Summary of Discussion Question 4: Energy Expandability of a Linear Collider

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We report on Discussion Question 4, in Sub-group 1 ('TeV-class') of the Snowmass Working Group E3: 'Experimental Approaches: Linear Colliders', which addresses the energy expandability of a linear collider. We first synthesize discussions of the energy reach of the hardware of the 500 GeV designs for TESLA and NLC/JLC. Next, we review plans for increasing the energy to 800-1000 GeV. We then look at options for expanding the energies to 1500 GeV and sketch the two-beam accelerator approach to achieving multi-TeV energies.

1. Introduction

The original statement of E3 SG1 DQ4 was:

'What is the energy for the initial phase of the LC (350 GeV, 500 GeV)? Assuming the energy reach is expanded using the same technology as in the initial phase, what is the high energy goal for a secondary phase of the LC? What R&D issues remain before such an expansion is possible? What constraints on the initial phase would ultimate conversion to two-beam drive impose?'

The scope of these questions, as posed, seemed too far-reaching for a third-order sub-group to address. The questions of desirability of a particular initial energy, or the energy goal for a secondary phase, will clearly be determined by the physics that is (hopefully) discovered between now and the Linear Collider turn-on, or upgrade, respectively. We feel that a reasonable summary of the current situation, in order of decreasing confidence, is:

· A minimum energy of 350 GeV will be needed to produce and study the top quark.

· Precision electroweak data imply that an energy of 500 GeV will be more than sufficient to produce the Standard Model (SM) Higgs boson, if it exists, in association with the Z^0. If the 95% c.l. limit is taken seriously an energy of 300 GeV is sufficient.

· In all currently known SUSY models, the lightest SUSY Higgs boson lies below 200 GeV in mass, and could therefore be produced by a collider with energy of 300 GeV or more.

· Many, but not all, SUSY models predict new particles that can be pair-produced by a collider with energy 1000 GeV; many, but fewer, SUSY models predict observable states at an energy of 500 GeV.

· Other beyond-SM models predict observable effects at e^+e^- colliders of energy beyond that explored at LEP2.

Discussion of particular models can be found elsewhere in these proceedings.

It therefore seems clear to us that it would be desirable to build a collider with the flexibility to operate initially within a range of energies between 200 and 500 GeV. Physics discoveries between now and its turn-on will serve to define the initial energy, as well as the details of the optimal luminosity/energy running strategy during the first years of operation [1]. It also seems clear to us that, almost independent of the details of such discoveries before or at the collider, it is

desirable that the capability for an upgrade to the highest energy allowed by the technology be designed from the start. Here we consider possible target energies for such an upgrade of 1000 GeV and 1500 GeV.

We therefore modified the terms of E3 SG1 DQ4 to address the following narrower set of questions:

1. What is the maximum energy that could be achieved using ONLY the hardware installed for the 500 GeV baseline design? How would you achieve this; what is the corresponding luminosity?

2. What would you need to do to achieve a c.m. energy of 1000 GeV: a) at your 'preferred' site, i.e. the one in your back yard, and (b) at an 'ideal' site, i.e. one unconstrained by local geographical boundary conditions? What luminosity could you achieve? Are any changes to the beam delivery system required? What are the incremental construction and operating costs? What R&D is needed?

3. Same as the previous question, but relating to a c.m. energy of 1500 GeV.

4. What do you need to do in your baseline design to allow eventual upgrade to a multi-TeV collider?

We posed these questions to Reinhard Brinkmann, Nobu Toge and Tor Raubenheimer, accelerator physicists associated with the TESLA [2] JLC [3] and NLC [4] projects respectively. We also received valuable input on the last of these questions from Jean-Pierre Delahaye of the CLIC project [5], and from Ron Ruth [6]. Here we attempt to synthesize the results of the presentations on these issues and the lively discussion that followed.

2. The Maximum Energy Reach of the Nominal 500 GeV Collider

We asked the machine designers to try to extrapolate the energy reach of the nominal 500 GeV baseline machine under the assumption that they received no funds for hardware upgrades. We also asked them to evaluate the corresponding luminosity.

