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A First Assessment of Two-Beam Linear Colliders and Longer-Term Two-Beam R&D Issues at SLAC

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Purpose of this Document

The purpose of this document is to summarize the work that has been done at SLAC in the last three or four months to assess the possibilities of two-beam linear colliders proposed by Ron Ruth, and to compare these colliders to the current NLC designs and their costs. The work is based on general discussions with C. Adolphsen, D. Burke, J. Irwin, J. Paterson, R. Ruth, T. Lavine and T. Raubenheimer, with considerable work done by the latter two. Given the complexities of these machines, the fact that the designs are far from complete and that all cost estimates are still in a state of flux, it is clear that the conclusions drawn in this report cannot be cast in concrete. On the other hand, it does not seem too early to present the results that have been gathered so far, even if the facts contain significant uncertainties and the costs have large error bars. Now that R. Ruth has returned to SLAC, he will be able to add his point of view to the discussion. At this time, the conclusions presented here are the sole responsibility of the author.

This document is comprised of three parts:

1) An assessment of the technical design and cost of a Two-Beam Linear Collider Site Filler (TBLC-SF for short) that could fit on a 7.8 km-long site at Stanford.

2) A comparison of the nature and cost of the components needed for a 500 GeV c.m. and a 1 TeV c.m., 11.4 GHz Two-Beam Linear Collider with those of the current NLC, both machines using the same main linacs and operating at the same gradient.

3) Some thoughts regarding longer-term prospects of two-beam R&D for an expandable 1 TeV c.m. linear collider.

The new artwork was done by E. Mitchell.

Background: Ron Ruth's SLAC Presentations of a New Two-Beam Linear Collider

During the week of April 27, 1998, Ron Ruth interrupted his sabbatical at CERN to visit SLAC. During this visit he gave a number of widely attended lectures at which he presented a new type of Two-Beam Linear Collider (TBLC). The basic idea of this new TBLC started with an elegant simplification of the CLIC drive beam, which Ruth developed in collaboration with the CLIC group. This simplification makes it easier to generate the drive beam (by means of a room-temperature linac) and to transport it along the main linac for energy transfer (by breaking it into a train of successive lower power pulsed beams). Ruth at first described the scheme as a potential drive beam for a 1-3 TeV c.m. $e^{\pm}$ linear collider. The main linac would operate at an rf frequency of 30 GHz like CLIC, and a gradient of 100-150 MV/m.

Having described the principles using the 3 TeV design in considerable detail, Ruth applied the idea to a power source for the NLC 1 TeV machine, first using 11.4 GHz and then using twice the NLC gradient at the higher frequency of 22.8 GHz (K-band). Finally, Ruth concluded his talk by suggesting that the higher gradient, higher frequency machine could be driven by an S-band Drive Beam Linac and might fit on an extended SLAC-Stanford site. All these issues are discussed in this document, as outlined above.

1. TBLC Site Filler

A. Description of the Machine

The questions that must be answered to assess the center-of-mass energy of a Stanford site filler are 1) to decide how much real estate might be available, 2) how much length must be reserved for the beam delivery section, and 3) what fraction of the available length can therefore be used for acceleration.

In studying the available Stanford maps, an arbitrary straight length of 7.8 km has been chosen, which stretches from Whiskey Hill Road in Woodside to Page Mill Road in Palo Alto (see Fig. 1). Two additional kilometers might be acquired from Page Mill Road to Arastradero Road along this line but they would probably require complicated negotiations due to interference with the existing Stanford Industrial Park. Other longer sites centered around SLAC would require boring tunnels under inhabited areas, an option which at this point seems unlikely. If these assumptions were to be found incorrect, the upper bound of 7.8 km could be reconsidered.

The second question has to do with what fraction of the 7.8 km must be reserved for the beam delivery section. T. Raubenheimer points out that such a beam delivery section must contain sub-sections for:

a) Collimation
b) IP Switch and Big Bend
c) Diagnostics
d) Chromatic corrections in X and Y
e) β−match
f) Final Transformer

From existing NLC designs for 1 and 1.5 Tev, he proposes the following scaling laws:

$$L/side\,(\mathrm{m}) = 2000\left(\frac{E_{CM}}{1\,TeV}\right)_{COLL} + 500\left(\frac{E_{CM}}{1.5\,TeV}\right)^{3/2}_{IPSW,BB}$$

$$+400\left(\frac{E_{CM}}{1.5TeV}\right)_{DIAG} + 1200\left(\frac{E_{CM}}{1.5TeV}\right)^{3/2}_{CCX,Y}$$

$$+250(\,\beta\text{−match}\,) + 150(FT)$$

The last two lengths are assumed to be independent of energy in the range of interest. If we assume that E_{CM} might fall in the range between 350 and 450 GeV, we find that

$$1400 \le L/side\,(\mathrm{m}) \le 1700$$

If we arbitrarily pick $L = 1500\ m$ and keep 250 m at each end for beam turn-around loops, the total length available for acceleration is 7.8-3.5 or 4.3 km. Assuming a fill factor of 80%, the total active length that is left for the two linacs is 3.44 km. Note at this point that the beam delivery system assumed here is of a conventional nature. J. Irwin is currently working on a different idea in which the beam delivery hardware is replaced by "dynamic focusing lenses" using intense fields from trains of demagnified e^+ and e^- bunches. While this scheme is very interesting and would occupy less real estate at the Final Focus, it requires additional linacs and storage rings to produce these bunch trains. There is not enough information at this point to assess and incorporate such an idea in the design of the Site Filler.

Now, let us discuss the question of linac gradient. Having no experience with rf frequencies above 11.4 GHz, we can only guess what gradients might be obtainable at, for example, 22.8 GHz. Gradients might scale as $f^{1/3}$ or $f^{1/2}$ for rf breakdown, and will scale as f for dark-current capture. Hence, a lower bound might be ~90 MV/m and an upper bound 122 MV/m, giving an E_{CM} range of 310 to 420 GeV.

Figure 2 shows the basic schematic diagram of such a collider. The left-hand side of the figure recasts the basic configuration of a foreshortened NLC. The injector, damping rings and pre-linacs are unchanged but the main linacs are only 2.15 km long, each. The collimation sections are each 0.75 km long, and the final focus length is 1.5 km.

The drive linacs and beams are shown on the right-hand side of Figure 2. The scheme works as follows:

1. An S-band linac (2.856 GHz) generates a 13.9 μs-long beam pulse with an energy of 1.2 GeV and a current of 7 A. Only every second rf crest is populated, with a bunch of roughly 5 nC of charge. Each S-band linac has ninety 55 MW klystron pairs which supply roughly 100 MW of peak power to ninety S-band, 0.91 m-long accelerator sections. Each klystron is fed by one modulator. The unloaded gradient is 28.46 MV/m and the loaded gradient is 14.81 MV/m. Hence, with 81.9 m of active length, one obtains roughly 1.2 GeV of energy.

2. The drive linac injector actually has two guns and sub-harmonic bunchers which create alternate sets of even and odd bunches. At the exit of the linac, this quasi-continuous 13.9 μs-long train of bunches (see Figs. 3 and 4) is sent sequentially through:

    - Two conjugate 1.428 GHz rf separator sections separated by a times-two 65 m long combiner delay system,

    - Two successive rings, roughly 130 m and 520 m in circumference.

