R&D Progress Toward Future Linear Colliders

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During the last twenty years, there has been a world wide effort to develop the physics and technology of linear colliders. Present goals at SLAC, KEK, and DESY are to bring the R&D efforts to the point where proposals for 500/1000 GeV cms electron-positron colliders can be officially submitted in the years 2002/2003. The CLIC study at CERN aims at a second generation very high energy electron-positron collider, to be considered after completion of the LHC. The main areas of hardware R&D include efficient accelerating waveguides without harmful higher order mode (h.o.m.) effects, high peak power klystrons, klystron modulators, and rf-power compression. Test facilities have been put in place for the testing of h.o.m. behavior of new waveguide designs (ASSET), focusing of low emittance beams to spot sizes in the nanometer range (FFTB), and damping particle oscillations in a special damping ring (ATF) to prepare low emittance bunch trains of electrons for injection into linear colliders. The TESLA collaboration is making a major effort to develop the required technology for a superconducting linear collider. Test accelerator sections, which employ all the necessary new accelerator components, have been built and are currently being tested at SLAC and DESY.

1 Introduction

Figure 1 is meant to give the reader an impression of the time evolution of R&D efforts worldwide on linear colliders. Equipment and infrastructure costs and manpower costs on a relative scale are shown for the most important linear electron-positron collider projects. The evolution in time is highly simplified, but the time integrated values are more or less correct and allow comparisons between different projects. For the Russian VLEP project, it was assumed that the ruble had about the same purchasing power in Russia as the dollar in the U.S.

Figure 1 shows that R&D on linear colliders started some 25 years ago. At present, the most intensely pursued projects are NLC at SLAC, JLC at KEK, and TESLA at DESY. The proponents of these projects in the three laboratories believe that in the years to come, enough R&D work will have been completed to justify official submission of proposals in the years 2002/2003. CLIC at CERN is a collider project based on a radically new technology. The CLIC proponents believe

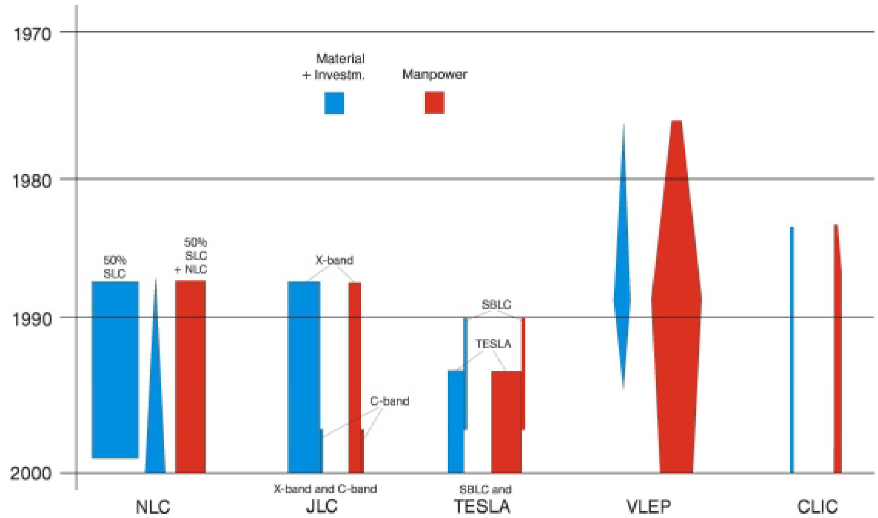

Figure 1: R&D efforts on the most important collider projects. The widths of the bars correspond to annual lay-outs for equipment and infrastructure and separately for man power. The time dependence is highly simplified but the time integrated values allow comparisons between different projects.

that with this new technology, higher collider energies will be more affordable. CLIC requires considerably more R&D than the aforementioned projects and is, even by its proponents, only considered an option in the CERN program after the completion of LHC. The VLEP project pursued by the Protvino-Novosibirsk group has been under study since 1973. Many important contributions to the physics and technology of linear colliders have been made by the VLEP group. The present difficult economic situation in Russia makes construction of VLEP in the next few years unlikely. The R&D work on JLC and NLC was, to a large extent, done jointly by SLAC and KEK and could be used in either project. The NLC work was summarized in 1996 in a 1082 page “Zeroth Order Design Report" [1]. The JLC efforts resulted in a 617 page “JLC Design Study" in 1997 [2]. In 1996, KEK started R&D on a C-band collider, a linac running at a frequency half as high as that planned for NLC and JLC. This work is now being pursued in parallel to the original JLC work. DESY started R&D work on an S-band linear collider in 1990. In 1992, R&D work started in parallel on the TESLA project, a superconducting linear collider at L-band frequency, half the S-band frequency. In 1997, a 1181 page “Conceptual design" report was written for a “500 GeV Collider with an Integrated Free Electron Laser Facility", which could use either technology, S-band or superconducting L-band [3]. A year later, all R&D efforts toward an S-band collider were terminated to concentrate all manpower on the superconducting

