CHALLENGES IN FUTURE LINEAR COLLIDERS

Swapan Chattopadhyay† and Kaoru Yokoya††

Abstract

For decades, electron-positron colliders have been complementing proton-proton colliders. But the circular LEP, the largest e^-e^+ collider, represented an energy limit beyond which energy losses to synchrotron radiation necessitate moving to e^-e^+ linear colliders (LCs), thereby raising new challenges for accelerator builders. Japanese-American, German, and European collaborations have presented options for the "Future Linear Collider" (FLC). Key accelerator issues for any FLC option are the achievement of high enough energy and luminosity. Damping rings, taking advantage of the phenomenon of synchrotron radiation, have been developed as the means for decreasing beam size, which is crucial for ensuring a sufficiently high rate of particle-particle collisions. Related challenges are alignment and stability in an environment where even minute ground motion can disrupt performance, and the ability to monitor beam size. The technical challenges exist within a wider context of socio-economic and political challenges, likely necessitating continued development of international collaboration among parties involved in accelerator-based physics.

1. WHY LINEAR COLLIDERS?

For decades, electron-positron (e^-e^+) colliders and proton-proton (p-p) colliders have been complementing each other. In the latter, however, the energies of the constituents—that is, the quarks—are lower, and moreover the p-p interaction, involving as it does the strong force, is quite complicated. This makes data analysis hard. On the other hand electron-positron colliders yield collisions without much background and therefore also yield "cleaner" data. Proton-proton colliders can be thought of as grand instruments for particle discovery. Electron-positron colliders, meanwhile, are grand instruments for finer study of the physics of elementary particles.

Some lines from Lao-tzu illustrate this complementarity in terms of the contrast between what is gainful and what is useful. Using p-p collisions, the Large Hadron Collider (LHC) will likely provide something *gainful*: the distinct achievement of discovering the Higgs boson. A complementary and comparable new e^-e^+ linear collider (LC), however, will be *useful* in advancing general understanding of the mainly empty subnuclear realm in which such particles exist. Lao-tzu wrote:

Shape clay into a vessel;
It is the space within that makes it useful.
Cut out doors and windows for a room;
It is the holes which make it useful.
Therefore profit comes from what is there;
Usefulness from what is not there.

In "Livingston chart" for e^-e^+ colliders worldwide, Figure 1 traces the four-decade rise in center-of-mass energy from the sub-GeV to the 100 GeV scale.

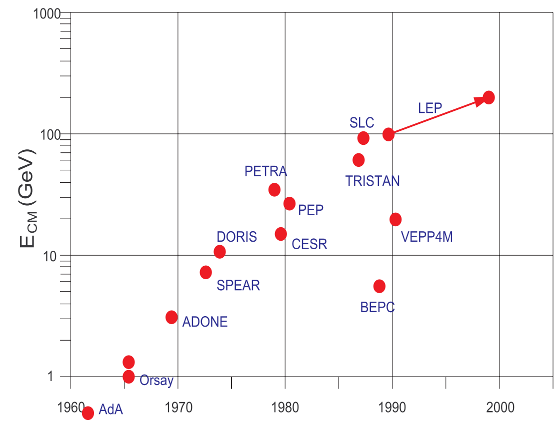


Figure 1: Four-decade rise in E_{cm} in electron-positron colliders worldwide.

However, there is a limit to this rise, and that limit has been reached in LEP, the circular Large Electron-Positron collider (See Figure 2) that operated at CERN (and whose tunnel will hold the LHC). In reaching 200 GeV energy, in the center of mass, LEP lost substantial energy to synchrotron radiation. Such energy loss in one turn is proportional to the fourth power of beam energy over the radius. This constraint makes it impossible to go to higher energies in an e^-e^+ ring.

That's why accelerator builders have for some time discussed the challenges of building e^-e^+ colliders that abandon the circular shape for a straight one: the linear collider (LC).

Figure 2: LEP reached the limit for ring-shaped e^-e^+ colliders.

