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CLIC, a Multi-TeV e$^{\pm}$ LINEAR COLLIDER

J.P. Delahaye and I. Wilson for the CLIC study team:
R. Bossart, H.H. Braun, G. Carron, W. Coosemans, R. Corsini, E. D'Amico, J.C. Godot, G. Guignard, S. Hutchins, E. Jensen, A. Millich, P. Pearce, J.P. Potier, A.J. Riche, L. Rinolfi, D. Schulte, G. Suberlucq, L. Thorndahl, M. Valentini, W. Wuensch, F. Zimmermann, CERN
O. Napoly, SACLAY, T. Raubenheimer, R. Ruth, SLAC, I. Syratchev, BINP.

Abstract

The CLIC study of a high energy (0.5 - 5 TeV), high luminosity (10^{34} - 10^{35} cm^{-2} sec^{-1}) e$^{\pm}$ linear collider is presented. Beam acceleration using high frequency (30 GHz) normal-conducting structures operating at high accelerating fields (150 MV/m) significantly reduces the length and, in consequence, the cost of the linac. Based on new beam and linac parameters derived from a recently developed set of general scaling laws for linear colliders, the beam stability is shown to be similar to lower frequency designs in spite of the strong wake-field dependency on frequency. A new cost-effective and efficient drive beam generation scheme for RF power production by the so-called "Two Beam Acceleration (TBA)" method is described. It uses a thermionic gun and a fully-loaded normal-conducting linac operating at low frequency (937 MHz) to generate and accelerate the drive beam bunches, and RF multiplication by funnelling in compressor rings to produce the desired bunch structure. Recent 30 GHz hardware developments and results from the CLIC Test Facility (CTF), assessing the feasibility of the scheme, are described.

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ABSTRACT

The CLIC study of a high energy (0.5 - 5 TeV), high luminosity (10^{34} - 10^{35} cm^{-2} sec^{-1}) $e^{\pm}$ linear collider is presented. Beam acceleration using high frequency (30 GHz) normal-conducting structures operating at high accelerating fields (150 MV/m) significantly reduces the length and, in consequence, the cost of the linac. Based on new beam and linac parameters derived from a recently developed set of general scaling laws for linear colliders, the beam stability is shown to be similar to lower frequency designs in spite of the strong wake-field dependency on frequency. A new cost-effective and efficient drive beam generation scheme for RF power production by the so-called "Two Beam Acceleration (TBA)" method is described. It uses a thermionic gun and a fully-loaded normal-conducting linac operating at low frequency (937 MHz) to generate and accelerate the drive beam bunches, and RF multiplication by funnelling in compressor rings to produce the desired bunch structure. Recent 30 GHz hardware developments and results from the CLIC Test Facility (CTF), assessing the feasibility of the scheme, are described.

1 INTRODUCTION

The Compact Linear Collider (CLIC) covers a centre-of-mass energy range for $e^{\pm}$ collisions of 0.5 - 5 TeV [1] with a maximum energy well above those presently being proposed for any other linear collider [2]. It has been optimised for a 3 TeV $e^{\pm}$ colliding beam energy to meet post-LHC physics requirements [3] but can be built in stages without major modifications. An overall layout of the complex is shown in Fig.1. In order to limit the overall length, high accelerating fields are mandatory and these can only be obtained with conventional structures by operating at a high frequency.