TESLA project. SLAC should be considered a special case: by building and running the SLC, the SLAC people were the first to confront many of the real world problems of linear colliders. The SLC has been a great stimulant for keeping a lively international discussion going. The SLAC machine is also a beautiful testing ground for work on some of the most relevant potential problems of linear colliders. In Fig. 1, it was—quite deliberately—assumed that about 50% of the SLC costs for equipment and infrastructure and half of the manpower could be considered R&D for linear colliders. If you add up all the money spent so far world wide and include all the salaries of those who worked on linear collider R&D, you might end up with a sum as large as $500 M. This is not unreasonable if you keep in mind that this amount is only about 10% of what a linear collider at 1 TeV cms might cost. One should also be mindful of the fact that in contrast to previous large accelerator projects, almost none of the colliders under study can refer to a similar well tested smaller machine which could serve as the basis for a safe extrapolation. So, special care and thoroughness must be applied to this R&D work!

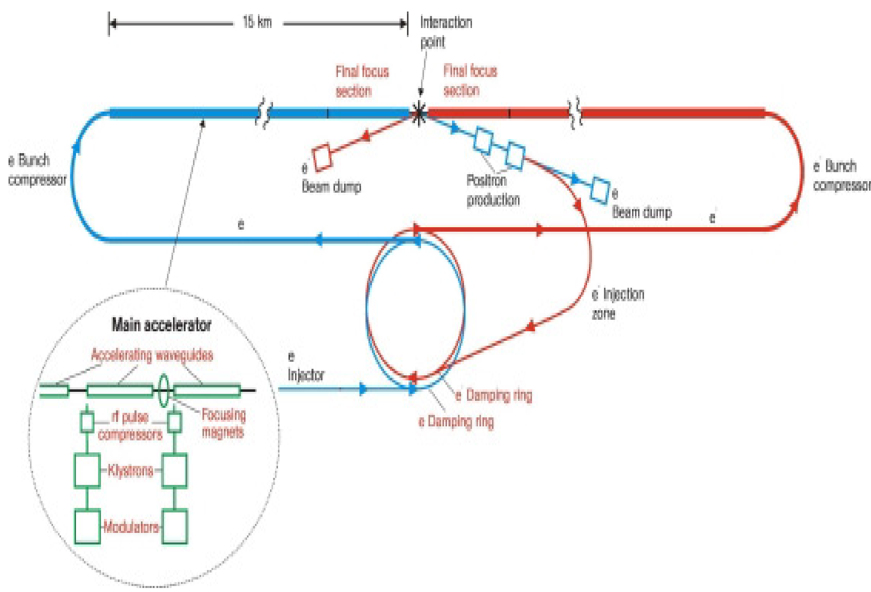

Figure 2: Generic linear collider showing the main areas of R&D work.

Figure 2 shows a generic linear collider in order to identify some of the main areas of R&D work:

1. There are two linacs, each some 15 km long and consisting of many thousand accelerating waveguides. These structures are critical in two respects:

first, they must be power efficient and second, they must suppress build-up of unwanted rf deflecting fields which could lead to single bunch and multibunch instabilities with resulting increase of beam size and loss of luminosity.

2. There are many thousands of pulsed klystrons to provide the rf power for the accelerating fields in these structures. Power efficiency and reliability are two of the most important aspects.

3. Several designs of modulators are needed for powering these klystrons.

4. Pulse compressors to reach higher peak rf power are two more components of the rf power system.

Because most of the money for a linear collider goes into items 1 to 4, low fabrication costs for these components are most important.

5. In order to get the unusually low emittance in the colliding beams (so important for high luminosity), special damping rings are required to prepare the bunch trains for injection.

6. Large pulse currents of electrons and positrons are required. In particular, the accumulation of high positron currents with very low emittance is one of the many challenges in building a linear collider.

7. Focusing the high energy beams to unprecedentedly small cross sections at the interaction point is another challenge.

8. No large accelerator can be built without at least some standard unit sections, in which all the necessary accelerator components can be tested together.

