Tr. J. of Physics
22 (1988) , 529 – 539.

International Workshop on Linac-Ring
Type $ep$ and $\gamma p$ Colliders

# A review of $e^+e^-$ Linear Colliders

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## 1. Introduction

There is a strong interest of the physics community to study the physics of $e^+e^-$ interactions at CM energies well beyond the reach of LEP. The hope is to find and study the Higgs particle and supersymmetric particles. CM energies of order 500 GeV will be needed to look for new interesting physics [1].

Energies in that range are not accessible by $e^+e^-$ storage rings any more. The product of radiated power by synchrotron radiation $P_b$ and bending radius of the magnets $\rho$ scales as [2]

$$P_b\rho \sim \beta_y L E^3 \tag{1}$$

E is the CM energy, $\beta_y$ is the vertical $\beta$-function at the interaction point and L the luminosity. The scaling with energy may be reduced to $E^2$ by a cost optimisation [3], but the fact that the luminosity has to scale with $E^2$ to keep interaction rates up still has to be taken into account.

In Table 1, numbers are given, taken from ref. [2], for the layout of a 520 GeV cm energy storage ring of 126 km circumference at a luminosity of $10^{32} cm^{-2}s^{-1}$. Note that the beam power is 160 Mwatt !!! Assuming a conversion efficiency from AC-power to beam power of 0.5, this would correspond to an AC-power of 320 MW.

**Table 1**

| | |
|---|---|
| Beam energy [GeV] | 260 |
| Circumference [km] | 126 |
| Luminosity [$cm^{-2}s^{-1}$] | $10^{32}$ |
| Synchrotron radiation power [MW] | 161 |

The concept of a linear collider requires even for the longest versions about a factor 4 smaller lengths and about a factor of 2 - 3 less AC-Wallplug-power but delivers more that ten times the luminosity. So clearly in this energy regime the linear collider concept is superior to a storage ring. Already a machine like LEP has crossed the border, but that was, of course, not clear when the machine was built.

## 2. Overview of Proposed Linear Colliders

Table 2 shows some design parameters of the latest common published list [26] from the various linear collider concepts. The table shows that the largest lengths for a 500 GeV linear collider corresponds to about the circumference of the LEP tunnel. The design luminosities are clearly more than an order of magnitude higher than the storage ring design from Table 1 and the AC-power at least a factor of about 2 less. But the table also shows that the designs differ significantly. The used rf frequency for the linac range from 30 GHz for the CLIC design from CERN down to 1.3 GHz for the design of the TESLA collaboration. The vertical beam size at the I.P. differs by a factor of 6. The gradients aimed for range from about 20 MV/m for the SBLC to about 100 MV/m for the VLEPP design, and quite different technologies are applied.

**Table 2**

| | TESLA | SBLC | JLC (x) | NLC | VLEPP | CLIC |
|---|---|---|---|---|---|---|
| $E_{cm}$ [GeV] | 500 | 500 | 500 | 500 | 500 | 500 |
| $f_{RF}$[GHz] | 1.3 | 3 | 11.4 | 11.4 | 14 | 30 |
| Total length [Km] | 32 | 35 | 14.1 | 28 | 10 | 9.9 |
| Luminosity $[10^{33} cm^{-2} s^{-1}]$ | 6.0 | 5.3 | 5.1 | 5.5 | 9.7 | 6.4 |
| RF rep. rate [Hz] | 5 | 50 | 150 | 180 | 300 | 700 |
| Number of particles per bunch $[10^{10}]$ | 3.6 | 1.1 | 0.65 | 0.75 | 20 | 0.8 |
| Loaded gradient $[MV/m]$ | 25 | 17 | 57 | 35 | 91 | 95 |
| Number of bunches per pulse | 1130 | 333 | 85 | 90 | 1 | 20 |
| Beam power/beam $[MW]$ | 8.2 | 7.35 | 3.7 | 4.8 | 2.4 | 4.5 |
| Wallplug to beam power efficiency [%] | 17.4 | 10.4 | 7.4 | 7.9 | 8.4 | 9.3 |
| Total AC-power $[MW]$ | 94 | 140 | 99 | 121 | 57 | 96 |
| $\sigma_x$ [nm] | 845 | 335 | 260 | 294 | 2000 | 264 |
| $\sigma_y$ [nm] | 19 | 15.1 | 3 | 6.3 | 4 | 5.1 |
| $\epsilon_{yn}$ $[10^{-6}$ m×rad] | 0.25 | 0.25 | 0.05 | 0.09 | 0.08 | 0.1 |

Several years ago, G.-A. Voss [4] already wondered why accelerator builders, experts in the field, given the task to design an optimum linear collider in the several 100 GeV range, came up with so vastly different approaches. To better understand the present situation it is very helpful to review the historical development of linear collider ideas.