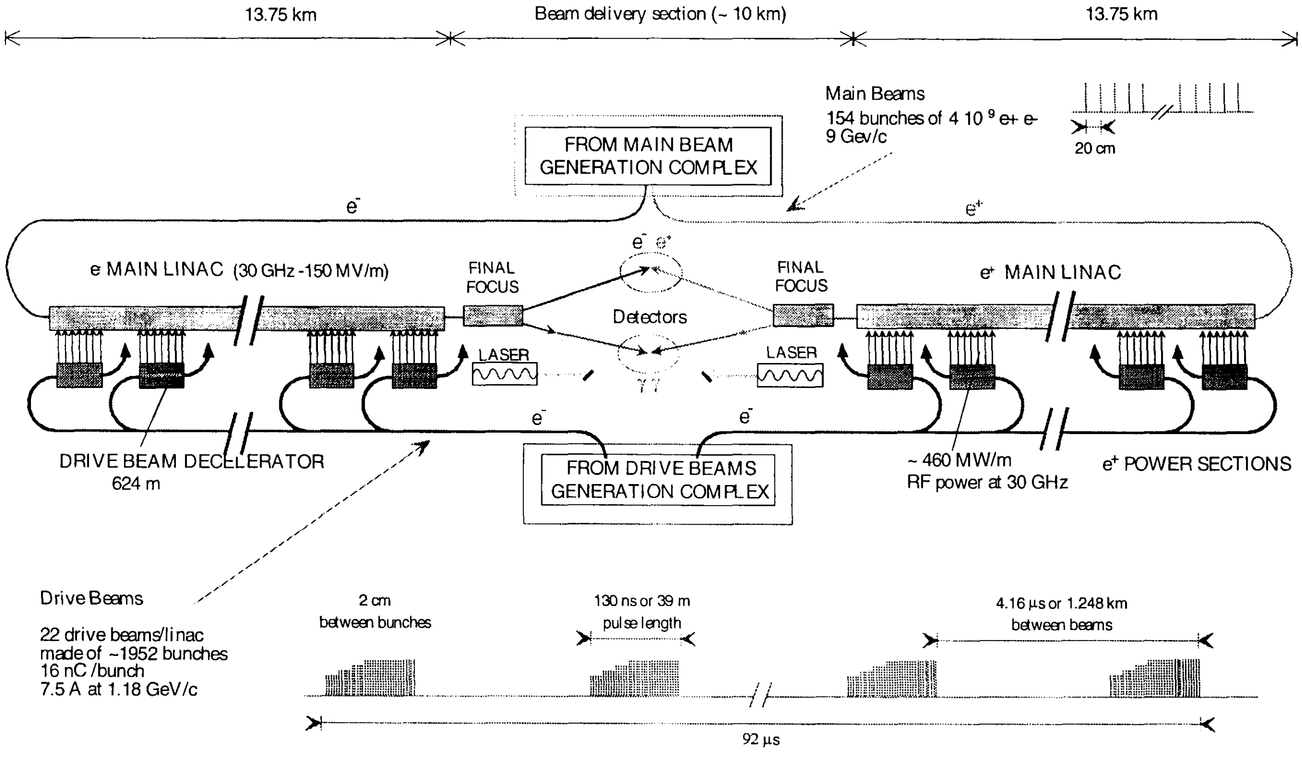

Fig.1: Overall layout of the CLIC complex for a centre-of-mass energy of 3 TeV.

The choice of 30 GHz is considered to be close to the limit beyond which standard technology for the fabrication of normal-conducting travelling-wave structures can no longer be used [4]. The RF power to feed the accelerating structures is extracted by transfer structures from high-intensity/low-energy drive beams running parallel to the main beam (Fig. 2). A single tunnel, housing both linacs and the various beam transfer lines without any modulators or klystrons, results in a very simple, cost effective and easily extendable arrangement (Fig. 3).

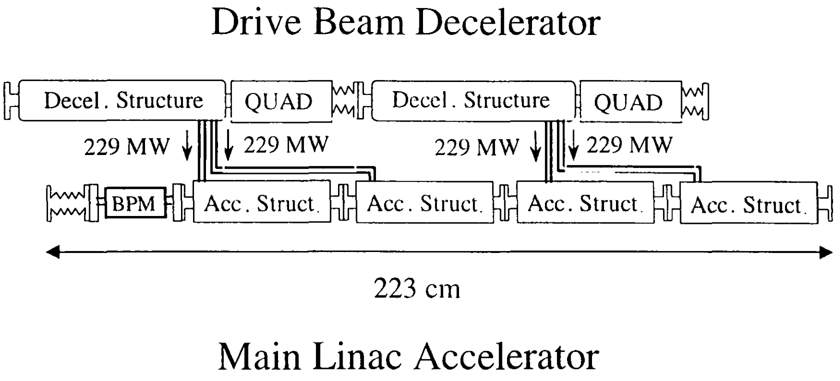

Figure 2: One main beam and drive beam module.