    The net result of this scheme is to move the bunches together by a factor of 16, thereby increasing the peak current by a factor of 16 from 7A to 112A, and to create gaps in the continuous bunch train that have the correct spacing for the timing of the distribution of the trains. The new train consists of 4 pulses, each 217 ns-long, spaced 3.46 μs apart.

3. The train is sent "upbeam" along the counterflowing main linac beam. When the first 217 ns-long beam pulse reaches the front-end of this main linac, it is turned around by 180° through a small arc of bending magnets and quadrupoles, which also produces some individual bunch shortening.

4. Like a bunched beam passing through the output structure of a klystron, the drive beam pulse is now ready to induce rf power in the first 520 m-long array of 228 "transfer structures", each 1.6 m-long. As the 112A beam travels through each structure, it generates 217 ns-long pulses of about 500 MW peak power at 22.8 GHz (K-band) in four outputs of 125 MW each. The power is combined to deliver 240 MW of power to each of two K-band, 0.9 m accelerator sections. At the end of the 520 meter "sector", the spent beam has lost about 85% of its energy and it is sent to a dump.

5. At this time, when the next 217 ns beam pulse arrives at the head of the next downstream sector, it is deflected by a kicker magnet and sent around its 180° bend to start a second drive beam deceleration and main beam acceleration sequence. This step is subsequently repeated two more times, completing the acceleration of the full ~200 GeV main beam. An identical mirror-image system operates on the other main linac.

Overall parameters of the 400 GeV c.m. TBLC-SF are summarized in Tables 1a and 1b (second column). For the 500 GeV c.m. NLC, the parameters are shown in the first column for comparison.

B. R&D Implications

Areas of Accelerator R&D required to establish the feasibility of a 500 GeV c.m. machine with an NLC on an unconstrained site versus a 400 GeV c.m. TBLC-Site Filler can be compared by looking at Table 2. Careful examination of this table reveals the following points for comparison:

1. The injector systems are the same for both approaches and require the same R&D for all systems up to 10 GeV.

2. There are significant differences in the rf systems:
   a. All the NLC X-band klystron and pulse compression systems are eliminated in the TBLC-SF. Klystron R&D is shifted to S-band 55 MW, 13.9 μs pulse length klystrons and their modulators. Pulse length and average power are up significantly with respect to the 5045 klystron, requiring much more cooling, probably the redesign of a more efficient klystron with improved multiple windows, and conventional focusing. All of this technology is probably feasible but not trivial, given the difficulties experienced with the original 5045 klystron

with a 5μs pulse. There apparently exist two long-pulse Thomson tubes (20 MW and 40 MW) in a catalogue but it is not clear that they have been tested in the field. Note that this klystron R&D would also benefit the S-band injector klystrons.

b. The drive-linac S-band sections have to be designed as DDS structures because one cannot allow much emittance growth in the drive beam, and wakefields (single bunch and multibunch) must be controlled. This should be feasible.

c. The K-band transfer structures must be designed for high group velocity ($v_g / c \geq 0.4$), low HOM's, the correct ΔV (beam energy loss per 1.6 m structure) for good efficiency, and the correct peak power output (~500 MW). RF power tests performed with commensurate drive currents (~112 A) will be indispensable to show the feasibility of this approach. CERN has so far built several transfer structures at 30 GHz and generated lower level power outputs at lower drive beam currents. Some additional information will be obtained from tests at the CLIC Test Facility, later this year, but further tests will be required.

d. The X-band 1.8 m-long DDS structures would be replaced by K-band 0.9 m-long structures. These would have to support twice the peak no-load accelerating gradients (~160 MV/m versus 80 MV/m) with commensurate pulse lengths (217 ns versus 375 ns). Given the problems experienced at X-band, this will not be an easy task and will require ~250 MW K-band power sources feeding single K-band structures to establish feasibility. There are some ideas about how to generate K-band power with a high current beam produced in the NLCTA at 11.4 GHz and passed through another structure at 22.8 GHz. A considerable long-term new R&D program will be required to check that these gradients can be obtained reliably.

3. The main linac mechanical tolerances at K-band are a little more than a factor of two tighter, and supports and movers would need finer adjustments. Quadrupole arrays are different in the transfer linacs from the adjacent main linacs because the beam energy decreases in the transfer linac (from 1.2 GeV to maybe 180 MeV for good efficiency) whereas the main linac beam energy goes up linearly. This difference explains the fill factor of ~ 80% assumed earlier. Vacuum conductances in the main linac structures are smaller at K-band because the iris and other hole diameters (probably also those of the manifolds if one wants to cut off the fundamental mode)

are half the size of those at X-band. Closer pumpouts, because of shorter lengths, help somewhat. All of this would have to be tested.

4. Beam manipulation can probably be simulated at both X-band and K-band. However, the generation and transport of the 112 A K-band beam is very challenging, and one would probably want to do a real test to see if the bunch combination process with rf deflectors works with realistic currents.

5. In the NLC with expandability to 1.5 TeV there are 10.4 kilometers reserved for the beam delivery system. In the Site Filler, it has been assumed above that only 3 kilometers are available for this purpose. No space is left for future expansion unless the site can be expanded beyond 7.8 km and/or a different type of final focus can be adopted.

C. Cost Comparisons Between NLC and TBLC Site Filler

On the basis of the TBLC-SF design outlined here, it has been possible to develop a WBS based on the methodology originally used for the ZDR of March 1996 for the NLC. In the meantime, many of the costs and numbers of components for the NLC have been modified. The NLC tunnel and conventional facilities are built from the beginning to accommodate the 1 TeV design but only half the tunnels are filled with rf equipment to achieve the 500 GeV c.m. parameters. The following cost assumptions have been made for the TBLC-SF:

1. Building costs are simply scaled in relation to length.
2. All injector systems costs are the same as for the updated NLC.
3. Drive beam klystron and modulator costs are roughly doubled with respect to X-band costs because the average powers are higher (see discussion above).
4. K-band accelerator structure costs/unit are the same as X-band structures costs/unit because there are twice as many cells, couplers, etc., even though the lengths come in the ratio of 0.9/1.8.
5. K-band transfer structure costs/unit are half those of X-band structure costs/unit, because they are assumed to be easier to build.
6. The costs of magnets, power supplies, beam instrumentation and controls are scaled to reflect the addition of the drive beam linacs, turnarounds and transfer-structure linacs.

The details of the cost estimate calculated as a percentage of the current NLC total cost (100%) are given in the second column of Table 3. As can be seen, the Total Base Cost is roughly 62% of the current NLC Total Base Cost, both without escalation and contingency.

D. Conclusions on the Site Filler

A decision to "shift" SLAC's Linear Collider program from the NLC approach to a Two-Beam Linear Collider Site Filler approach would have major political and scientific consequences. The political consequences would be multifaceted and will not be discussed here. The scientific consequences, based on the contents of this report, can be summarized as follows:

1. Within the assumed length constraints, the TBLC Site Filler c.m. energy is limited to about 400-420 GeV, unless one goes to higher rf frequencies and gradients.