## 3. Short History of Linear Colliders Development

The concept of a linear collider to investigate the physics of $e^+e^-$ interactions was first proposed by M. Tigner [5] in 1965 - more than 30 years ago - but at that time as an alternative for storage rings in the range of a few GeV.

Very early (about 1971) a group around V. Balakin and A. Skrinsky in the Budker Institute in Novosibirsk started to develop ideas for linear colliders for several hundred GeV. At the ICFA workshop in 1979 [6] a very detailed design was presented for the first time outside the Soviet Union (see Fig. 1) where many problems typical for linear colliders also nowadays were addressed like emittance dilution, pinch effect and beam strahlung at the interaction point, and alignment tolerances of optical and accelerating structures.

Also a scheme to produce polarised positrons and electrons using the spent beam after the interaction point was presented. The high energy beam is sent through an undulator where photons of several MeV are radiated to produce a large number of $e^+e^-$ pairs in a target. A fraction of the produced positrons for example is transfered to a damping ring to be used for injection into the linear accelerator subsequently.

The luminosity aimed for was $10^{32} cm^{-2} s^{-1}$ at an energy of 2 x 500 GeV. It is important to note that only a single bunch was to be accelerated in one rf pulse with 100 MV/m accelerating gradient. To achieve the luminosity of $10^{32} cm^{-2} s^{-1}$ at a bunch repetition rate of 10 Hz, not only a very high bunch charge of $10^{12}$/bunch is required as can be seen from the expression for the luminosity

$$L = \frac{N^2 f}{4\pi\sigma_x\sigma_y} \tag{2}$$

but also very small beam dimensions at the I.P. of order $1\mu$. As a very large pulsed rf power (about 200 MW/m for VLEPP) is required in this concept, one of the main directions of R&D was the development of rf sources, the output power of which had to exceed that of available sources by an order of magnitude.

This was the main stream thinking for about the next ten years:

Aim for very high gradients in a very short rf-pulse and try to extract a large fraction of the energy stored in the accelerating structure by one bunch (or may be a few).

The figure of merit for such a scheme is given by [7]

$$\frac{(\text{accelerating gradient})^2}{\text{stored energy per unit length}}$$

which scales with the square of the rf-frequency, thus clearly favouring high rf-frequencies.

However, there was a parallel development considering superconducting accelerating structures at 3 GHz and 1.5 GHz mainly followed by U. Amaldi at CERN [8] and the Cornell group around M. Tigner [9], but see also [10].