† Jefferson Lab, Newport News, VA 23606, USA
†† KEK, Tsukuba, Ibaraki 305-0801 Japan

2. WHAT IS A LINEAR COLLIDER?

In basic form, a linear collider consists of two linear accelerators pointed at each other in 180-degree opposition. The beam from each linac is not recirculated; instead, it is dumped after the collision point, following its sole acceleration pass. Thus the basic, continuous process in each linac is: beam generation, then beam acceleration, then collision, then beam disposal; and repetition of the same as frequently as possible. This process was used in the first linear collider, the Stanford Linear Collider (SLC). However, as shown in Figure 3, the SLC, at a relatively low energy, used only one linac instead of a pair of opposing linacs for the sake of economy. The linac accelerated both electrons and positrons via a process involving the generation of positrons by electron bombardment of a target, and damping rings for both electrons and positrons at the lower-energy end of the linac. At the high-energy end, single-pass beams of concurrently accelerated electrons and positrons were extracted and sent through 180-degree arcs to the collision point. The SLC could attain 50 + 50 = 100 GeV center-of-mass energy. Figure 4 shows an aerial view of the SLC.

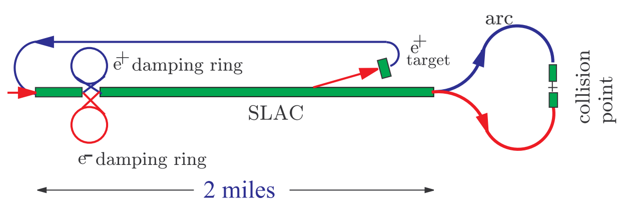


Figure 3: The SLC's single-linac configuration.

Figure 4: The Stanford Linear Collider (SLC).

Three major concepts are now competing worldwide as the prospective "Future Linear Collider" (FLC). They are:

- JLC/NLC (Japan/USA), based on normal-conducting accelerating cavities, and aiming to reach 1 to 1.5 TeV. (See Figures 5 and 6.)
- TESLA (Germany), based on superconducting cavities, and aiming at up to 0.8 TeV. (See Figures 7 and 8.)
- CLIC (Europe), aiming to reach above 3 TeV, with use of a long drive beam.

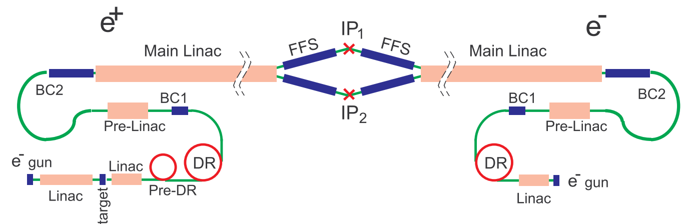


Figure 5: Planned layout of JLC/NLC.

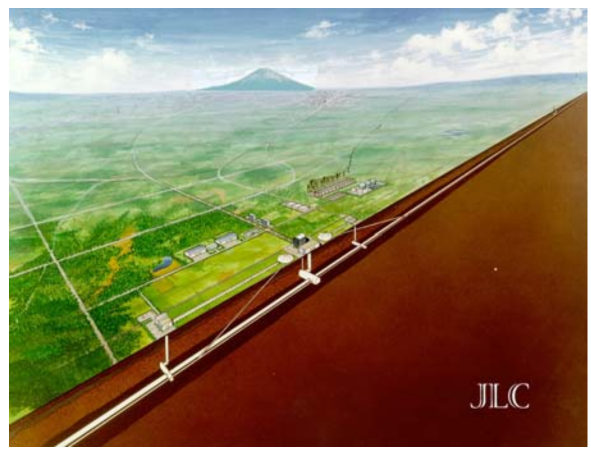


Figure 6: JLC artist's impression.

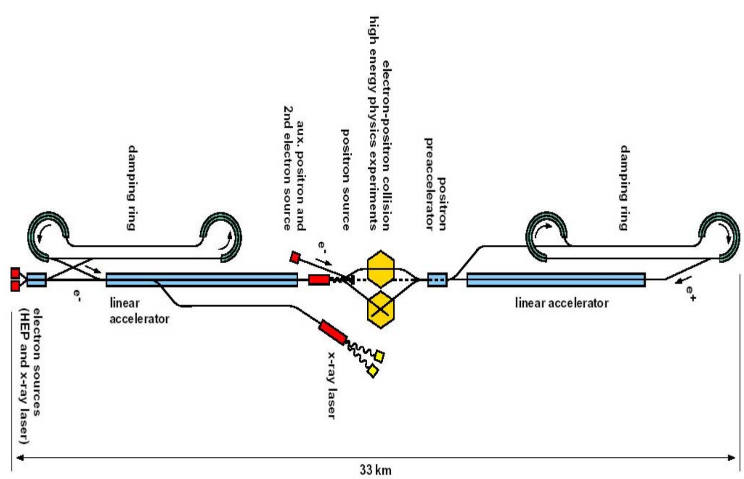


Figure 7: Planned layout of TESLA.