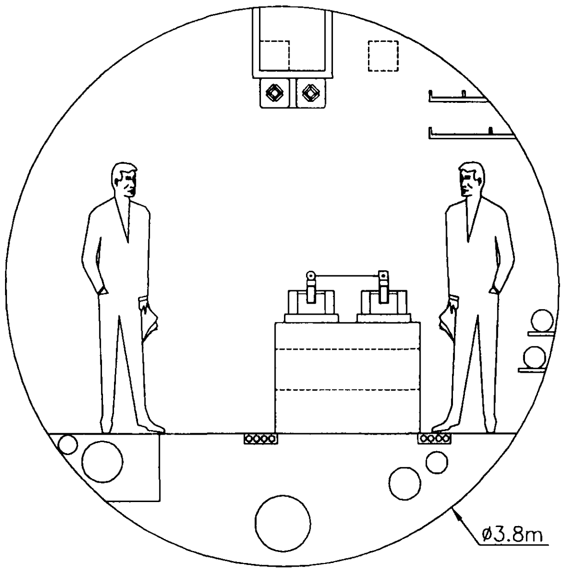

Figure 3: Tunnel cross-section.

2 MAIN PARAMETERS

The main beam and linac parameters are listed in Table 1 for various colliding beam energies. The luminosity L normalised to the RF power, P_{RF}, depends on a small number of parameters in both low and high beamstrahlung regimes:

$$\frac{L_{\Upsilon<<1}}{P_{RF}} \propto \frac{\delta_B^{1/2}}{U_f} \frac{\eta_b^{RF}}{\varepsilon_{ny}^{*1/2}} \quad \text{and} \quad \frac{L_{\Upsilon>>1}}{P_{RF}} \propto \frac{\delta_B^{3/2}}{U_f^{1/2} \beta_y^{*1/2}} \frac{\eta_b^{RF}}{\sigma_z^{1/2} \varepsilon_{ny}^{*1/2}} \qquad (1)$$

where δ_B, is the mean energy loss, η^{RF}_b the RF to beam efficiency and U_f, σ_z, β_y, ε^*_{ny} the beam energy, bunch length, vertical beta function and vertical normalised beam emittance at the I.P respectively [5]. The parameters have been deduced from general scaling laws [5] covering more than a decade in frequency. These scaling laws, which agree with optimised linear collider designs, show that the beam blow-up during acceleration can be made independent of frequency for equivalent beam trajectory correction techniques. As a consequence and in spite of the strong dependence of wakefields on frequency, CLIC whilst operating at a high frequency but with a low charge per bunch N, a short bunch length σ_z , a strong focussing optics and a high accelerating gradient G, preserves the vertical emittance as well as low frequency linacs. The RF to beam transfer efficiency is optimised by using a large number of bunches and by choosing an optimum accelerating section length. In spite of the reduced charge per bunch and the high gradient, excellent RF to beam efficiency is obtained because the time between bunches is shorter and the shunt impedance of the accelerating structures is higher.

Table 1: Main beam and linac parameters

Beam param. at I.P.	**0.5 TeV**	**1 TeV**	**3 TeV**	**5 TeV**
Luminosity (10^{34}cm^{-1}s^{-1})	1.4	2.7	10.0	10.0
Mean energy loss (%)	4.4	11.2	31	37
Photons /electrons	0.7	1.1	2.3	3.2
Coherent pairs per crossing	700	3×10^{6}	6.8×10^{8}	1.8×10^{9}
Rep. Rate (Hz)	200	150	100	50
$10^9 e^\pm$ / bunch	4	4	4	4
Bunches / pulse	154	154	154	154
Bunch spacing (cm)	20	20	20	20
H/V ε_n (10^{-8}rad.m)	200/2	130/2	68/2	78/2
Beam size (H/V) (nm)	202/2.5	115/1.75	43/1	31/0.78
Bunch length (μm)	30	30	30	25
Accel.gradient (MV/m)	150	150	150	172
Two linac length (km)	5	10	27.5	40
Accelerating Sections	6940	14140	42940	62564
Power / section (MW)	229	229	229	301
Number of 50 MW klystrons	364	364	364	364
Klystron pulse length (μs)	16.7	33.3	92	134
RF to beam effic. (%)	24.4	24.4	24.4	21.3
AC to beam effic. (%)	9.8	9.8	9.8	8.5
AC power (MW)	100	150	300	290

Up to 1 TeV, where the beamstrahlung parameter $Y<1$, the beam parameters are chosen to have a small δ_B. To limit the power consumption above 1 TeV, ε_{ny} is reduced and Y allowed to be >>1. In this regime (see Eq.1) high frequency linacs are very favourable because σ_z is small. As a consequence, even with Y>>1, neither the L spectrum (Fig. 4), nor the number of emitted gammas which increase the background in the detector, significantly deteriorate with energy [1] (see Table 1).