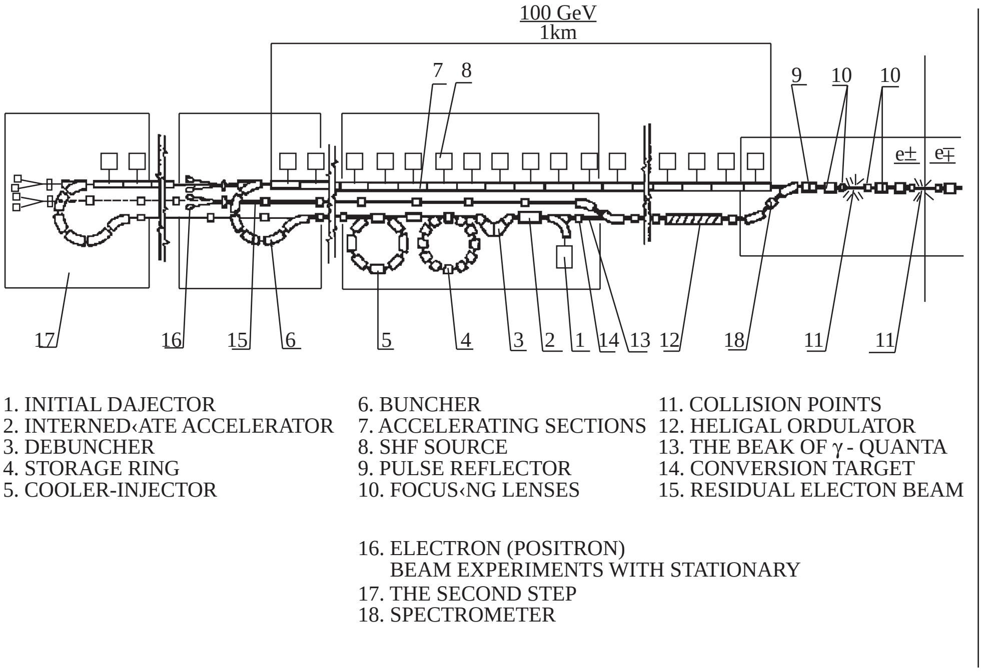

**Figure 1**

These machines were to be operated at high duty cycles with many bunches accelerated during rf on time. For such an operation the shuntimpedance per unit length, which is defined as

$$\frac{(\text{accelerating gradient})^2}{\text{loss per unit length}}$$

is the relevant figure of merit. For superconducting cavities the shuntimpedance scales with rf-frequency $\omega$ like

$$\frac{\omega}{A\omega^2 + B} \tag{3}$$

where A and B are constants. This scaling favours frequencies between about 0.5 and 3 GHz.

Due to the fact that superconducting cavity technology was not sufficiently developed at that time - the achievable gradients were only a few MeV/m - this concept was not adopted by the community. But a few groups continued to work on improving the technology. Then in 1980 the first and up to now the only linear collider to be built - SLC - was proposed and the concept presented at the international accelerator conference [11] (see Fig. 2).

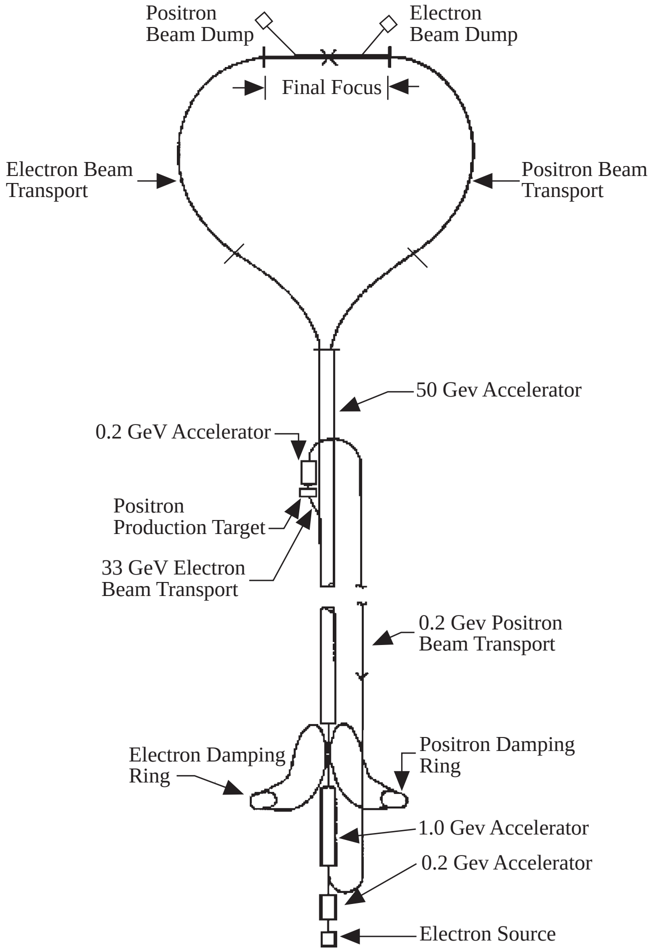

**Figure 2.** Layout of the SLC

It made use of the SLAC linac, increasing the achievable energy by applying rf-pulse compression (SLED) to reach a CM energy of 100 GeV. The initial luminosity was to be $10^{30} cm^{-2} s^{-1}$. Three bunches of $5\times10^{10}$ particles each, a positron bunch followed by two electron bunches, are accelerated down the linac. The last electron bunch is extracted at about 2/3 of the linac length and is directed onto a positron production target. Whereas the positron bunch and the remaining electron bunch are guided through their corresponding arcs to collide at the interaction point.