It is quite impossible in such a brief paper to do justice to all the efforts so many people have made to the R&D of linear colliders over the last decade. I will therefore concentrate on some of the more important hardware for linear colliders. By doing this, I have to ignore the large efforts in theoretical work, *e.g.* analyzing the limits of linear colliders as given by beam-strahlung at the interaction point, trying to understand experimental background conditions and cleaning up the background producing halos of the beams, studying possible beam instabilities during acceleration, determining stability requirements for linear collider components and many other items. There is now a mind boggling amount of literature on all of this. In the effort to reach luminosities in the $10^{33} - 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ range which are required at these high center of mass energies, linear colliders have to move on all fronts into new uncharted regions.

2 Accelerating waveguides

When the 2 mile SLAC linac was to be built 35 years ago, an effect called pulse shortening had plagued all earlier linacs. Later, it was discovered that pulse shortening was due to a build-up of strong deflecting fields in each single accelerating waveguide. The invention of constant gradient guides (in which the structure constants are varied over the length of each waveguide such that even with decreasing rf power flow along the guide, the accelerating gradient is kept constant) unexpectedly also seemed to cure pulse shortening. The variation of structure constants along the guide produced variation of the deflecting mode frequencies, such that their effect in a single guide could no longer add up.

SLAC was the first longer accelerator where these new types of accelerating waveguides were used. There was quite some consternation when, after building the two mile linac, another destructive albeit weaker instability limited the product of pulse length and current. In this cumulative instability, as it was dubbed, residual beam induced deflecting fields in each waveguide would shake the beam to amplitudes which increased with pulse length and distance along the linac. At that time, this effect was quickly understood, analyzed, and minimized by additional beam focusing and artificially introduced variations between waveguides down the line.

This effect is still one of the dominant concerns in linear colliders: the smaller transverse emittances and larger pulse currents required to produce the high luminosity result in a much higher sensitivity to this kind of multibunch effect, particularly in the case of the higher frequency structures. At SLAC, 1.8 meter long waveguides were developed for the NLC with coupling slots in each of the single cups which make up the guide to absorb any deflecting field. By furthermore varying the structure constants along each waveguide in a Gaussian way, beam deflection forces produced by off-axis beams should be minimal.

The higher-mode-free structures developed for the C-band collider under study at KEK are even more extreme in trying to avoid any deflecting fields. Only the accelerating mode is contained in this structure. Fields of all other modes leak out and are absorbed.

In the SBLC-study at DESY, cumulative beam instabilities are avoided by strong damping of deflecting modes through lossy material in those parts of the structure where it has little effect on the accelerating fields, plus variation of the structure constants along each guide and from guide to guide.

The superconducting TESLA cavities are built with such large irises, that only the lowest frequency fundamental accelerating mode was thought to be trapped and higher frequency deflecting and accelerating modes were expected to leak out at the ends, where ferrite absorbers are placed.

The fundamental problem is that the number of higher modes which can be excited in such wave guides is infinite and even sophisticated computer programs are unable to take all conceivable beam-field interactions into account. Moreover, in long accelerating structures there is the phenomenon of trapped modes, *i.e.*, modes with frequencies so high that one would expect their energy to leak out through the ends. But, miraculously this does not happen. Absorbers at the ends of the waveguides have no damping effect and you might not even know of the build-up of such destructive fields if the beam did not tell you.

The ASSET-facility at SLAC allows you to observe such effects: A single bunch of the SLAC beam can be steered off-center through the wave guide which is to be investigated, and the deflecting effect on a second bunch which follows at a variable distance can be observed. SLAC and KEK structures have been investigated in this way and found to be deflection free, within the accuracy of the measurement.

3 Klystron development

Except for CLIC, where a secondary “drive beam" excites the rf-accelerating fields, klystrons are the principal rf-generators of choice. Economy calls for tubes with high peak power and high efficiency, something which gets increasingly more difficult at higher frequencies.

There are now 75 MW peak power x-band tubes developed at SLAC, with pulse lengths of 1.5 μs and efficiencies of 48%. Considering the 25 kW average power consumption of such a klystron, it is important that this number is not dwarfed by the power required for the focusing coils of the tube. ppm-focusing stands for “periodic-permanent-magnet-focusing", a technology by which the focusing fields are produced with permanent magnets. The first SLAC ppm-focused klystron has reached 50 MW at a pulse length of 1.5 μs.

Toshiba is developing the klystrons for the JLC. For the C-band version, klystrons with 54 MW peak power and pulse length of 2.5 μs have been built and tested over many thousands of hours, while the X-band tubes with solenoid focusing have so far reached 50 MW.

