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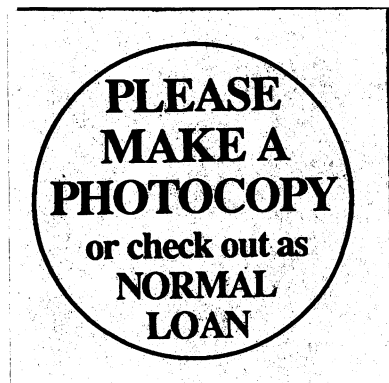
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**LINEAR COLLIDER WORK AT CERN**

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### 1. Introduction

An Advisory Panel chaired by K. Johnsen was set up at CERN in 1985 with the mandate to analyze the possibility to reach a high luminosity in the TeV range with an  $e^+ e^-$  collider. After detailed scrutiny the Panel concluded that a two-beam scheme (ref. 1) using classical linac technology seems to hold the promise of leading to a real project (ref. 2).

In the favoured two-beam scheme (ref. 3-7), proposed by W. Schnell, the main beam is accelerated by a classical linac which however operates at 30 GHz. The accelerating sections are short iris-loaded waveguides. The rf power is generated by a relativistic beam consisting of a train of high-intensity, very short bunches. This drive beam runs in parallel close to the main beam and passes decelerating, so-called transfer structures, where it excites a 30 GHz travelling-wave (TW). This wave is coupled out and fed to the individual main linac TW sections. In order to keep the drive beam relativistic, it is periodically accelerated in superconducting rf cavities operating at 350 MHz which are of the type as used in LEP. The drive beam being ultra-relativistic guarantees proper phasing of the TW relative to the beam.

The present work at CERN is concerned not only with the acceleration scheme proper but an attempt is made to cover all important aspects as injection, damping rings,  $e^+$  production, alignment and final focus. This report gives a summary of the present status of this two-beam scheme and of the results obtained by the working group which is formed by members of several European laboratories and by CERN staff. The emphasis in this report is on explaining how various constraints and choices lead to the present key parameters. In order to make the approach more transparent, certain simplifications have to be made. References to more rigorous accounts are included. A comprehensive review comparing the CERN Linear Collider (CLIC) with other acceleration schemes is also available (ref. 8).

### 2. General Layout

Figure 1 gives a schematic layout of the facility. Positrons are created in a converter target downstream of a linear accelerator (linac) producing a high-intensity electron beam. After acceleration to about 3 GeV the positrons are injected into a damping ring where their emittances are reduced by synchrotron radiation damping to the small values required for the high-luminosity interaction point at the final focus. After a few damping times the positrons are extracted and accelerated to about 10 GeV. The damping ring produces bunches of small energy spread but of a relatively large bunch length. In order to shorten the bunch length to the re-

quired  $\sigma_z = 0.2$  mm, the bunch is rotated in longitudinal phase space by a combination of a of a short linac and a bend (bunch compressor). Whether the acceleration to 10 GeV is done before or after the bunch rotation, or even in two stages, needs a study not yet done. Using the same linac for accelerating both particles to 10 GeV should also be investigated.

The injection of the electrons is similar. If it turned out that a gun can produce the required small emittance electron beam directly, the electron damping ring being on top of the positron damping ring would not be needed.

Each of the two main linacs is about 15 km long delivering a 1 TeV beam to the interaction point at a rate of 1.7 kHz producing a luminosity of  $10^{33}$   $\text{cm}^{-2}$   $\text{s}^{-1}$ . The magnetic elements preceding the final focus will probably take up  $\pm 2$  km. The small crossing angle is not shown; it will be needed to avoid that the spent beam hits the downstream low-beta quadrupoles. The high-intensity drive linacs running in parallel to the main linacs are also not shown in Fig.1.