2. The R&D program to prove feasibility of the K-band TBLC-SF is quite different from that for the X-band. While the injector systems are probably identical (up to 10 GeV), the higher-gradient nature of the K-band main linac (which shortens the machine and therefore makes the Site Filler thinkable) pushes the rf technology and the tolerances to harder levels of feasibility and manufacturability. The drive linac with its very high average power and high current is probably feasible but would also have to be tested. So would the charge combination scheme (factor of 16) with rf separators and rings, and the generation of rf power, stability, timing, reliability and so on.

3. The major items that would drop out of the R&D program if the NLC were abandoned in favor of the TBLC would be the X-band klystrons and modulators, and the rf pulse compression systems (MDLDS or some variation thereof). The required NLC and TBLC-SF R&D programs cannot adequately be pursued in parallel at equal levels at SLAC with existing staff and resources. Both programs would become diluted and would risk failure.

4. Building a Site Filler at Stanford has obvious local psychological appeal but would constrain us to a limited site and energy from the beginning.

5. With perhaps the exception of the MDLDS system, the two-beam R&D program, because of all the reasons mentioned in this report, would be two or three years behind the current X-band R&D program.

6. The estimated Total Base Cost (i.e., without escalation and contingency) of the Site Filler, admittedly rough at this time, is about 62% of the current cost of the NLC Total Base Cost for the 500 GeV c.m. design with expandability to 1 TeV c.m. built in from the beginning. Although the Site Filler is obviously less costly, it does not appear to be a "bargain," given the space and energy limitations, and the up-front R&D costs that would have to be added to prove feasibility of this machine.

2. Comparisons of TBLC-X and NLC at 500 GeV c.m. and 1 TeV c.m., 11.4 GHz, Same Gradient

Having looked at the possibilities of the TBLC as a site filler, it now seems appropriate to compare the TBLC with the NLC at equal energy (500 GeV c.m. and 1 TeV c.m.), equal main linac rf frequency (11.4 GHz), equal gradient (57 MV/m) and site compatible with 1 TeV c.m. energy expandable to 1.5 TeV c.m. Concentrating on such a TBLC does not necessarily optimize its potential for higher gradient at higher frequency nor its design for expandability to higher energies (1 TeV and above), but it removes the problem of comparing apples and oranges. A set of TBLC parameters for a 500 GeV c.m. X-band machine is shown in the third (right-hand side) column of Tables 1a and 1b.

A. Description of the TBLC-X at 500 GeV c.m.

The basic schematic diagram of the TBLC-X is shown in Figure 5 and the comparisons of required accelerator R&D issues and components are shown in Table 4. The footprint is very similar to the NLC but longer by about 500 meters for reasons inherent in the drive beam timing requirements of the design.

It is assumed that for both 500 GeV c.m. machines, the tunnels and all conventional facilities are built from the beginning to accommodate the ultimate 1 TeV c.m. colliders. Hence, for the first stage, only half the rf equipment is installed and the two beams are allowed to drift through the second halves at constant energy.

Operation of the TBLC-X is similar in principle to the TBLC-Site Filler but exhibits the following differences:

1. Since the main linacs are now identical to the NLC and run at 11.4 GHz, the drive linacs must operate at a lower frequency, for example 714 MHz (UHF) in order to achieve the ultimate compressed drive beam current of 116 A at 11.4 GHz. The current in the UHF drive linac is 3.62A instead of 7A and is compressed by a factor of 32 by the combiners to 116 A. As for the Site Filler, only every second rf crest at 714 MHz is populated, with a bunch of about 10 nC. Each UHF linac contains 125

(714 MHz) 50 MW klystrons which individually power 125 2-meter long structures. The unloaded gradient is 11.5 MV/m and the loaded gradient is 5.72 MV/m. The active length being 250 m, the total loaded energy is 1.43 GeV. The rf pulse length is 37 μs, and the beam pulse length is 35.5 μs . It is generated, as for the Site Filler drive linac, by two separate injectors which create alternate even and odd bunch trains.

2. The bunch train compression system consists of a 110 m delay, a 220 m circumference ring and an 880 m circumference ring. The ultimate drive bunch pattern requires three bunch trains, each 375 ns long, and spaced 11.8 μsec, to match the pattern of three transfer linac sectors, each 1.77 km long. To achieve this pattern, the bunches must spend four turns in the 880 m circumference ring.

3. Each 1.77 km sector contains 396 X-band transfer structures and 792 X-band accelerator structures, for a total of 2376 accelerator sections per side. The peak output power generated by the 116 A compressed drive beam in each transfer structure is 360 MW peak, which gets divided evenly between two accelerator sections. Instead of four sectors and 180° turn-arounds in the Site Filler, the TBLC-X only uses three longer sectors and 180° turn-arounds.

   The various rf and modulator efficiencies are assumed to be the same as for the Site Filler and hence yield similar wall-plug power to beam conversion efficiencies. With these assumptions, it turns out that the NLC uses a slightly lower amount of AC power for the main linacs but the differences are small and within known error bars.

B. Cost Comparisons Between NLC and TBLC-X

Similarly to the TBLC Site Filler, we have calculated comparative costs for the 500 GeV c.m. TBLC-X as shown in the third column of Table 3. As stated earlier, the cost estimates of both 500 GeV c.m. NLC and TBLC-X assume that tunnels and conventional facilities are installed from the beginning to accommodate expandability to 1 TeV c.m. Again, the TBLC-X costs are normalized to the total 500 GeV c.m. NLC costs, both without escalation and contingency. It is seen that with the current assumptions, the costs for the two machines, both at 500 GeV c.m., main linac frequency at 11.4 GHz and loaded gradient at 57 MV/m, are almost identical. Again, the error bars are probably significantly greater. What seems to be happening is that the costs of the rf system (klystrons, modulators, pulse compression and drive) for the

NLC are similar to the costs of the drive linacs, combiners and transfer structures in the TBLC-X. The conventional facilities for the single-tunnel TBLC-X are not much cheaper than the costs of the NLC tunnel with its klystron-modulator "alcoves" when one includes the costs of 180° turn-arounds, dumps, cable plants and electrical site preparation. The other costs (injectors, collimation, final focus, IR, final dumps) are by definition unchanged; hence, the grand totals are very close.

Note that the fractional cost of the drive linacs for the TBLC-X is not much higher than that for the Site Filler (9.3% vs. 7.1%) even though their beam power ratio is 22/14. This is due to the fact that, following R. Ruth's idea, we assumed a higher gradient for the TBLC Site Filler linacs and a larger number of klystrons at 2856 MHz. We could have gone to a frequency of 1428 MHz for the drive linac with a lower gradient and less klystrons. Accordingly, the cost of the Site Filler drive linacs would have come down somewhat, but they would have occupied more space. In that case, to attain similar currents in the transfer structures would have required a compression factor of 32 rather than 16, i.e., the same as for the TBLC-X. Clearly, these are somewhat arbitrary choices.