2.1. JLC/NLC

For the X-band JLC/NLC the effective accelerating gradient in the linac is less than the nominal value due to the effect of 'beam loading.' The designers aim to achieve a nominal unloaded mean gradient of 70 MV/m, corresponding to roughly 50 MV/m of actual mean gradient at nominal beam current of 190 bunches $\times$ 10^{10} particles/bunch. A tradeoff between beam current, i.e. luminosity, and gradient, i.e. energy, is therefore possible. The maximum gradient of 70 MV/m, and hence c.m. energy of 650 GeV, is in principle achievable in the limit of zero current. Figure 1 shows the expected luminosity vs. c.m. energy. If the energy were increased from 500 GeV to 600 GeV the luminosity would decrease from 2 to 0.8×10^{34} cm^{-2}s^{-1}

2.2. TESLA

For TESLA, the accelerating gradient needed for 500 GeV c.m. energy is 23.4 MV/m. The cavities can be run at higher gradient, in principle up to and beyond 40 MV/m, at the cost of higher power dissipation. Hence, the headroom in the cryogenic plant can be traded off to achieve higher gradients. Using all of the 50% built-in cooling overhead of the 500 GeV machine, it would in principle be possible to achieve a c.m. energy of 750 GeV, however at reduced repetition rate below the nominal 5 Hz. In order to contain the RF power at higher gradients, one must lower the beam current (via increased bunch spacing) and shorten the RF pulse length. Improved emittance compensates for this loss of current so that with no other effects, the luminosity would be unchanged. In fact, the luminosity declines because at the higher gradient, the cavity filling time (that is, the time required to achieve gradient) increases, so less of each pulse is useable for bunch acceleration. Figure 2 shows the expected luminosity vs. c.m. energy. If the energy were increased from 500 GeV to 700 GeV the luminosity would decrease from 3.4 to 1.1×10^{34} cm^{-2}s^{-1}.
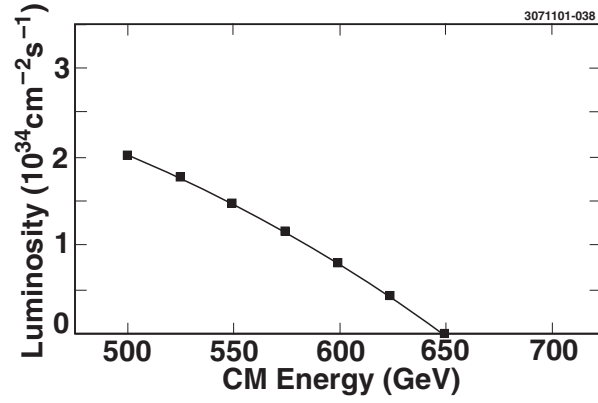
Figure 1: The projected NLC luminosity as a function of c.m. energy using only the hardware of the 500 GeV baseline design. Energies above 500 GeV are attained by reducing the beam current and therefore the beam-loading of the accelerating structures.
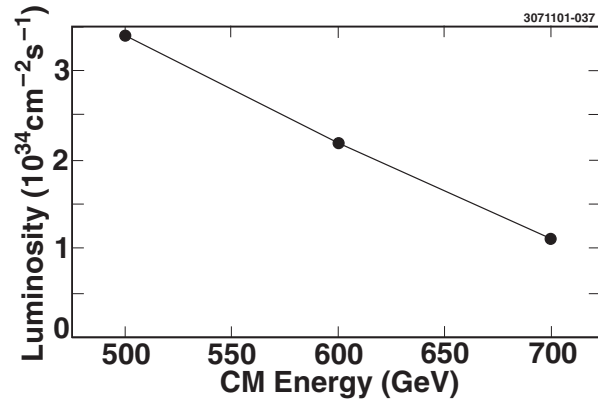

Figure 2: The projected TESLA luminosity as a function of c.m. energy using only the hardware of the 500 GeV baseline design. Energies above 500 GeV are attained by increasing the gradient and therefore the demands on the cooling plant.

3. Energy upgradeability to 1000 GeV

We asked the machine designers to explain the scenaria by which the initial nominal energy of 500 GeV could be doubled.

3.1. JLC/NLC

If the mean accelerating gradient for the X-band technology is assumed to be fixed at a (loaded) value of 50 MV/m, the energy could be doubled by doubling the RF system, i.e. doubling the number of: accelerating structures, klystrons, modulators and power supplies. This is anticipated in the JLC/NLC designs, the baseline 500 GeV site being designed to accommodate the extra components without any need to lengthen the tunnels. Some increase in the cooling plant would also be required. The A.C. power is estimated to rise by roughly 100 MW, bringing the two-linac power to about 230 MW. For c.m. energies above 700 GeV the currently-envisioned permanent magnets in the final doublet system of the final focus would need to be replaced. The total additional construction cost is estimated to be +25%, or $1.5B.