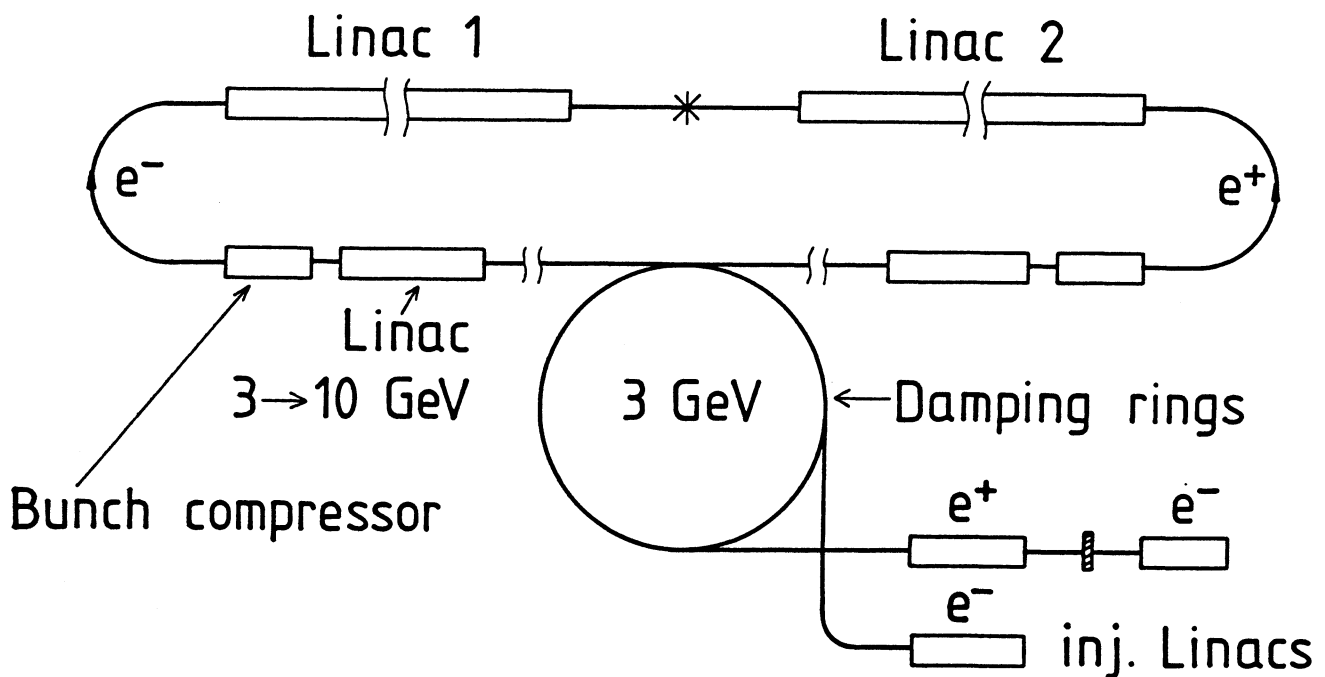


Fig. 1 Schematic Layout of CLIC

### 3. General Parameters

#### 3.1 Beam-beam effects

The luminosity is given by

$$L = \frac{N^2 f_r H_x H_y}{4 \pi \sigma_x \sigma_y} \quad (1)$$

where  $N$  - number of particles per bunch,  $f_r$  - repetition frequency,  $\sigma_x, \sigma_y$  - beam dimensions at the interaction point. Since the particles are focused during the interaction by the electro-magnetic forces generated by the other bunch, the luminosity is enhanced by  $H_x H_y$ , the product of the enhancement factors in the two planes. We assume a vanishing crossing angle.