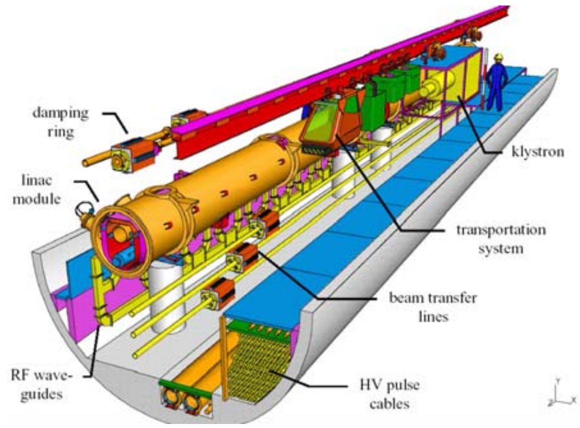


Figure 8: View into TESLA tunnel.

Of the three major approaches, the first one is pushing the limits of conventional room temperature high frequency microwave technology to its limits in an otherwise simple conceptual design and layout. The second one represents a change to the newly emerging technology of superconducting microwaves but still with a simple conceptual design and layout (albeit with a rather dominating damping ring system needed due to the special pulse structure and format for the TESLA beam). The third one represents a significantly complex design, still based upon conventional microwaves, but now pushed to limits of extremely high frequencies and in a sophisticated weaving of a large number of simple radio-frequency bunch manipulation steps into a complex pattern. Yet, one can argue that CLIC is significantly simple, given that the number of klystrons and modulators is one or two orders of magnitude smaller than in other designs, and that there are no active rf elements in the CLIC tunnel, but only two very simple beam lines. The bunch combination required for the CLIC drive beam generation is on a clear path of R&D demonstration, while the klystron development for the NLC has been challenging indeed. The CLIC scheme is a significant shift from the simple paradigm of the first two and has the added advantage of having a potential energy reach of a few TeVs in the center-of-mass. However it will require a sustained research and development time. This last promising concept of CLIC is sufficiently different that it warrants a separate treatment, as exposed elsewhere in these proceedings. We will not address it further in this report.

3. CHALLENGES

Fundamental to the overall challenge of building a successful FLC are two main accelerator physics challenges: energy (rf technology) and luminosity (small spot size and high beam power). Specific issues for small spot sizes are low-emittance damping rings, the final focus system, alignment and jitter tolerances, and beam-based alignment and feedback. Specific beam-power issues are charge extraction from sources, long-range wakefields, and radiation damage to accelerator components. Both issues, involving very high charge densities, carry implications concerning damping ring instabilities as well as beam collimation and machine protection.

It is noteworthy that the luminosity needed for the FLC is a few 10^4 times higher than that in the SLC. A few observations follow immediately from the luminosity expression below, where $\sigma_{x,y}$ are the horizontal (, vertical) beam size, N the number of particles per bunch, E_{cm} the collision energy in the center-of-mass, P_b the power per bunch, f_{rep} the repetition rate of the bunch train each containing n_b bunches and H_D a form factor representing luminosity enhancement due to beam disruption in collision:

$$L = \frac{f_{rep}}{4\pi}\frac{n_b N^2}{\sigma_x \sigma_y} H_D \;\rightarrow\; L = \frac{2P_b}{4\pi\, E_{cms}}\frac{N}{\sigma_x \sigma_y} H_D \,.$$

Long bunch trains will lead to increased beam power. An SLC bunch train can be characterized as 120 Hz × 1 bunch @ 3.5 × 10^{10} particles per bunch. An NLC bunch train would need to exceed that by a factor of 200 (120 Hz × 190 bunches @ 0.75 × 10^{10}); in fact, at TESLA, the plan is to exceed it by a factor of 340 (5 Hz × 2820 bunches @ 2.0 × 10^{10}). Control of long-range wakefields is essential to assure multi-bunch stability. The NLC will also require larger beam cross-sectional densities ($N/\sigma_x\sigma_y$) than the SLC's (3.5 × 10^{10} / (1.6 μm × 0.7 μm)). (The FFTB measurement is (0.6 × 10^{10} / 1.7 μm × 0.06 μm)). The NLC will need to exceed the SLC cross-sectional density by a factor of 330 (0.75 × 10^{10} / (250 nm × 3.0 nm)). (The TESLA plan is for a factor of 230: 2.0 × 10^{10} / (550 nm × 5 nm)). A factor of 5 from energy (adiabatic damping) and a factor of 10 from stronger focusing (similar to FFTB) but at higher energy, could easily lend to a factor of 15 to 30 arising from decrease in beam emittance.