Finally, Table 3 also includes the cost estimates for the 1 TeV c.m. NLC and TBLC-X where the machines are installed to 1 TeV in their entirety. For the NLC, this means filling the main linacs with rf equipment (klystrons, modulators, pulse compression and structures) all the way to the end. For the TBLC-X, it means doubling the pulse lengths of the rf and the drive beam to accommodate the longer linacs. Note that in this latter cost estimate, it has been assumed that the 714 MHz klystrons are built from the beginning with the ultimate rf pulse length capability (74 μs), but the modulator costs would have to be increased by about 75% to upgrade the average power and the pulse length by a factor of 2. The drive beam linac structures and combiners are assumed to be the same. The number of transfer linac structures, 180° turn-arounds, dumps, main linac structures, quadrupoles, etc., has to be doubled. We see that with these assumptions, the ultimate TBLC-X cost for 1 TeV c.m. is about 6% less expensive than the 1 TeV c.m. NLC.

C. Conclusions on the TBLC-X

The conclusions on the TBLC-X are somewhat different from those for the TBLC Site Filler. At first glance, the Site Filler has a strong psychological appeal, unfortunately tempered by major risks (uncertainties about higher gradients, unproven drive beam generation, compression and manipulation, etc.), and disadvantages (no room for expansion). At 400 GeV c.m. it is less expensive than the NLC but it is not a bargain.

The TBLC-X, on the other hand, by definition uses the same main linac frequency and gradient as the NLC. It thus involves less technical risk for the main linac than the Site Filler but it still requires the development of the drive linac technology (very high average powers for the klystrons and modulators) and the manipulation of a 22 MW beam for each of the two transfer linacs (admittedly broken into three ~ 7MW trains after the three 180° turn-arounds). From a machine-protection point of view alone, this problem cannot be considered lightly. Considerable R&D and experimental tests for several years will be needed to prove that these risks can be brought down to an acceptable level. If the reward for this work were a significant reduction in overall machine cost, one could argue that a rapid "shift" to the two-beam technology, as R. Ruth first proposed, would still be worthwhile. But this does not seem to be the case. Hence, if one looks at the first stage of an expandable 500 GeV c.m. linear collider, there does not seem to be a strong incentive at this time to divert large funds and resources away from the current NLC effort.

3. Longer-term Two-Beam R&D Issues

Having drawn some specific and short-term conclusions on the TBLC Site Filler at 22.4 GHz and the TBLC-X at 11.4 GHz, let us now end this report by reviewing where we stand on our overall R&D linear collider program and where Two-Beam R&D might fit in.

1. The current NLC R&D program, based on klystron technology tested all over the world for almost five decades, has greatly advanced in the last few years. Having said this, the most important and/or most costly components in the NLC main linacs, namely the modulators, the klystrons, the rf pulse compression (DLDS) and the accelerator structures with their quadrupoles, supports and vacuum systems, still need considerable work. However, except for the DLDS pulse compression system which has not yet been built and needs to be tested at 600 MW peak power, all the other components in the current design are in the "D" stage of R&D, i.e., they still need a lot of engineering, but solutions seem to be within reach. A 50-60 MW PPM klystron is in hand, the 75 MW PPM klystron still needs work. A conventional modulator (albeit not very efficient) can be built, a more efficient solid-state modulator is under design. SLED II (as contrasted with DLDS) works in the NLCTA. The first DDS structures (DDS-1 and DDS-2) accelerate a beam in the NLCTA with an excellent narrow energy spread. Gradients up to 65 MV/m have been reached, although too slowly (i.e., requiring too much processing time), but provided that the proper methods of controlling surface quality and cleanliness are

developed, this processing time should be brought under control in the next year or so. Alignment and fabrication tolerances at 11.4 GHz are tight but they seem to be attainable. Another year will also be needed to complete the first, 20% more efficient RDDS (round-contour cup) accelerator structure prototype.

Under all these assumptions, the cost of the 500 GeV c.m. NLC has been reduced in comparison with the ZDR by initially filling only half of each tunnel with rf equipment and letting the e^+ and e^- beams drift through the second halves. The method by which expansion to 1 TeV c.m. and beyond is achieved in the more distant future does not have to be decided now as long as such a method is compatible with the initial 500 GeV c.m. design. The full-length tunnels and complete conventional facilities will be there from the beginning.

2. The simplification brought about by R. Ruth to the two-beam CLIC design approach makes this technology more practical than it was a year ago: it definitely opens a new option to extend the NLC to 1 TeV c.m. and beyond. However, this technology becomes more interesting and has a cost advantage at higher gradient because there is a one-to-one relationship between the length of the main linac and the required beam pulse from the drive linac. Higher gradient probably means higher main linac rf frequency: for example 22.4 GHz or 34.3 GHz. Such higher rf frequency linacs, if properly designed and developed, could be tacked onto the respective ends of the 11.4 GHz 500 GeV c.m. NLC linacs at a later time to increase the energy. What this means, however, is that structures at these higher frequencies and higher gradients must first be tested along with a prototype of a high-current drive beam linac, combiners and transfer structures, to generate the rf power. This effort, which will take several years, is ideally suited for a possible NLC upgrade.

3. We are very fortunate, in our LC international community, to have the strong CLIC group at CERN which will concentrate on this research, and with which SLAC will be able to collaborate. There is no reason to believe that a small contingent of accelerator physicists at SLAC will not and should not find the time to engage actively in such a collaboration, theoretically and perhaps even experimentally, without detracting from the urgent NLC program currently being mounted. After all, the 1-3 TeV frontier is still on the horizon, and such a frontier should be explored.