The enhancement factor  $H_y$  for flat beams ( $H_x = 1$ ) derived from simulations (ref. 9) is plotted in Fig. 2 as a function of the number of oscillations  $n_y$  in the vertical plane a particle performs during the collision with the other bunch. For flat beams

$$n_y = \frac{1}{2\pi} \left[ \frac{2r_e \sigma_z N}{\gamma \sigma_y (\sigma_x + \sigma_y)} \right]^{1/2} \quad (2)$$

For CLIC  $n_y = 0.3$  leading to  $H = H_y = 2$  read from the plot. Other simulations (ref. 10) give a slightly different  $H_y(n_y)$  and indicate that  $H_y$  is monotonically increasing at least for  $n_y < 1.5$ . Hence,  $H_y$  is likely to change in future when more sophisticated simulations become available.

Since there is a certain inflation in beam-beam parameters, it is instructive to relate  $n$  with the other parameters commonly used to describe the strength of the beam-beam effect.

The bunch acts like a thin lens with focal length  $F$  on the particles of the other bunch. The disruption parameter  $D$  (ref. 11) is given by

$$D_i = \sigma_z / F_i \quad i = x, y \quad (3)$$

and in terms of  $n$

$$D_i = (2\pi n_i)^2 \quad (4)$$

For storage rings, the so-called beam-beam tune shift  $\xi$  (ref. 12) is used. It is equal to the betatron tune shift per crossing point

$$\xi_i = \pi \frac{n_i^2 \beta_i}{\sigma_z} \quad (5)$$

Table 1 gives three examples. It can be seen that the beam-beam effect is much stronger in CLIC than in LEP where the perturbation of the circulating beam must be limited.

	CLIC	LEP
$n_y$	0.29	0.05
$D_y$	3.3	0.09
$\xi_y$	0.38	0.03

Table 1

Comparison of beam-beam parameters

Since the trajectory during the interaction with the other bunch is curved, the particle loses energy by synchrotron radiation. This effect is called beam-beam radiation or beamstrahlung. It will be shown that this effect constrains the repetition frequency  $f_r$  (ref. 13). The mean relative energy loss  $\delta$  is given by (ref. 15)

$$\delta = 1.8 \frac{2\pi r_e^2}{\lambda_c} (H_Y \gamma) \sqrt{\frac{L}{f_r}} \left[ \frac{2 \sqrt{R H_x H_y}}{H_x + R H_y} \right] \quad (6)$$

$R$  is the beam aspect ratio  $\sigma_x/\sigma_y$ . The factor  $\gamma$  is proportional to the ratio of the critical photon energy, calculated classically, to the beam energy (ref. 11). The critical photon energy  $h\omega_c = 3 h \gamma^2 eB/2 m_e c$  depends on the magnetic field  $B$  produced by the other bunch; for CLIC  $\gamma = 1.3$ . If  $\gamma > 1$  the energy loss is smaller than calculated from classical theory and the factor  $H_Y$  describes the reduction in energy loss. In the classical case the energy of the critical photon is much smaller than the particle energy. The product  $H_Y \cdot \gamma$  is rather constant and is equal to 0.2 in the range of interest (ref. 11, 14).

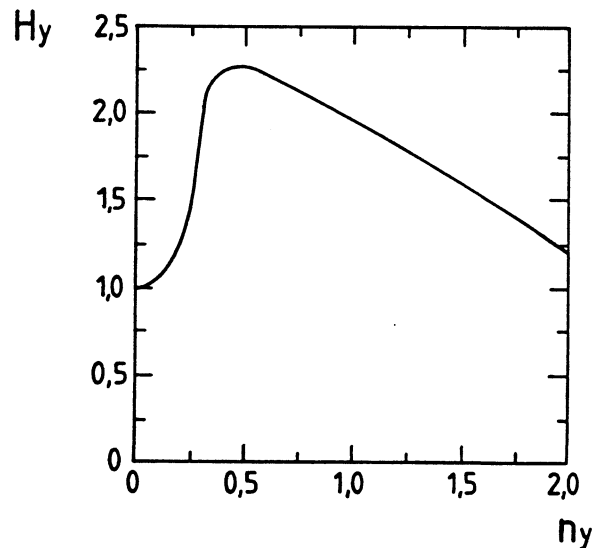


Fig. 2 Luminosity Enhancement Factor  $H_Y$  as a Function of the Beam-beam Parameter  $n_Y$  according to V.E. Balakin and N.A. Solyak (ref. 9)