In addition to serving as an important machine for the study of $Z^0$ production and decay using polarised beams, the SLC was and still is an invaluable source of experience for future linear colliders. It would take too much time to list everything that has been learned at the SLC and been presented at various conferences and workshops. But I would like to mention at least a few aspects.

The complex of emittance blow-up and means to fight it via BNS damping has been studied experimentally [12]. The understanding of the wakefield effects enlarged and the development of computer programs to calculate wakefield effects was stimulated.

A number of diagnostics tools to measure the properties of small intense bunches were developed for example the measurement of the small spotsize at the IP by Compton scattering off an intereference pattern from a laser beam. Beam based alignment and various orbit feedback techniques have been developed.

As there are large numbers of klystrons and modulators (243) which have been operated for many years there is very valuable statistical information available on the reliability of components [13]. These experiences show which components have to be improved and where technical development is necessary for future linear colliders. The SLC project also stimulated the work on future linear colliders in accelerator laboratories around the world.

About 1985 W. Schnell and his group at CERN started working on a 1 TeV linear concept (CLIC) [14] which again was a single bunch machine. The rf-frequency was 30 GHz and gradients of 80 MV/m (see Fig. 3) were aimed for. The design luminosity was $10^{33} cm^{-2} s^{-1}$ at 1 TeV. The peak power needed of about 100 MW/m is generated by excitation of wakefields by a second high current beam of lower energy. This drive beam is accelerated in a superconducting linac operating cw, thus allowing for a high repetition rate of the rf-power generation.

In 1986 KEK [15] and SLAC [16, 17] both started to work on a layout for a 1 TeV linear collider with luminosities exceeding $10^{33} cm^{-2} s^{-1}$. Both groups considered X-Band frequencies (10 GHz and 11.4 GHz). Both colliders were again single bunch machines.

In the already quite specific SLAC design gradients of 186 MV/m and a rf peak power of more than 1 GW/m at a repetition rate of 100 Hz were proposed. To reach the large luminosites very small beam spots ($\sigma_y = 1.5$ nm, $\sigma_x = 270$ nm) were required.

During this time period also the scaling of the wakefield effects with rf-frequency was realized [18]], namely

$$\frac{1}{\omega^2} \qquad \text{for longitudinal} \tag{4}$$

and

$$\frac{1}{\omega^3} \qquad \text{for transverse wakefields.} \tag{5}$$

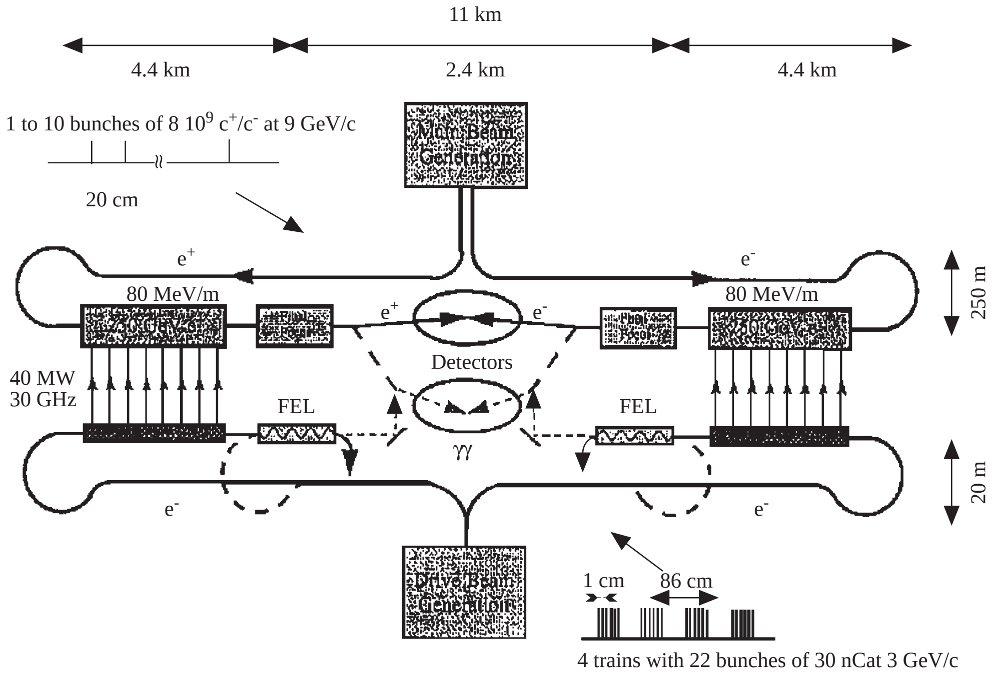

**Figure 3.** Schematic layout of CLIC

Also the fact that the only free parameters for the luminosity of a linear collider - with a limited energy spread due to beam strahlung - are the beam power and the vertical normalized emittance [17, 19]

$$L \sim \frac{P_{beam}}{\sqrt{\epsilon_{yn}}} \tag{6}$$

was discovered.