Key areas of R&D for NLC are in the RF system and accelerating structures. Since 1000 GeV is achieved by doubling the number of components, the R&D for the 500 GeV baseline design also addresses 1000 GeV operation. R&D is ongoing at SLAC to demonstrate the reliable operation of Cu accelerating structures at high gradient. As of the time of writing, travelling-wave cavities have been successfully operated with unloaded gradients as high as 80 MV/m; it is desirable to

reach 90 MV/m in order to allow more 'headroom'. This will need to be achieved for structures with the NLC iris radius and with long-range wakefield suppression. The needed gradients have been achieved in standing-wave cavities, which provide a possible alternative, albeit one requiring substantial modification of the linac design.

For the RF system, a full-scale 500 kV modulator is being tested, an X-band klystron has been operated at low repetition rates, and low power operation of a delay line distribution system has been demonstrated at the ATF in Japan. A full-power test of a complete prototype RF unit is planned in the NLCTA in 2003.

The luminosity achievable at 1000 GeV is estimated to be 3.4×10^{34} cm^{-2}s^{-1}.

3.2. TESLA

The official goal of TESLA, as outlined in the TDR, is to reach a maximum energy of 800 GeV. It is planned to achieve this by increasing the mean gradient from 23 to 35 MV/m. The cost to upgrade from 500 GeV to 800 GeV is estimated to be 600-650 MEuro (an additional 20% over the cost of the 500 GeV machine), which arises from the necessary expansion of the RF-power and cooling plants. The two-linac power consumption would increase to about 160 MW.

An ongoing R&D program into the electropolishing of small Nb cavities has yielded cavities that exceed 35 MV/m gradient. These cavities have yet to be tested under full power at the TTF. It also remains to test new cryogenic "superstructures", which improve the packing-density of the cavities by 6% by housing them in pairs, and therefore reduce the linac cost. Tests of the superstructures will begin in 2002, leading to a full scale test at TTF, possibly with the high-gradient cavities, in about 2004.

Theoretically, the maximum gradient achievable with the Nb cavities is about 50 MV/m; naively this would allow an energy of more than 1 TeV to be reached, but this is not thought to be realistic. Assuming a highest mean gradient of 35 MV/m, it would be necessary to lengthen one or both linacs in order to go beyond 800 GeV. At the DESY site two possibilities are:

a) extending the northern (positron) linac by 8 km; this would yield asymmetric collisions of 625 GeV positrons on 400 GeV electrons. The cost is estimated to be an additional 900MEuro, on top of the cost of the 800 GeV machine.

b) adding 4 km to each linac to achieve symmetric 500 ⊕ 500 GeV collisions. The incremental cost, on top of the 800 GeV machine, would be similar to a), However, because of the constraint imposed at the southern end by the River Elbe, the central site containing the beam delivery system, the interaction region(s) and the detector(s) would effectively have to be translated to the north to accommodate the extra 4 km of southern linac. This would have a serious impact on the present site planning, the consequences of which would have to be carefully investigated. The linac power load would increase by about 40MW to a total of 200 MW. The beam delivery system would also have to be modified from its current design to accommodate the higher beam energy(ies); this might be achieved within the length of the present design by applying a Raimondi-Seryi scheme, as planned for the JLC/NLC.

The luminosity achievable at 1000 GeV is estimated to be 6×10^{34} cm^{-2}s^{-1}.

3.3. C-band JLC

An alternative scheme for a 500 GeV collider has been developed in Japan; it is based on C-band RF technology with a mean loaded gradient of 36 MV/m needed in order to reach an energy of 500 GeV. 1000 GeV could be achieved either:

a) by doubling the active length of the RF system.

b) by building a site-filler tunnel from the start, increasing the gradient from 36 MV/m to 50 MV/m, and adding RF as needed. The peak klystron power would need to be doubled from 50 MW to 100 MW; this, in addition to corresponding improvements in the other RF components, would require an R&D programme. Note that the gradient would then be comparable with the X-band case.