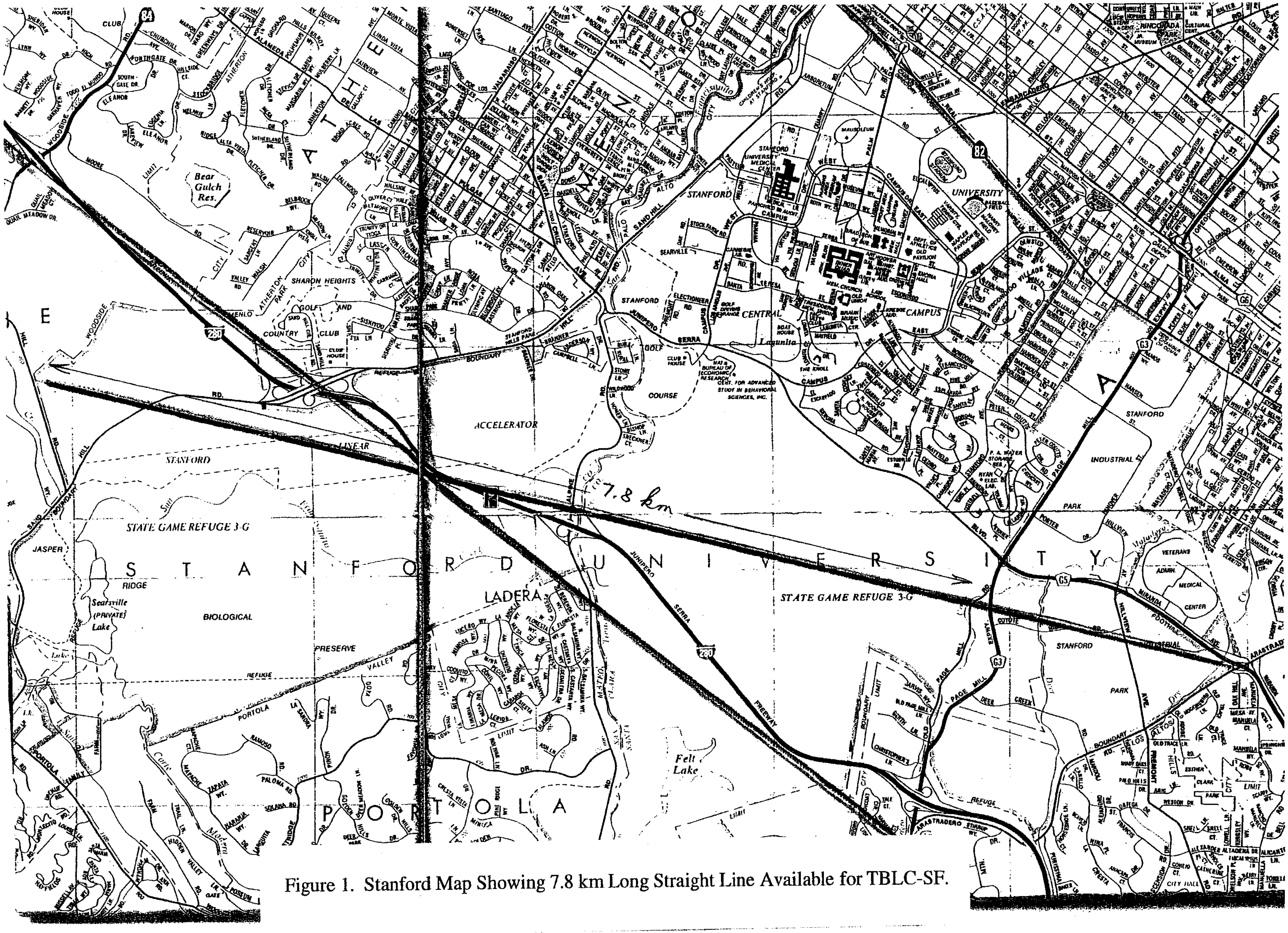
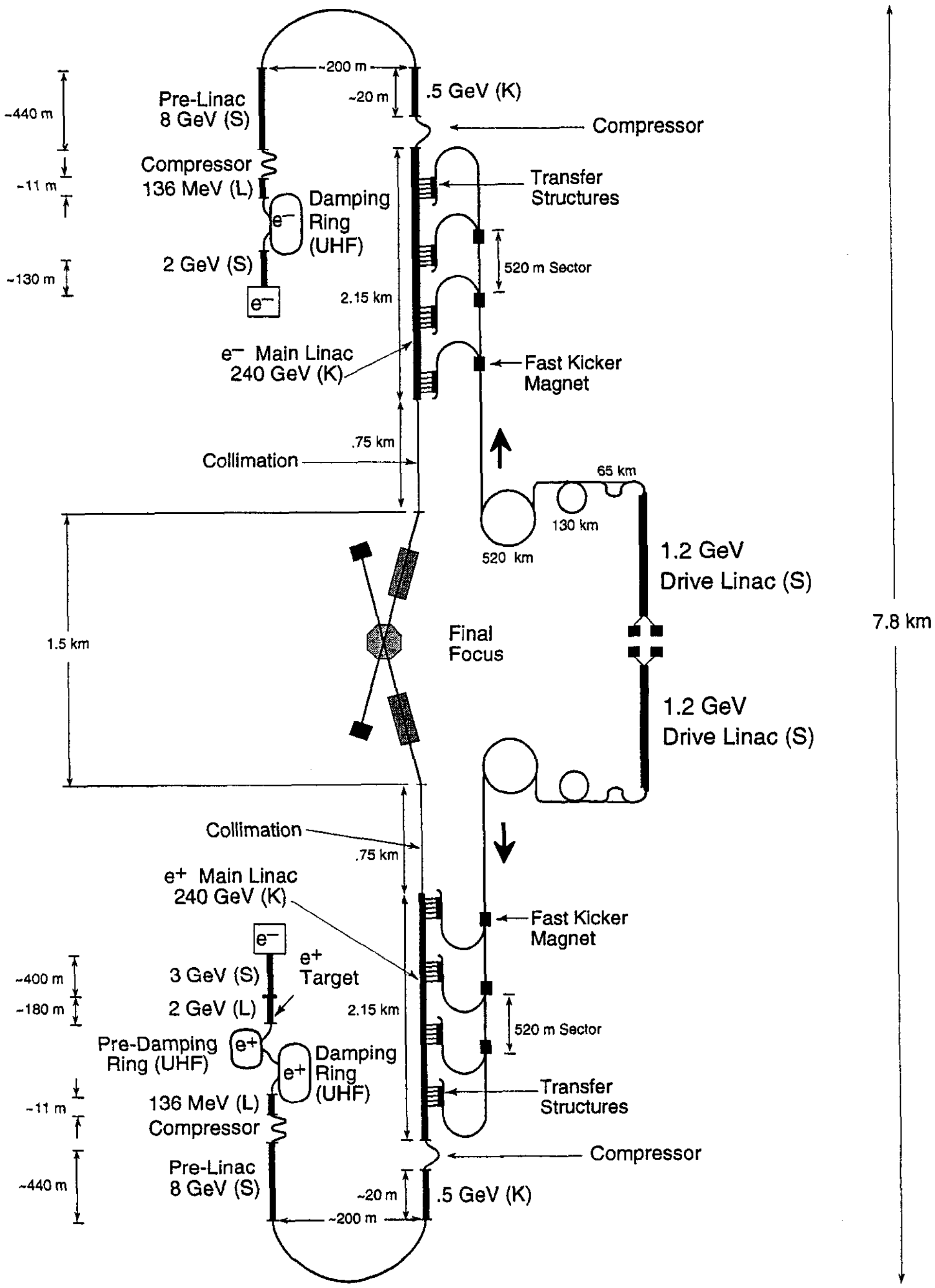


Figure 1. Stanford Map Showing 7.8 km Long Straight Line Available for TBLC-SF.

RF Systems	
(K)	22.848 GHz
(X)	11.424 GHz
(S)	2.856 GHz
(L)	1.428 GHz
(UHF)	0.714 GHz



Not to Scale

Figure 2. Schematic Diagram of a ~400 GeV c.m., K-band Two-beam Linear Collider Site Filler (7.8 km)