Two 150 MW S-band klystrons for the SBLC have been built in a collaborative effort between SLAC and DESY for pulse lengths of 2.5 μsec. 208 MW have been reached at a pulse lengths of 1 μs.

An interesting development has been carried out by the Protvino-Novosibirsk group. Grid controlled klystrons with ppm-focusing, running at dc voltages of 1 MeV have reached 60 MW at the frequency of 14 GHz. This development is most interesting because such klystrons would not require klystron modulators, the most costly components of a linear collider. Unfortunately, the development of this promising tube has never reached the stage where it could be reliably duplicated and produced in larger numbers.

The TESLA collider is different from other colliders in the long fill times of the superconducting structures. In TESLA, tubes with modest peak power can build up the required high accelerating fields. But, the pulse length of the klystron pulse is then 1.5 ms, more than one thousand times longer than for the high frequency copper structures. 10 MW peak power is sufficient for the TESLA tube, but the average power will be large. For this, a multi-beam klystron is being developed by Thompson.

4 Modulators

The energy for each single klystron pulse is first accumulated in a modulator, consisting of a dc power supply to charge up storage capacitors, a pulse forming network, thyratron switches, and pulse transformers to produce the high voltage pulses required for the klystrons.

A few thousand modulators are needed in a 30 km long linear collider, presenting the most costly component of such a machine. The basic technology is more than half a century old and has not changed significantly during that time. Some improved technologies can be used today in order to reduce prices and bulk dimensions while at the same time increasing efficiencies: Thyristor controlled power supplies can charge up the capacitor storage bank with constant charging current or constant energy flow, and it also seems to be feasible to produce the klystron voltage (typically of the order of 500 kV) directly without the need of a pulse transformer, by putting a large number of smaller transistor controlled power supplies in series. Such experiments are going on at SLAC. TESLA needs to store much more energy in its modulators. A development is underway to use the large stored energy in a superconducting coil and switch that through thyristors (Superconducting Magnet Energy Storage, SMES).

5 Pulse compression

Rf-filling times in normal conducting linear accelerators typically decrease with higher frequency. This allows the beam pulse lengths to be shorter. Compressing a longer klystron pulse in time and thereby gaining peak power is therefore advantageous. SLAC has been pioneering this technique of rf pulse compression and has been using it now for decades. Rf pulse compression is even more important at the high x-band frequency. But while it is relatively simple to accelerate 1 or 2 single bunches in the rf compressed pulse of the SLC, it requires some effort to keep the rf voltage very constant for a longer bunch train. The well known SLED system will now be replaced in the NLC by a system of circulators and long delay lines. To increase efficiency, higher circular rf modes will be used in these delay lines. At KEK, an ingenious way of shortening these long lines and decreasing power losses has been invented (the DLDS-scheme), which involves the combination of several klystrons powering through circulators a larger number of staggered rf accelerating guides. This may well turn out to be the method of choice in NLC or JLC.

6 Damping rings

Linear colliders use bunch trains of up to 10^{13} particles with invariant emittances as small as $10^{-6}/10^{-8}$ m. This has to be compared with the 3 orders of magnitude smaller pulse charge and the up to 3 orders of magnitude larger invariant emittance in the SLC. Because this is such a critical issue, KEK built the ATF damping ring six years ago, in which accelerator experts from all interested laboratories (KEK, SLAC, DESY, CERN, and VLEPP) can study damping ring technology and conceivable problems in preparing high density currents for injection into a linac. This $60 M test facility now produces bunches with emittances close to the requirements of a linear collider. However, so far most of the work was limited to single bunches and much smaller pulse charges.

7 The FFTB

Linear colliders are supposed to get their high luminosity from large bunch currents and extremely small spot sizes at the interaction point. The extremely small spot is the result of the exceedingly small emittance of the beams and the demagnification of beam size through clever optics by factors of up to 300. It was mostly the wish to test the feasibility of such clever optical systems and at the same time test new methods for beam size measurements, that the “final focus test beam" FFTB was installed at SLAC with the participation of many outside laboratories. Vertical beam sizes of single bunch beams of 60 to 70 nm were observed, within a factor of 2 of expectations. The discrepancy is likely to be due to jitter in beam position during the time it takes to make a spot size measurement. A truly ingenious new method of beam size measurement has been successfully tested: At the beam focus point, an interference pattern is set up with light from a powerful laser. The spacing of the light fringes is comparable to the vertical beam size to be measured. The modulation of the high energy photon beam signal produced by Compton scattering, as the beam is moved over this optical interference pattern, allows the measurement of beam size.