4. Energy upgradeability to 1500 GeV

Although energy upgrades to 1000 GeV (JLC/NLC) and 800 GeV (TESLA) are being designed into the projects, the foundations that would allow eventual upgrade to energies substantially above 1000 GeV seem less secure. Presumably an upgrade path, if possible, will become clearer after many years of experience with either the X-band or superconducting technology.

At the higher energies, AC power usage limits the beam current. TESLA and NLC therefore assume constant luminosity as their energies increase from 1000 to 1500 GeV. The high energy also increases beamsstrahlung, and therefore energy spread, for both machines.

4.1. JLC/NLC

Assuming the use of the planned X-band technology, two possibilities could be envisaged to achieve a c.m. energy of 1500 GeV:

a) If the accelerating gradient were fixed, at 50 MV/m loaded, an energy increase would require a lengthening of the linacs. In the JLC/NLC design the injection and pre-acceleration systems form a 'trombone' structure at the head of each linac; the trombones could be extended to accommodate longer linacs, with the addition of transport lines. This path would require additional klystrons.

b) If the site length were fixed, an energy increase would require an increase in gradient, from 50 to 75 MV loaded. This would double the power consumed by the RF system. The power could be preserved at about the same level as that needed for 1 TeV operation by running at a repetition rate of 90 Hz rather than the nominal 120 Hz; this would imply a luminosity reduction of roughly 25%.

4.2. TESLA

Assuming the use of the planned superconducting technology, with a maximum mean gradient of 35 MV/m, the linacs would need to be lengthened by a total of 14 km in order to achieve a c.m. energy of 1500 GeV. The total cost of such a machine would be in the ballpark of 5.5 to 6 BEuro. Given geographical limitations at DESY, either the central site would have to be relocated, as discussed in the previous section, or the tunnel would need to be dug deeper from the project start, so as to allow tunnel passage beneath the River Elbe. The latter is not currently envisaged.

5. Energy upgradeability to multi-TeV scales

Achieving very high energies requires both very high accelerating gradients and very efficient delivery of RF power. Even in an ideal case, it is likely that the luminosity achieved will be limited by the need to contain power use.

The most mature ideas for a Multi-TeV e^+e^- collider are based on so-called 'two-beam' technology. This is the basis of the design for CLIC [5, 7], which is under development at CERN. In the CLIC design, power is 'stored' in a high-current (190A), low energy (1.3 GeV) drive beam and transferred to the low-current, high-energy main beam. The design requires an accelerating gradient of 150 MV/m in Cu structures operating at 30 GHz; gradients above 100 MV/m have been achieved, but so far only in single-cell structures operating at low power. In order to achieve a useful luminosity, CLIC will need very small emittance and beam spots; in the vertical plane the beam size must be less than 1 nanometre, a factor of 3 and 5 smaller than the already-ambitious beam sizes planned for JLC/NLC and TESLA, respectively. In order to achieve this, the emittance must be preserved in the face of vibrations, strong wakefields and other disruptions. Like the NLC, CLIC requires a crossing angle (20 mrad) in order to avoid parasitic collisions by closely-spaced bunches. CERN is now planning a facility, CTF3, that will test the two-beam accelerator proof-of-principle. The facility will also test whether gradients of 150 MV/m can be sustained under operating conditions. The goal of the designers is to have demonstrated the needed technology by 2008.

Should the CLIC design prove feasible, it will draw on experience gained at a first generation linear collider, particularly in the area of attaining and preserving low emittance. Many of these

extreme challenges are shared by the NLC/JLC, though CLIC would push them substantially further.

A scheme was presented [6] for an 'adiabatic' upgrade of the JLC/NLC to multi-TeV operation via phased installation of a drive beam, doubling of the RF frequency, and replacement of the accelerating structures. This plan for multi-TeV operation is similar to CLIC's, and shares critical R&D areas.

6. Summary and Conclusions

Using the hardware envisioned for 500 GeV operation at TESLA and NLC/JLC, it should be possible to push the c.m. energy of a linear collider up to about 650 GeV at the cost of reduced luminosity. Expansion to energies in the 800-1000 GeV range, at full luminosity, is incorporated into the designs of both TESLA and NLC/JLC. Reaching c.m. energies above 1000 GeV goes beyond the current plans, and if such energies are attainable, achieving them will build on experience gained at 1000 GeV and below. The multi-TeV regime requires a new strategy such as the two-beam technique envisioned for CLIC. The parameters for such a machine might be established late this decade.

Acknowledgments

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