### 3.2 Linac Repetition Frequency $f_r$

If  $\delta$  is too high, the available average centre-of-mass energy is lowered appreciably and the spread  $\Delta E/E$  in the centre-of-mass system means a loss of resolution as  $\Delta E/E \approx \delta/3$  according to simulations. Usually,  $\delta$  is limited to 0.3. For a round beam  $R = 1$  and from (6)

$$f_{ro} = L \left[ 1.8 \frac{2\pi r_e^2}{\lambda_c} \frac{(H_Y \gamma)}{\delta} \right]^2 = 6 \text{ kHz} \quad (7)$$

Since this high repetition rate implies high beam power and, therefore, excessive average rf power, a flat beam is favoured where  $R$  can be chosen to adjust  $f_r$  (ref. 15). With  $R \gg 1$  and  $H_x = 1$  (6) yields

$$f_r = \frac{4}{R H_y} f_{r0} \quad (8)$$

Avoiding excessive beam aspect ratios,  $R = 5$  has recently been chosen for CLIC leading to  $f_r = 1.7$  kHz (ref. 16).

### 3.3 Choice of the Linac rf

The average beam power is given by

$$P_b = e N U f_r \quad (9)$$

where  $eU = 1$  TeV is the energy gain per linac. The average rf power per linac is

$$P_{rf} = \frac{P_b}{\eta \eta_t} \quad (10)$$

and the required power from the mains is

$$P_m \approx P_{rf} / 0.2 \quad (11)$$

The parameter  $\eta_t = 0.78$  takes into account the dissipation during filling of the TW structure before the beam arrives. The beam extracts energy from the TW structure with an efficiency  $\eta$

$$\eta = \frac{2\pi f^2 e N Z}{c E_z} \left(1 - \frac{\Delta E_z}{E_z}\right) \quad (12)$$

$Z$  is the shunt impedance of the accelerating structure divided by the quality factor  $Q$  per rf wavelength. It varies between 300 and 500  $\Omega$  for commonly used structures; it is 290  $\Omega$  for CLIC (ref. 13). A particle at the head of the bunch sees a higher electric field  $E_z$  than a particle at the tail of the bunch, because the bunch removes a certain field energy during its passage. The quantity  $\Delta E_z/E_z$  is the relative difference between the field at the head and the field at the tail. Although the resulting energy spread can be compensated partially by letting the bunch go through the structure ahead of the crest of the travelling-wave, the spread  $\Delta E_z/E_z$  has to be limited to a few percent. Thus the last factor in (12) is close to 1.

Combining (9), (10) and (12) gives

$$P_{rf} = \frac{e}{2\pi Z \left(1 - \frac{\Delta E_z}{E_z}\right)} \frac{U E_z f_r}{\eta_t f} \quad (13)$$

Once  $f_r$ ,  $E_z$  and  $U$  are chosen, the only way to reduce the average rf power and, therefore, the mains power is to adopt a high frequency  $f$  for the linac. Tentatively, 29 GHz has been chosen.

This choice allows to explore structure fabrication techniques at the limit of technical feasibility, an effort which is not lost in case one is forced later

to go to a lower frequency. Furthermore, should it be possible to increase  $R$  by a more advanced final focus design, the repetition frequency can be lowered by virtue of (8) and, consequently, the average rf power is reduced.