G. Loew/7-9-98

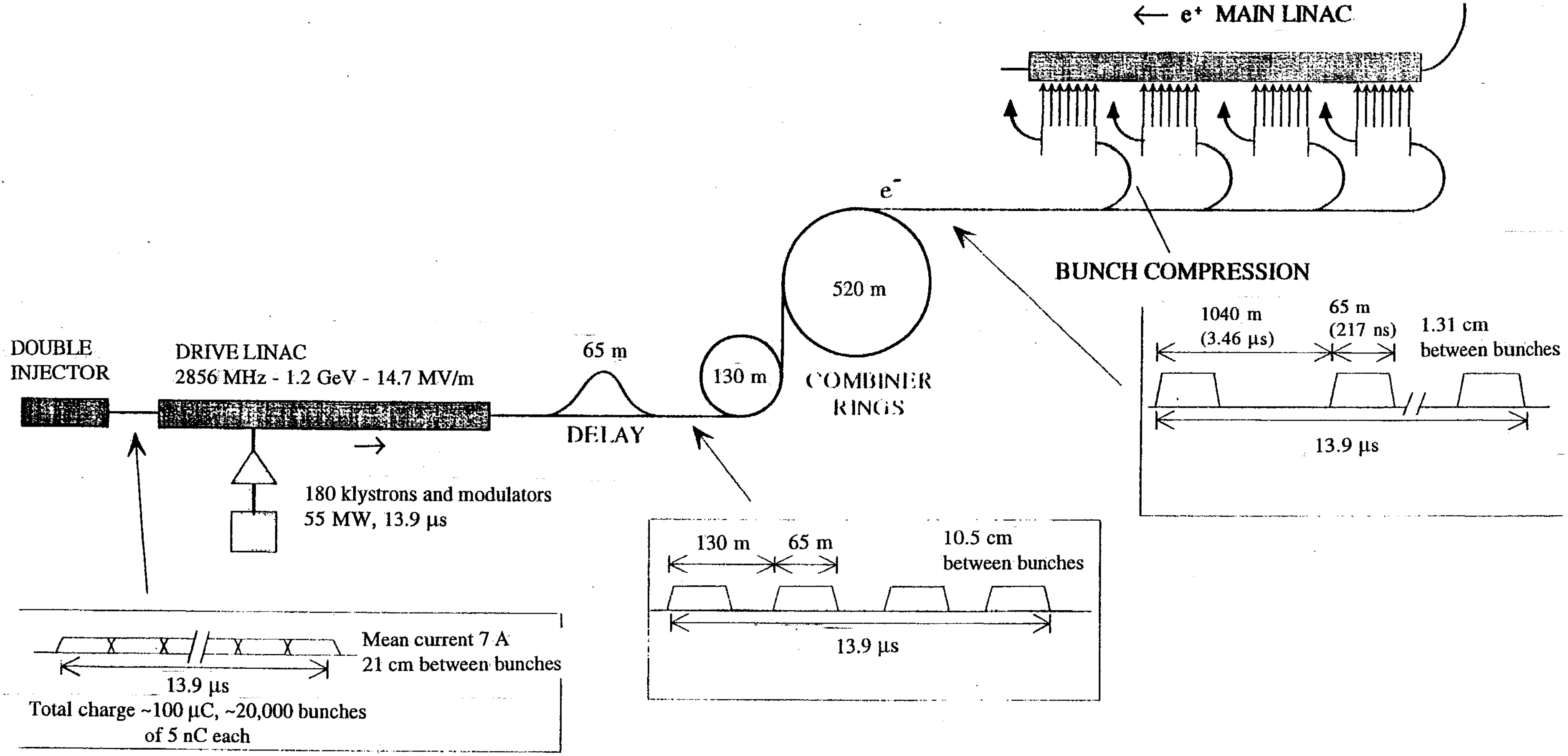
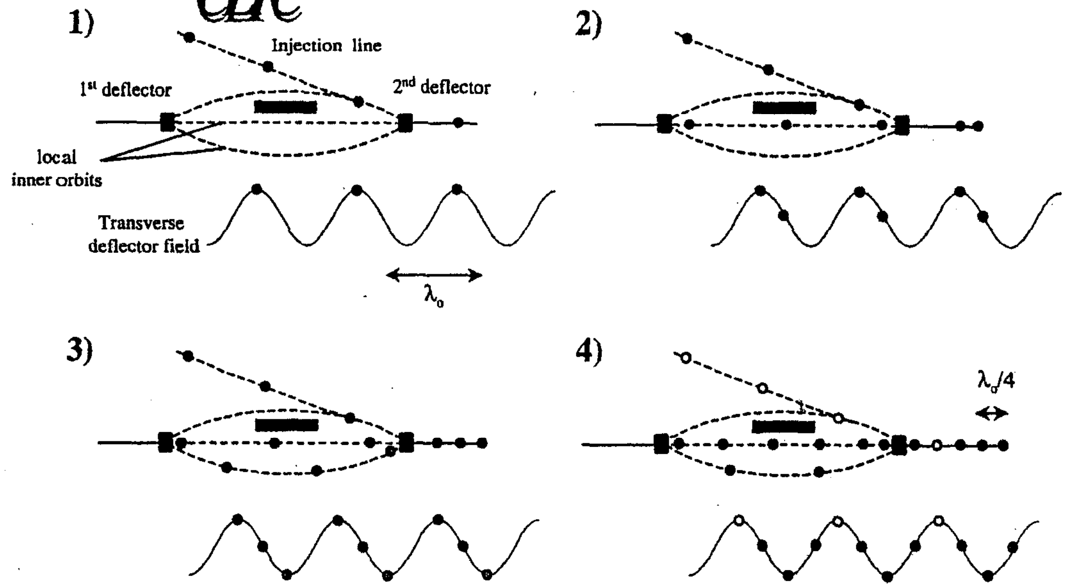


Figure 3. RF Beam Generation and Timing Sequence from Drive Linac to Main Linac for Site Filler.