In Livingston-chart fashion for e^-e^+ colliders, Figure 9 traces a crucially important historical trend in beam quality: decreasing beam size. What's wanted in such a collider is not really a beam-beam collision, but particle-particle collisions. The arithmetic of the practical effect of decreasing beam size is simple. If you reduce the size of the collision area by a factor of 100, you increase the event rate by the same factor. Thus you can now conduct in one year an experiment that would previously have required an entire century!

To create the needed high-quality beams requires capitalizing on electrons' loss of energy via the phenomenon of synchrotron radiation. This can be thought of as analogous to the frictional loss by a ball placed off-center at the top of a downward-sloping groove. Friction damps out the oscillation observed initially in the ball's downward travel. In a collider, a damping ring can be used to exploit the "friction" or damping of synchrotron radiation, leading to a small beam in less than a second. Figures 10 and 11 show the Accelerator Test Facility and its damping ring at KEK in Japan, where the world's record low emittance was achieved, 4×10^{-8} m, which is almost what is needed for the FLC.

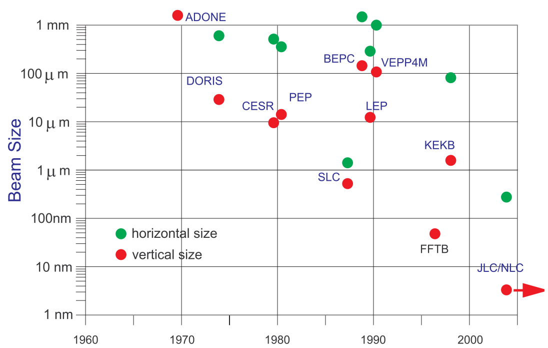


Figure 9: Decreasing beam size in e^-e^+ colliders.

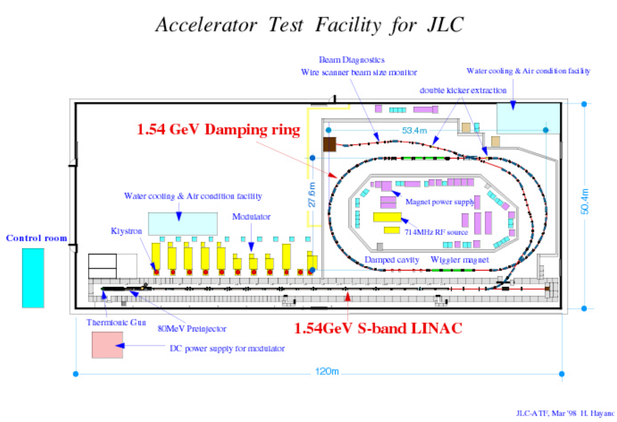


Figure 10: The Accelerator Test Facility at KEK, used for the JLC, contains a damping ring where the record low emittance of 4×10^{-8} m was achieved.

Figure 11: The KEK Accelerator Test Facility damping ring. (See also Figure 10.).

Several deleterious processes anticipated in the damping rings also present challenges for the FLC. These include intrabeam scattering, fast ion instability, and electron cloud instability. It is believed that these can be managed.

Once a high-quality beam has been generated and formed, it is accelerated in a linear accelerator (linac) at microwave frequency (e.g., 11.4 GHz, wavelength 26 mm for the JLC/NLC as shown in Figure 12). The inner surfaces of the accelerator cavities must be accurate to within a micron, and the cavities must be aligned straight within 10 microns (See Figure 13.).

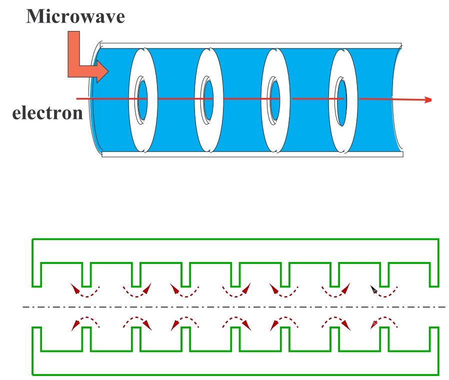


Figure 12: Acceleration of high quality beams.