8 The test linacs

It is important to at least build a standard unit of the linac so that all the new technologies can be tested.

At SLAC a “Next Linear Collider Test Accelerator" (NLCTA) was set up with five 1.8 m long accelerating guides powered by three 50 MW ppm focused klystrons. A SLED-II delay line type pulse compressor is used to quadruple the instantaneous rf power to values close to 200 MW. This produced loaded acceleration gradients of 40 MeV/m.

For the last three years, this linac has been the testing ground for many new technologies, *e.g.*, compensation of energy transients with large pulse currents. At DESY, a prototype section of the SBLC was built with three 6 m long S-band accelerating guides, powered by two 150 MW klystrons. The aim of this test set-up was to try out new manufacturing technologies for long and very straight waveguides with h.o.m. damping, supported by ultra stable support structures with micro-movers, focusing quadrupoles with active vibration feedback control and many other improvements to a—by now classical—technology. A special injection system into this linac allowed bunch trains with variable bunch spacing which could be transversely deflected in different bunch-bunch modes. In this way, beam interaction with residual deflecting waveguide modes could be experimentally investigated.

At this point, I want to address the often voiced criticism, that, at lower frequencies like the 3 GHz S-band, high gradients cannot be reached because of field emission and subsequent trapping of “dark currents". Very important tests done at KEK show, that properly manufactured S-band waveguides have much smaller dark currents and even at gradients up to 80 MeV/m, far above any rational design number (where investment and operations costs are minimized) dark currents, which could be trapped, are quite negligible.

In Protvino, installation of a test linac section was also started, but regrettably could not be completed as planned because of lack of funds.

The short term goal of the superconducting TESLA-project at DESY is the development of a test accelerator consisting of three module tanks, each with eight one meter long 9-cell cavities. The total active accelerator length is therefore 24 meters. With the design gradient of 25 MeV/m in the TESLA collider, the energy of this first test accelerator, which ultimately should be reached, will be $24 \times 25 = 600$ MeV.

The challenge in building a superconducting linac of course is how to get the high gradients and how to keep the costs down. A major development program has been started with many outside institutes having joined the TESLA collaboration. At the DESY site, a big effort is being made to understand gradient limitations and to improve and develop superconducting rf technology. Chemical treatment labs, clean rooms and test stations for rf conditioning have been put in place. An intense collaboration with industry is also taking place. Success in this effort slowly becomes evident by the fact that almost 50% of all newly built cavities exceed, in the test station, the design gradient of 25 MeV/m.

Two of the three modulator tanks for the first test accelerator are in place and have accelerated electrons to energies of 120 and 160 MeV.

Parallel to this effort a free electron laser installation is being prepared to make use of the 600 MeV beam of the completed pilot test section of TESLA. In a second step, this superconducting linac is to be extended to 7 module tanks corresponding to an active accelerator length of 56 m and an energy of 1.4 GeV. With this energy, a free electron laser might reach photon energies of 0.4 keV.

Finally, I want to report on the R&D activities at CERN, *i.e.*, the CLIC project. The CLIC collider is very different from all the other projects mentioned so far. During the last year, the conceptual design of CLIC has been dramatically changed and improved. I cannot go through the new design, which is based on a long pulse length, very high power electron linac in combination with a series of beam pulse compressor rings, and bunch compressors. This will produce short trains of very high power, high current electron pulses to drive individual sections of the main linac of the collider. The ideas behind this breathtakingly new approach, particularly the novel electron beam pulse compression, will require much more R&D preparation than any of the other approaches described. But the effort CERN can muster at this moment is so limited that only some very basic aspects may be tested: Production of high rf power (50 MW) at the high CLIC frequency of 30 GHz with an S-band drive beam has been demonstrated by actual beam acceleration in a 30 GHz waveguide section (30 MeV/m).

A number of component models for a 30 GHz collider have also been developed and tested, such as structures for rf generation from a relativistic drive beam, accelerating guides and couplers, rf quadrupoles to implement the so-called BNC damping for single bunch stabilization, rf position monitors and many more. But work on the required novel generation of high power electron pulses requires a much larger effort which probably can be pursued only after LHC is finished and CLIC can get more support.

Looking at the R&D effort made during the last ten years, one cannot help but be truly impressed. However, this huge effort is in no way disproportionate to the newness and complexity of the task at hand. All the important questions have been or are being addressed and may find or have already found good technical and economical answers.

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