Injection in Combiner Rings

R.CORSINI - J.P.DELAHAYE / CERN



X4 PULSE COMPRESSION AND FREQUENCY MULTIPLICATION USING A COMBINER RING

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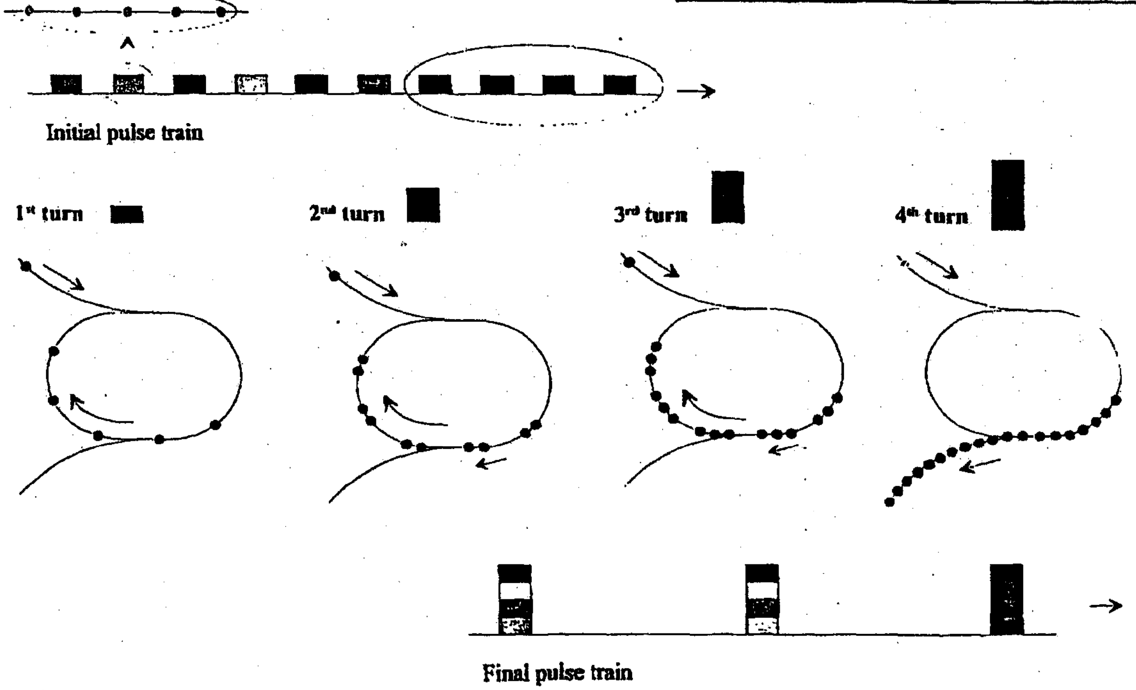
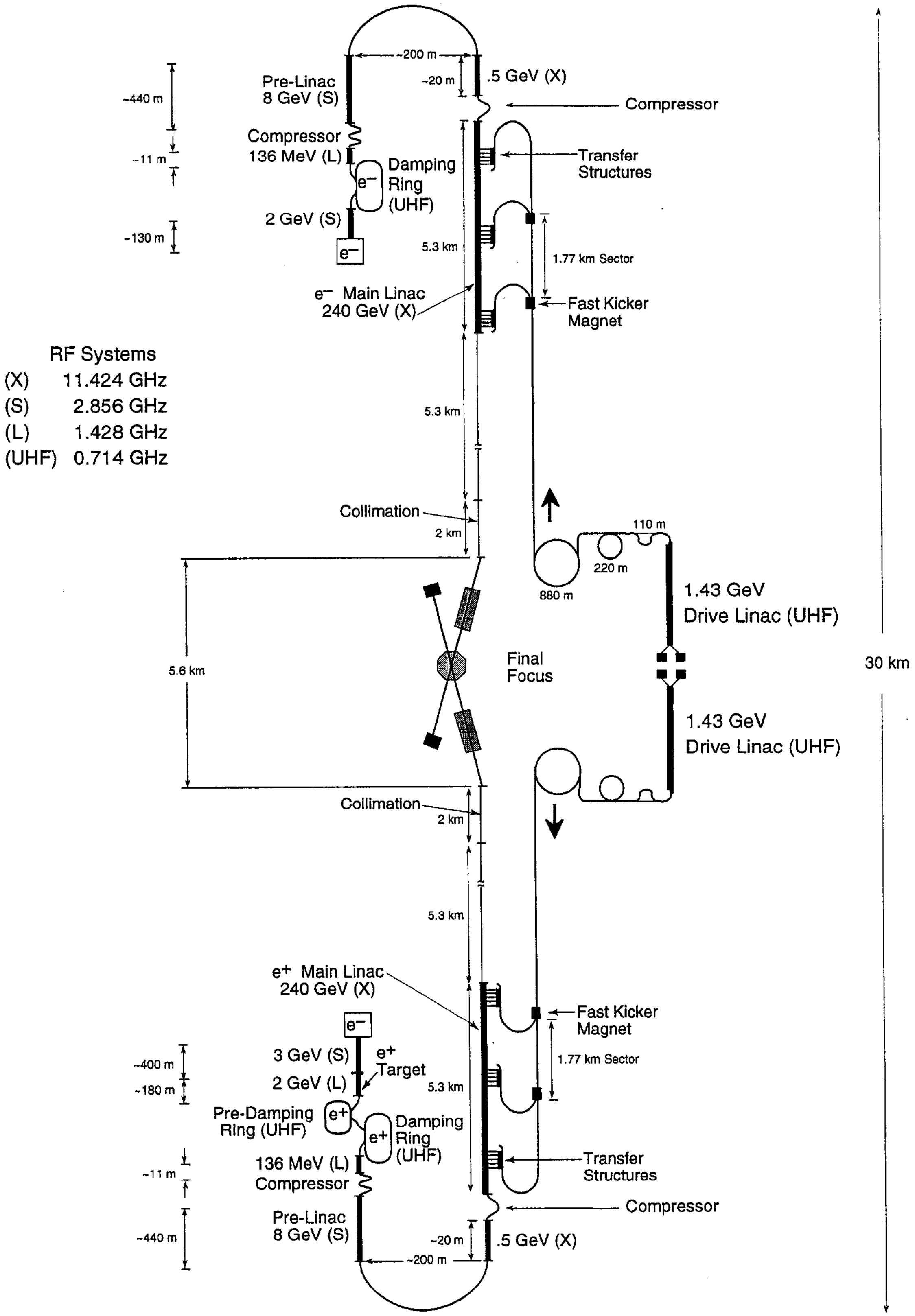


Figure 4. Schematic diagrams showing how one might use rf separators and rings to slip and compress bunch trains to achieve ultimate drive beam time profile (courtesy of CLIC/CERN Group).



Not to Scale

Figure 5. Schematic Diagram of a 500 GeV c.m., X-band Two-beam Linear Collider (30 km) Comparable to the Equivalent NLC.

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Table 1a. IP and Main Linac Parameters for NLC, TBLC-SF and TBLC-X

	NLC	TBLC Site Filler	TBLC X-band
IP			
CM Energy (GeV)	500	400	500
Luminosity w/ IP dilutions (10^{33})	6.25	7.75	
Repetition Rate (Hz)	120	120	120
Bunch Charge (10^{10})	0.95	0.60	0.95
Bunches/RF Pulse	~ 90	116	~ 90
Bunch Separation (ns)	2.8	1.4	2.8
Bunch Train Length (ns)	252	162	252
$\gamma\varepsilon_x/\gamma\varepsilon_y$ (10^{-8}m-rad) into Main Linac	300/3	300/3	300/3
$\gamma\varepsilon_x$ at IP (10^{-8}m-rad)	500	400	500
$\gamma\varepsilon_y$ at IP (10^{-8}m-rad)	10	5	10
β_x/β_y at IP (mm)	12/0.160	8/0.100	12/0.160
σ_x/σ_y at IP (nm)	350/5.7	255/3.2	350/5.7
σ_z at IP (μm)	125	65	125
Υ (Beamstrahlung Parameter)	0.10	0.17	0.10
Pinch Enhancement	1.6	1.6	1.6
Beamstrahlung δ_B (%)	4.0	4.4	4.4
Number of Photons per e^-/e^+	1.17	0.93	1.17
Main Linacs			
Main Linac RF Frequency (GHz)	11.424	22.848	11.424
Power/Beam (MW)	4.1	2.67	4.1
Unloaded Gradient (MV/m)	77	155	77
Effective Gradient (MV/m) †	56.9	117	56.9
Two-linac Active Length (km)	8.55	3.44	8.55
Two-linac Total Length (km)	10.12	4.5	10.6
Total Number of RF Structures (two linacs)	4752	3824	4752
Structure Length (m)	1.8	0.9	1.8
Structure Iris (a/λ)	0.171	0.183	0.171
Structure Attenuation (τ)	0.55	0.61	0.55
Average Shunt Impedance (MΩ/m)	95	126	95
Fill Time (ns)	118	48	118
Q	7800	5600	7800
Linac Tolerances (μm) ‡	16	7	16
Total Main Linac Number of Klystrons	3168	-	-
Klystron Peak Power (MW)	75	-	-
Klystron Pulse Length (μs)	1.5	-	-
RF Pulse Compression Method	4/4DLDS	-	-
RF Pulse Length to Structure (ns)	375	217	375
RF Peak Power to Structure (MW)	200	240	200

† Effective gradient includes rf overhead (8%) and average rf phase of 12 degrees off crest.