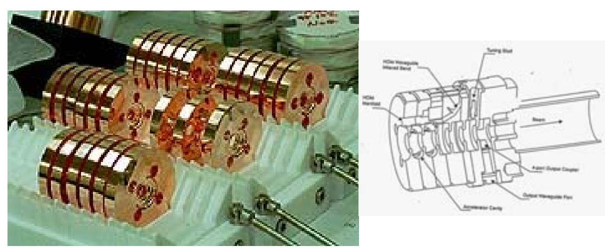


Figure 13: Fabricated linac waveguide with high demand on mechanical tolerance.

The beam is guided through the linac with the same well-known magnet technology that has been used for decades in accelerators. Figure 14 shows schematically the fields and poles of a typical quadrupole magnet, used to focus the beam vertically and horizontally. However, in the FLC, with its extremely small beam size, even so slight a vibration as 10 nm can cause mis-collision, and a 500 nm shift can make the beam fat. At these tolerances, the computer-based accelerator control system must take into account the fact that the ground is moving, requiring computer control of magnet position, beam based alignment and beam steering.. Faster ground motion—for example—is harder to correct. Figure 15 shows the typical ground motion spectrum at typical accelerator sites in Japan.

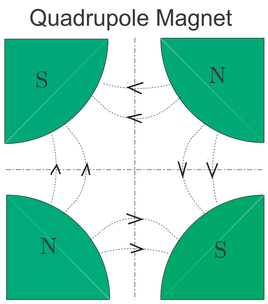


Figure 14: Schematic cross section of a quadrupole magnet for accelerator beam guidance.

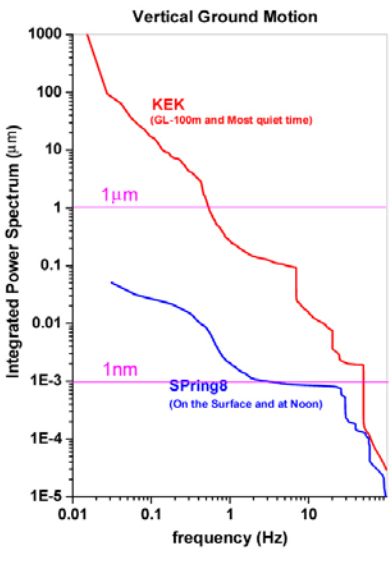


Figure 15: Power spectrum of typical ground motion near KEK and Spring-8 in Japan.

In a cutaway view, Figure 16 shows a collider collision point conceptually. In rms values, the beam at such a collision point for the NLC would need to be 100 μm long, 0.3 μm wide and 0.003 μm (3 nm) thick. Figures 17 and 18, beam-beam collision simulation outputs, show the dramatic beam disruption caused by a one-sigma offset transversely before collision.

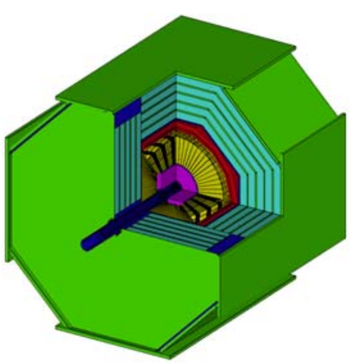
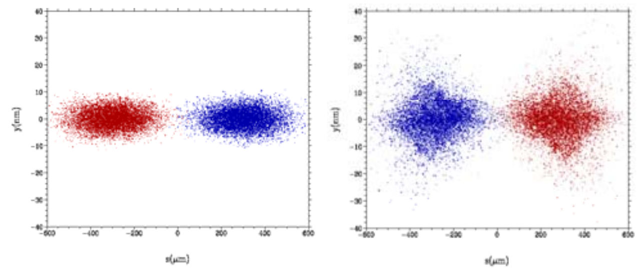
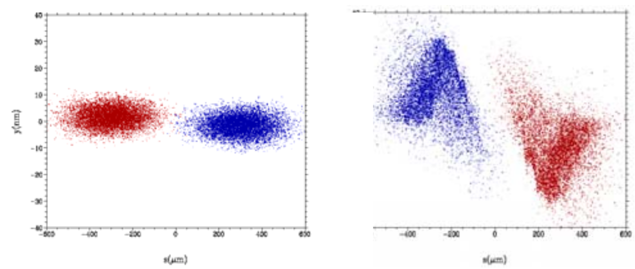


Figure 16: Conceptual view of a collider collision point.