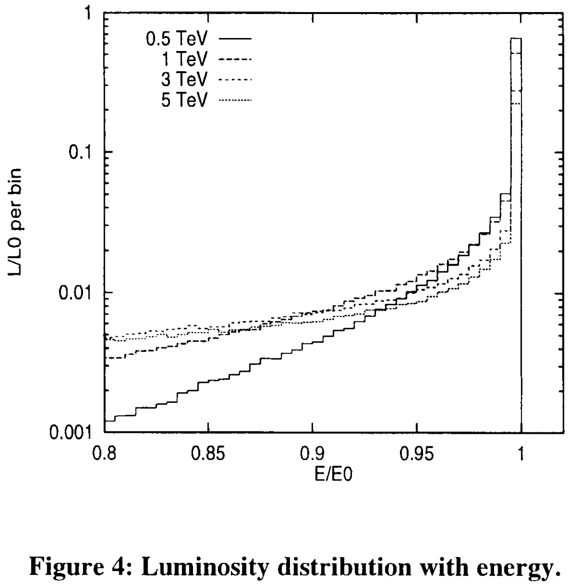

Figure 4: Luminosity distribution with energy.

3 MAIN LINAC

The effects of the strong 30 GHz wakefields (W_T) can be kept moderate by choosing N to be small (4 10^9 at all energies) and σ_z at the lower limit that results from the momentum spread acceptance of the final focus. With a high gradient G and strong focusing, the single bunch blow-up $\Delta\varepsilon_{ny}$ at all energies can be kept below ≈100 % (Fig. 5) [6].

To obtain the values of L given in Table 1 assumes a very small injected ε_{ny} of 1×10^{-8} rad.m. Limiting the overall $\Delta\varepsilon_{ny}$ relies in part on the use of bumps which are created locally at 5-10 positions along the linac by mis-aligning a few upstream cavities. The effects of these bumps are used to minimise the local ε_{ny} (Fig.5). Without these bumps, dispersive effects are ≈ 10 times weaker than W_T effects. The average lattice β-function starts from ≈ 4-5 m and is scaled approx. as $(\text{energy})^{0.5}$. The FODO lattice is made up of sectors with equi-spaced quadrupoles of the same length and normalised strength, with matching insertions between sectors. The RF cavities and quadrupoles are pre-aligned to 10 and 50 μm respectively using a stretched-wire positioning system. The off-set misalignments of the beam position monitors (BPMs) are measured as follows [7]. A section of 12 quadrupoles is switched off, and with the beam centred in the two end BPMs of this section, the relative mis-alignment of the other monitors are measured with an accuracy of 0.1μm. The beam trajectory and ground motion effects are corrected by a 1-to-1 correction. BNS damping is achieved by running off-crest of the RF-wave by 6° to 10°. Multiple bunches are required to obtain high luminosities. The multi-bunch emittance blow-up $\Delta\varepsilon_{ny}$ is ≈ 20%. To make the 154-bunch train stable requires a strong reduction of the transverse wakefields that are induced by the beam in the accelerating structures.

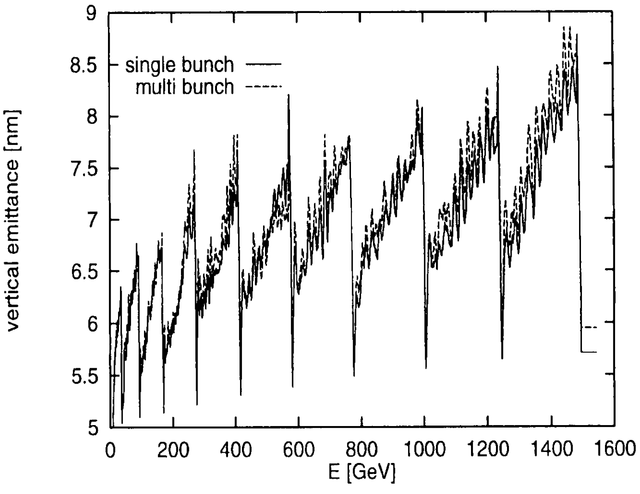

Figure 5: Emittance variation along the main linac.

