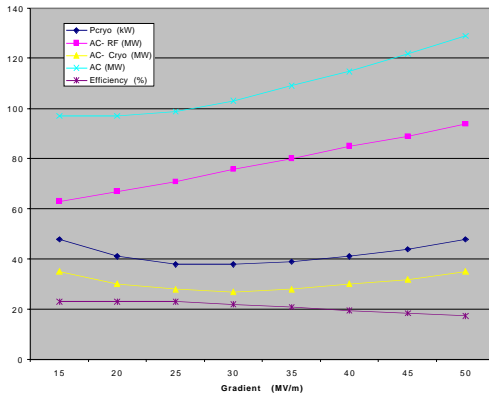


Figure 4: AC powers and efficiency for the optimistic case.

LINAC BUNCH SPACING

There are several motivations to *increase* the spacing. A longer beam rf pulse length lowers the peak beam power and therefore the number of (10 MW) klystrons as well as the peak power to be delivered by the couplers. For example, according to Figure 5, increasing the bunch spacing from the TDR value of $0.33 \mu\text{s}$ to $0.6 \mu\text{s}$ drops the number of klystrons from 600 to 333, and drops the coupler power from 237 kW to 131 kW at a gradient of 25 MV/m. Fewer klystrons, fewer modulators and reduced coupler power lower capital cost. (I assumed that doubling the RF pulse length will increase the overall RF capital cost coefficient by 15%). Lower coupler power will reduce the commissioning time. The AC power increases slightly from 100 to 107 MW and the linac efficiency falls slightly from 23 to 21%, but the total cost for the larger bunch spacing decreases slightly. However, the waveguide distribution tree has more branches and the low level RF system must deal with the vector sum from many more cavities. And there are other challenges. As the Qext rises, RF control issues get more difficult, especially Lorentz force detuning, but solutions may be possible by placing the piezo tuning element in a part of the tuner which has a larger lever arm. Microphonics (20 Hz) may still not be an issue since the bandwidth at Qext = 4×10^6 is still 250 Hz. The RF hardware must withstand higher average power due to the longer pulse lengths.

A judicious *combination* of higher gradient and longer bunch spacing is worth considering. For example a gradient of 30 MV/m at 1.5 times the nominal bunch spacing gives $Q_{\text{ext}} = 4.6 \times 10^6$ (BW = 284 Hz, rf pulse length = 2.2 ms) and a meaningful cost reduction. The capital cost is reduction over the 25 MV/m case is 20% and a total cost reduction of 12%, with AC power of 113 MW. There is still a substantial reduction in the number of klystrons (now 400). Certainly one may find a better optimum among these competing factors.

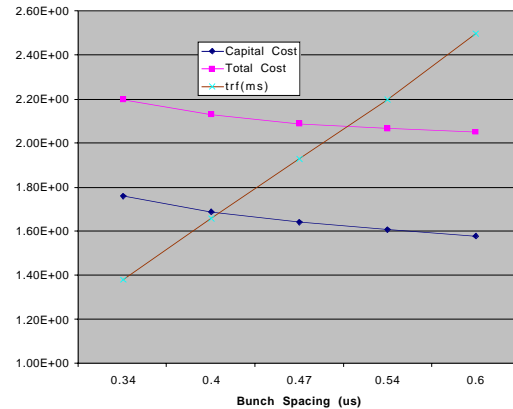


Figure 5: Capital and total cost variation with bunch spacing.

Smaller Damping Rings

There is considerable interest in reducing the length of the damping ring by a large factor. We explore a factor of two reduction in the number of bunches to make the damping ring smaller by a factor of two. Further decreases in damping ring size are possible with faster kicker under development underway at several labs. To bring the luminosity back to the same value as in the TDR we double the rep rate to 10 Hz. (We prefer not to increase the bunch charge because that makes the damping ring harder again.) But the higher rep rate pushes up the AC power, driving up operating costs. By doubling the bunch spacing in the linac (as discussed in the previous section), it is possible to keep the total cost the same as in the TDR because the capital cost (peak RF) decreases. The higher rep rate is better for bunch to bunch feedback.

OVERALL CONCLUSIONS

Besides raising gradients to lower cost, increased bunch spacing opens other options to lower cost but adds the challenge to operate with larger Qext. An optimal combination of increased gradient and increased bunch spacing is likely to provide benefits by lowering the number of klystrons. Reducing the number of bunches out of the damping ring will ease some of the present damping ring challenges. The loss of luminosity can be compensated by increasing the rep rate. The impact on cost of higher rep rates can be partially compensated by increasing the bunch spacing. Besides gradient, Qext is another useful parameter to open possibilities to lower cost.

REFERENCES

- [1] H. Padamsee, TESLA Parameters Program, 5th International SRF Workshop, Hamburg (1991)