(a) (b)

Figure 17: Simulation results for head-on collision before (a) and after (b) collision.



(a) (b)

Figure 18: Simulation results for one sigma transverse offset collision before (a) and after (b) collision.

It is important to note that a 1 nm miss-collision can cause a 100 micrometer shift at a monitor downstream – the beam-beam force is indeed a hundred thousand fold multiplier! Such amplification could be effectively used in a feedback or feed-forward system as shown schematically in Figure 19.

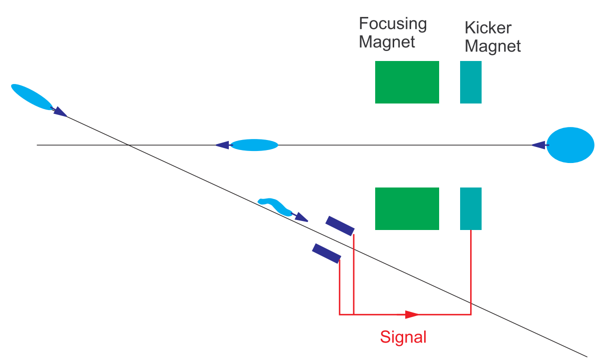


Figure 19: Feedback/feed forward system based upon the beam-beam amplification of transverse motion.

Another obvious challenge is to monitor the size of the beam, which is running at the speed of light. This can be done interferometrically with opposing laser waves creating a standing wave pattern. When a point electron beam comes to the node, it interacts almost not at all with the laser. If the beam is fat, many high-energy photons come out, as a result of Compton scattering. ($e + \gamma$ (laser) $\rightarrow e + \gamma$ (high energy)). Figure 20 shows the monitor that measured a 50 nm beam at the FFTB.

Other monitoring schemes are also under consideration, including use of a shorter-wavelength laser to measure down to a nanometer. To measure at the scale of 1 nm, use can be made of the low-energy debris (both electron and positron) created during collision. This debris is noise to the experimenter, but it is known that the fatness of the beam correlates with verticality in the debris paths. Further experiments are needed to develop a technique based on this behavior.

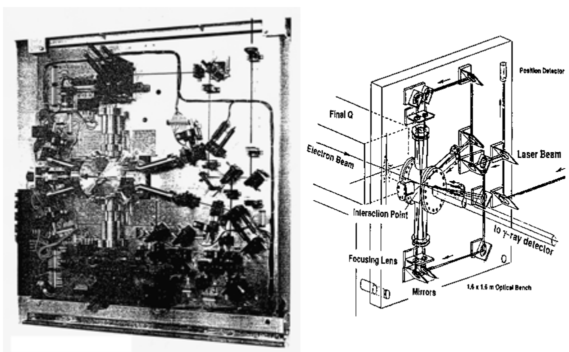


Figure 20: FFTB nanometer monitor.

4. OUTLOOK

Where do we go from here? Further work and simplification is needed to reduce complexity.

To summarize the technical challenges, then, we must simplify design further, as with, for example, the TESLA damping rings. We must reduce cost too. Do we really need damping rings? This question can be answered with further R&D on sources.

However, it is important to note, in conclusion, that all of these challenges exist within a socio-economic and political context. It may be that we will have to reduce our ambitions concerning energy and luminosity. At the level of $1B, one country could host the FLC. If the cost is several billion dollars, an international collaboration is obviously required. Since the likely cost does indeed far exceed $1B, it is clear that perhaps the biggest challenge is for accelerator planners, funders, builders, and users to continue learning how to collaborate globally.

5. ACKNOWLEDGMENT

With the exception of the beam-beam collision simulations, critical observations, judgments and comments, material presented in this article is not an original creation of the authors—it represents but a small sample of the collective knowledge contributed by professionals dedicated to linear collider studies over the last two decades. These contributions are reflected by the articles and the references quoted in the rest of these proceedings. We thank them all and the organizers of this workshop in particular, Dr. Frank Zimmermann and Dr. Ralph Assmann, for inviting us to represent them via this partial review. Private communication with Dr. Tor Raubenheimer is gratefully acknowledged.

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