‡ Tolerances are calculated for rms structure alignment assuming 60% of allowable emittance growth is due to short-range transverse wakefields.

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Table 1b. Drive Linac and Transfer Linac Parameters for NLC, TBLC-SF and TBLC-X

Two Drive Linacs	**NLC**	**TBLC Site Filler**	**TBLC X-band**
RF Frequency (GHz)		2.856	0.714
Energy per Linac (GeV)		1.2	1.43
Total Two-linacs Active Length (m)		163.8	500
Unloaded Gradient (MV/m)		28.46	11.5
Loaded Gradient (MV/m)		14.81	5.72
RF Pulse Length (μs)		13.9	37
Repetition Rate (Hz)		120	120
Beam Current (A)		7	3.62
Beam Power/Beam (MW)		14	22
Total Number of Structures		180	250
Structure Length (m)		0.91	2
Attenuation		0.08	0.125
Filling Time (μs)		0.121	1.51
Group Velocity (v_g/c)		0.025	0.044
Shunt Impedance (MΩ/m)		50	25
Q		13,500	27,000
RF Power into Structures (MW)		100	45
RF Power per Klystron (MW)		55	50
Total Number of Klystrons		360	250
Two Transfer Structure Linacs			
Active Length (km)		3.059	7.603
Number of Transfer Structures		1912	2376
Structure Length (m)		1.6	3.2
Attenuation		0.134	0.100
Normalized Group Velocity (v_g/c)		0.44	0.44
Structure Filling Time (ns)		12	24.2
Normalized Shunt Impedance r/Q(Ω/m)		57	28.5
Beam Current through Transfer Structure (A)		112	116
Peak Power at Output of Structure (MW)		500	360
Average Energy of Spent Beam (GeV)		~0.18	~0.15
Electric Power Parameters (Injector Systems Not Included)			
Peak Power out of Klystron (MW)	75(X)	55(S)	50(L)
Average Power out of Klystron (kW)	13.5(X)	91.7(S)	222(L)
Klystron Efficiency (%)	60	60	60
Average Power supplied to Klystron (kW)	22.5	152.9	370
Modulator Pulse Length (μsec)	1.5	13.9	37
Modulator Efficiency (%)	75	80	80
Power into Modulator (kW)	60	191.1	463
Number of Modulators	1562	360	250
AC Power for Modulators (MW)	94	69	116

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Table 2. Comparisons of Required Accelerator R&D Issues and Components

	NLC (500 GeV c.m.)	**TBLC Site Filler** (400 GeV c.m.)
1) Injector Systems	Electron injectors Positron source Damping rings Pre-linacs (up to 10 GeV) 138 S-band klystrons (5045-type) with SLED-I 32 L-band klystrons with SLED-I	Same as JLC/NLC 500 GeV c.m.
2) RF Systems	3168 X-band klystrons, 75 MW, 1.5 μs 1584 Modulators, 1.5 μs DLDS pulse compression (up to 600 MW) 4752 X-band DDS structures (up to ~100 MV/m, 375 ns)	366 S-band klystrons, 55 MW, 13.9 μs 366 Modulators, 13.9 μs 186 S-band DDS 0.9 m structures and deflectors 1912 K-band transfer structures (up to 500 MW, 217 ns) 3824 K-band DDS structures (up to ~160 MV/m, 217 ns)
3) Mechanical Systems for Main Linacs	Alignment tolerances down to 16 μm Support and movers Structure vacuum (1 cm diameter conductance)	Alignment tolerances down to 7 μm Support and movers Structure vacuum (.5 cm diameter conductance)
4) Beam Manipulation	Bunch compressors	a) Combiner rings, rf separators and bunch compressors b) Feasibility of 1.2 GeV, 112 A, bunched beam transport and manipulation
5) Collimation	2 km/side [ready for 1.5 TeV]	0.75 km/side
6) FF	2.8 km/side [ready for 1.5 TeV]	0.75 km/side

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Table 3. NLC, TBLC Site Filler and TBLC-X Cost Estimates in Percentages of NLC 500 GeV c.m.

	All Energies are Expressed in Center-of-Mass				
	500 GeV NLC %	400 GeV TBLC Site Filler % of 500 GeV NLC Total	500 GeV TBLC X-band % of 500 GeV NLC Total	1 TeV NLC % of 500 GeV NLC Total	1 TeV TBLC X-band % of 500 GeV NLC Total
Electron Injectors	2.6	2.6	2.6	2.6	2.6
Positron Injector	1.7	1.7	1.7	1.7	1.7
Damping Rings	4.9	4.9	4.9	4.9	4.9
Pre-linacs/Bunch Compressors	4.5	4.5	4.5	4.5	4.5
	13.7	13.7	13.7	13.7	13.7
Main Linacs	32.3	10.9	25.2	61.6	43.6
Drive Linacs and Combiners		7.1	9.3		11.7
Collimation and Big Bends	2.2	1.8	2.3	2.3	2.3
Final Focus, IR and Dumps	4.1	3.4	4.2	4.2	4.2
	38.6	23.2	41.0	68.1	61.8
Conventional Facilities	40.7*	20.4	37.4*	40.9	39.2
Computer Systems	3.1	2.2	3.1	3.1	3.1
Special Safety Systems (other than MPS, PPS)	0.7	0.2	0.7	0.7	0.7
Project Management/Support	3.0	1.8	3.1	4.0	3.8
	47.5	24.6	44.3	48.6	46.8
Total Base Cost	**100**	**61.6**	**98.8**	**130.4**	**122.3**

*It is assumed that Conventional Facilities are installed for 1 TeV c.m. energy from the beginning.

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Table 4. Comparisons of Required Accelerator R&D Issues and Components

	NLC 500 GeV c.m., 11.4 GHz, 57 MV/m	**TBLC-X** 500 GeV c.m., 11.4 GHz, 57 MV/m
1) Injector Systems	Electron injectors Positron source Damping rings Pre-linacs (up to 10 GeV) 138 S-band klystrons (5045-type) with SLED-I 32 L-band klystrons with SLED-I	Same as JLC/NLC 500 GeV c.m.
2) RF Systems	3168 X-band klystrons, 75 MW, 1.5 μs 1584 Modulators, 1.5 μs DLDS pulse compression (up to 600 MW)	256 714 MHz klystrons, 50 MW, 37 μs 256 Modulators, 37 μs 256 714 MHz 2 m structures and deflectors 2376 X-band transfer structures (up to 360 MW, 375 ns)
	4752 X-band DDS structures (up to ~100 MV/m, 375 ns)	4752 X-band DDS structures (up to ~100 MV/m, 375 ns)
3) Mechanical Systems for Main Linacs	Alignment tolerances down to 16 μm Supports and movers Structure vacuum (1 cm diameter conductance)	Same as JLC/NLC
4) Beam Manipulation	Bunch compressors	a) Combiner rings, rf separators and bunch compressors b) Feasibility of 1.43 GeV, 116 A, bunched beam transport and manipulation
5) Collimation	2 km/side [ready for 1.5 TeV]	Same as NLC
6) FF	2.8 km/side [ready for 1.5 TeV]	Same as NLC

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