A disadvantage of the high frequency  $f$  is the small iris radius  $a$  of the structure which makes the transverse wake fields  $W_t$  much worse as  $W_t \sim a^{-3} \sim f^3$ . These transverse wakefields are induced when the head of the bunch is not on the linac axis. They deflect particles further upstream the bunch, which leads to a blow-up of the effective emittance and to loss of particles. The best remedy is to introduce focusing by the rf fields in the accelerating structure. This is done by replacing in a fraction of the structures the round iris by elliptical slots (ref. 17). First computer simulations indicate that alignment tolerances become then  $10 \mu\text{m}$  instead of  $1 \mu\text{m}$  or below (ref. 18). Alignment to this precision seems feasible provided fast pulse-to-pulse feed-back techniques are used taking advantage of the high repetition rate.

Table 2 summarizes the main parameters.

Table 2. Main Parameters of CLIC

Energy per beam	eU	1	TeV
Luminosity	L	$1 \times 10^{33}$	$\text{cm}^{-2} \text{s}^{-1}$
Final Focus			
Beam Aspect Ratio	R	5	
Vertical Beam Height	$\sigma_y$	12	nm
Fraction. Energy Loss	$\delta$	0.3	
Bunch Length	$\sigma_z$	0.2	mm
Beam Emittance Ratio	$\epsilon_x/\epsilon_y$	3	
Vertical Emittance	$\beta\gamma\epsilon_y/\pi$	$10^{-6}$	rad.m
Repetition Rate	$f_r$	1.7	kHz
Bunches per Pulse	$k_b$	1	
Bunch Intensity	N	$5 \times 10^9$	
Radio Frequency	f	29	GHz
Acceleration Gradient	$E_z$	80	MV/m

#### 4. Acceleration Scheme

Figure 3 shows schematically the two-beam arrangement. On top the high-energy, low-intensity main linac. The average accelerating field in the about 30 cm long TW structures (70 cells) is 80 MV/m. The high-intensity drive linac is shown below. In each of the transfer structures 35 MW peak rf power is produced for 11.4 ns, the filling time of the main linac structure. In total, 1.8 TW peak rf power is fed to

the main linac. Each pulse of the 5 GeV drive beam consists of 4 bunch trains each consisting of 10 bunches spaced by the 30 GHz rf wavelength. The bunch length is about 1 mm, short enough to excite a 30 GHz TW in the transfer structure. The spacing between two heads of the train corresponds to one wave length of the 350 MHz so that each train is accelerated with the same phase by the LEP-type superconducting cavities. They provide 6 MV/m and their total length is 2.5 km per linac. The 350 MHz klystrons are the standard 1 MW cw tubes developed for LEP.

Various fabrication techniques for the accelerating structure are under investigation (ref. 19). Fig. 4 shows a cross-section through a stack of a few cells. The cells are precision machined with dimensional tolerances of  $2\ \mu\text{m}$  and a surface finish in the N2 class (50 nm), then stacked and brazed together. Electroforming is also studied. In this process, copper is deposited onto an Al mandrel that is etched out later. Obviously, only techniques eventually suitable for mass production can be considered as about  $10^5$  sections will have to be produced.

The transfer structure is a low impedance structure with the active part relatively far from the beam. A model scaled to 3 GHz is under test in the LEP Injector Linac (ref. 20).

In order to save rf power one could consider feeding the rf pulse emerging at the output of the TW accelerating sections back to the transfer structure. A recuperation pulse would transfer the energy back to the superconducting 350 MHz cavities (ref. 3). In another proposal, the cavity beat-wave transformer, the TW structures are replaced by coupled cavities (standing wave operation) where the stored energy would oscillate between the drive linac and the main linac allowing also for energy recovery with a recuperation beam in the drive linac (ref. 21).