It was also seen that the beam power and thus the luminosity could be increased by employing multiple bunches per rf-pulse, but this scheme was discarded due to problems seen with beam break-up by wakefields [24].

Only in 1989 both SLAC [20] and KEK [21] started to consider multibunch operation to gain on beam power and luminosity.

DESY joined the field of linear collider development near the completion of the HERA ep collider. In 1990 G.-A. Voss proposed the construction of a S-Band 3 GHz multibunch linear collider for 500 GeV [22, 4] and in 1992 the TESLA collaboration proposed a 500 GeV superconducting linear collider operated at 1.3 GHz with 25 MV/m accelerating gradient [23].

For a superconducting linear collider the choice of low frequencies and multibunch operation is obvious as I showed before. For normalconducting rf-structures G.-A. Voss argued very convincingly - I think - that cost optimisations for a normalconducting collider lead in general to lower gradients than those aimed for in the past.

Using longer rf-pulses and many bunches, which eases to reach large beam power, makes the shuntimpedance per unit length the relevant figure of merit which scales with the rf-frequency $\omega$ for normalconducting cavities like

$$\sim \sqrt{\omega} \tag{7}$$

This still favours higher frequencies, but due to the luminosity dependence

$$L \sim \frac{P_{beam}}{\sqrt{\epsilon_{yn}}} \tag{8}$$

and the frequency dependence of the wakefields (see above) it seems to be much easier to achieve high luminosities at a lower frequency.

I hope this short and incomplete presentation of the historical development of linear colliders give a better understanding of the reasons for the variety of approaches.

## 4. Concluding Remarks

It is worth noting that the cooperation within the linear collider community has been excellent and stimulating. Several collaborations for common R&D were formed, like the collaboration on the Final Focus Test Beam (FFTB) at SLAC and on a test damping ring (ATF) at KEK. Since 1988 a series of workshops on linear colliders have been organized.

In 1993/94 a world wide collaboration for R&D on a TeV scale linear collider was formed, "in anticipation of the need for international collaboration to realize such a collider". A technical review committee was formed and a report [25] was published which examined and compared all of the designs and technologies involved. This was also thought to be a first step in the attempt to come to one common concept. This has, however, not been achieved up to now.

By now there are three conceptual design reports. One by KEK in 1992, one by SLAC on the X-Band NLC which was completed last year and another one jointly by DESY and ECFA containing two options: the S-Band linear collider and the superconducting TESLA 500 GeV linear collider facilities, which are being reviewed by a committee nominated by the DESY Scientific Council in about two weeks.

It is natural, in a way that every group believes in its own design and thinks it to be superior. Giving a review I have to try to stay neutral, but I think it is fair to say, in the context of this workshop, that the TESLA design is the only linear collider concept that can be converted into an ep collider, as will be shown by R. Brinkmann [27]. The present design keeps the possibility for this option by planning the linear collider tangentially to the HERA p-ring (see Figure 4).