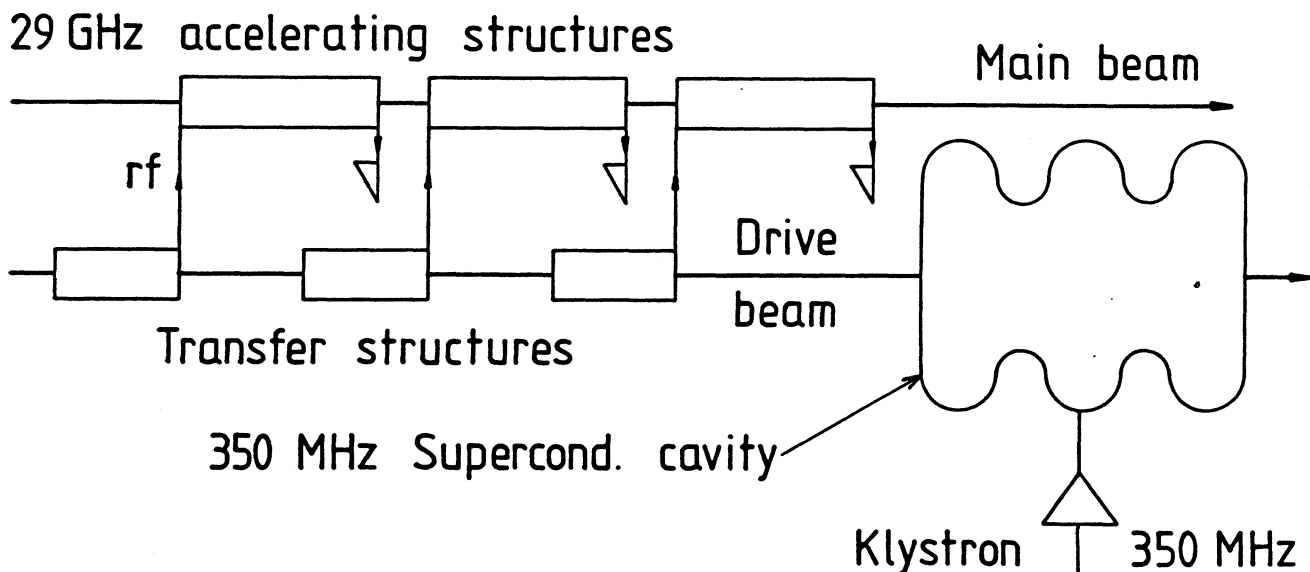


Fig. 3 CLIC Main Linac and Drive Linac



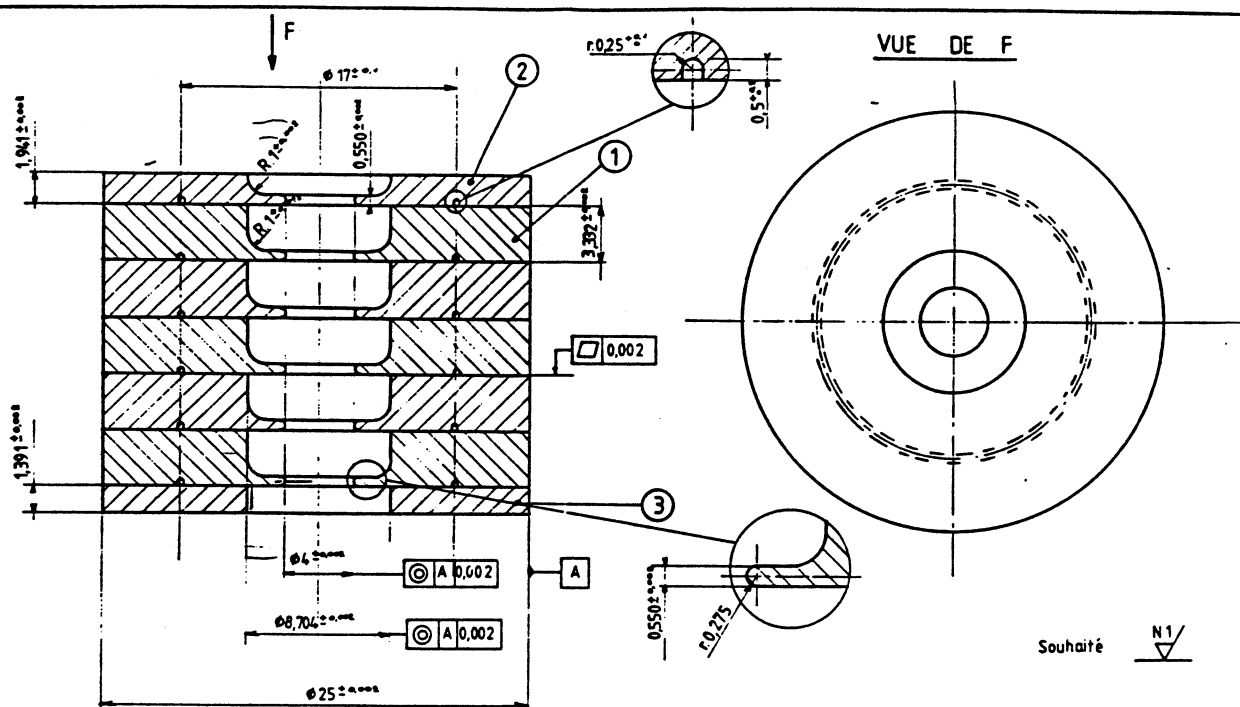


Fig. 4 Example of TW Accelerating Structure;  
Iris Diameter 4 mm, Cell Diameter 8.7 mm, Cell Height 3.33 mm

### 5. Other Subsystems

The desired beam size at the interaction point is  $\sigma_x = 60$  nm by  $\sigma_y = 12$  nm. The beam size should be fairly independent of energy within the energy spread of the beam, which requires a careful compensation of the chromatic effects in the magnetic focusing system. The total energy spread expected from the linac is 0.3% for particles within  $\pm 1 \sigma_z$ , obtained by carefully phasing the bunch relative to the accelerating wave so that the cosine shaped accelerating voltage balances the longitudinal wakefield.

The most promising approach is similar to the one used in SLC where a horizontal dispersion is created in the focusing channel upstream of the final focus (ref. 22). Particles of different momenta travel on different trajectories in the horizontal plane over a part of this channel. Sextupoles are inserted there acting differently on particles of different energy owing to their non-linear focusing strength which depends on the horizontal particle position. Dipoles are used to create the dispersion; their field has to be adjusted carefully in order to avoid emittance growth by radiation fluctuations (ref. 23).

The present solution (ref. 24) could provide  $\sigma_x = 125$  nm and  $\sigma_y = 15$  nm for particles with  $\Delta E/E = \pm 0.25\%$  if the emittance blow-up due to radiation can be reduced. The maximum lens gradient is 0.5 T/mm in 1 m long lenses, which seems feasible with permanent magnets.

Progress has been made with the damping ring design thanks to the effort at CERN, Cornell, INFN and SLAC (ref. 25). The required small emittances (cf. Table 2) can be obtained with damping times compatible with the repetition rate. However, more work is needed to select those solutions that provide good dynamic aperture and are insensitive to lattice errors. A conceptual design exists for the  $e^-$  to  $e^+$  converter target which has to withstand enormous thermal stresses and shocks (ref. 26). In order to test possible methods for the generation of the high-intensity drive beam, test facilities are under design at CERN and at LAL for testing various types of cathodes, guns and magnetic bunch compression schemes.

## 6. Conclusions

Impressive progress has been made in the conceptual design of the main linac, of the final focus and of the damping rings. Although a multitude of technical problems have not yet been solved, no basic flaw in the concept has been found. The concept is complementary to the approaches taken in Hamburg (DESY), Japan (KEK), Livermore (LLNL), Novosibirsk (INP), and Stanford (SLAC). However, more effort will be needed in the future so that soon full scale models of the various subsystems can be built. These are urgently needed before a decision can be taken whether the linear collider concept is a viable proposition for a reliable, high-luminosity facility in the TeV range.

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