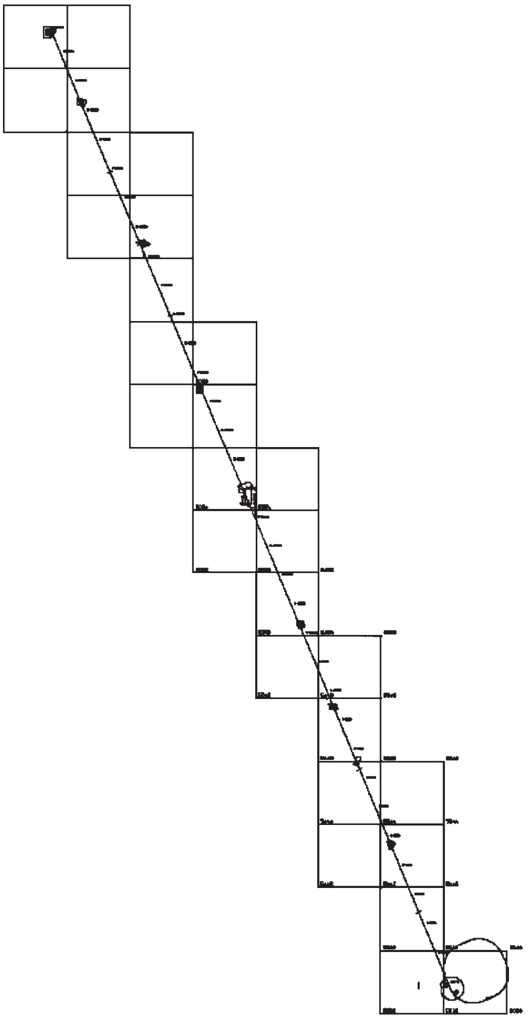

**Figure 4.** Planned linear collider TESLA tangentially to HERA-p ring to enable e-p option

## References

[1] " e+e- Collisions at 500 GeV, The physics potential", Proceedings of the Workshop, Munich, Annecy, Hamburg, ed. P. Zerwas, DESY 92-123A, 1992.

[2] E. Keil, Proceedings of the second ICFA workshop on Possibilities and Limitations of Accelerators and Detectors, 1979.

[3] B. Richter, SLAC-PUB-2274 (1979). Talk presented at the Washington meeting of the American Physical Society, April 25, 1978.

[4] G.-A. Voss, Proceedings of the Linear Accelerator Conference, Ottawa, Kanada, 1992.

[5] M. Tigner, *Nuovo Cimento*, **37** (1965) 1228.

[6] V.E. Balakin and A.N. Skrinsky, Proceedings of the second ICFA workshop on Possibilities and Limitations of Accelerators and Detectors, 1979.

[7] P.B. Wilson, SLAC-PUB-2285 (1979).

[8] U. Amaldi, *Phys. Lett.*, *B 61* (1976) 313, see also Proceedings of the second ICFA workshop on Possibilities and Limitations of Accelerators and Detectors, 1979.

[9] J. Kirchgessner *et al.,* Proceedings of the International Conference on High Energy Accelerators, Geneva 1980, p. 886.

[10] H. Gerke and K. Steffen, Internal Report DESY PET-79/04 (1979).

[11] B. Richter, Proceedings of the International Conference on High Energy Accelerators, Geneva 1980, p. 168.

[12] J.T. Seeman *et al.*, Proceedings of the 14th International Conference on High Energy Accelerators, Tsukuba 1989, in Particle Accelerators, Vol. 30, 31, p. 1061.

[13] A.R. Donaldson and J.R. Ashton, SLAC-PUB-5863 (1992).

[14] W. Schnell, Proceedings of 1987 ICFA Seminar on Future Perspectives in High Energy Physics.

[15] Y. Kimura, K. Takata and M. Yoshioka, Proceedings of 1987 ICFA Seminar on Future Perspectives in High Energy Physics.

[16] R. Ruth, Proceedings of 1987 ICFA Seminar on Future Perspectives in High Energy Physics.

[17] R. Palmer, New Developments in Particle Acceleration Techniques, Orsay 1987, CERN 87-11, ECFA 87/110.

[18] K. Bane, AIP Conference Proceedings 153, Physics of Particle Accelerators (1987), SLAC Summer School 1985, p. 9A1.

[19] R. Brinkmann, Internal Report DESY M-95-10 (1995).

[20] R. Ruth, Proceedings of the International Conference on High Energy Accelerators, Tsukuba 1989.

[21] K. Takata and Y. Kimura, Proceedings of the International Conference on High Energy Accelerators, Tsukuba 1989.

[22] G.A. Voss, Linear Collider Workshop LC 90, Tsukuba 1990.

[23] H. Padamsee, Proceedings of the 3rd European Particle Accelerator Conference, Berlin 1992.

[24] W. Schnell and A. M. Sessler, New Developments in Particle Acceleration Techniques, Orsay 1987, CERN 87-11, ECFA 87/110.

[25] International Linear Collider Technical Review Committee Report, 1995.

[26] G.A. Loew, Proceedings of the 18th International Linear Accelerator Conference, Geneva 1996.

[27] R. Brinkmann, This proceedings.