Each cell of the 150-cell Tapered Damped Structure (TDS) [8] is damped by its own set of four radial waveguides (Fig. 6) giving a Q of 16 for the lowest dipole mode. A simple linear taper of the iris dimension provides a de-tuning frequency spread of 2 GHz (5.4%). The waveguides are terminated with short silicon carbide loads [9].

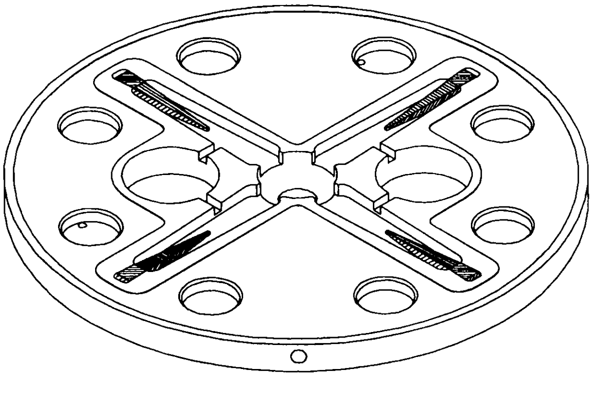

Fig.6 (a) : One disc of the CLIC TDS structure

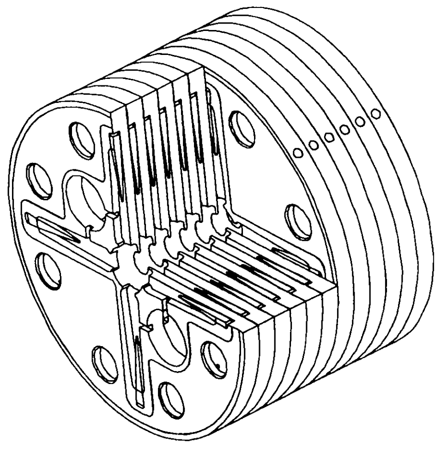

Fig. 6 (b) : A cut-away view of the CLIC TDS

Calculations of the transverse wakefields in this structure indicate a short-range level of about 1000 V/(pC·mm·m) decreasing to less than 1 % at the second bunch and with a long time level below 0.1 %. The simulated transverse wakefield behaviour is shown in Fig.7.

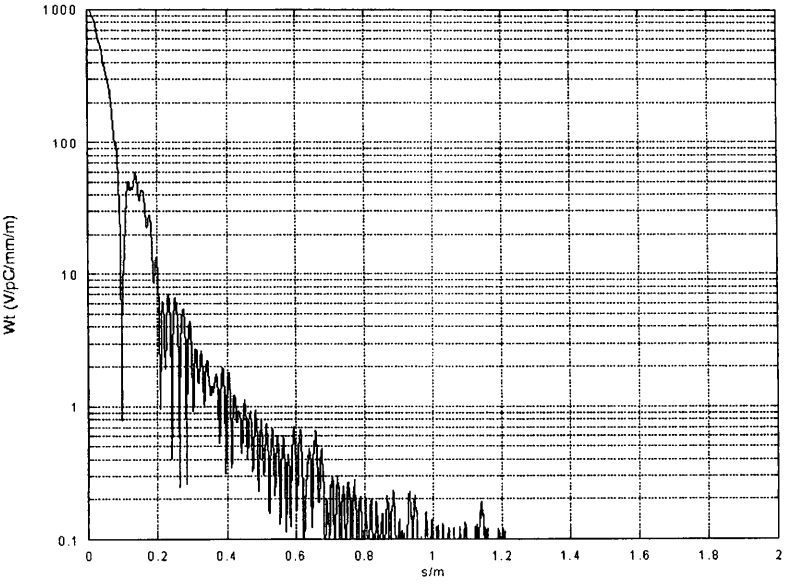

Fig.7 : Calculated transverse wakefield behaviour of the CLIC TDS

A 15 GHz scale model of this structure has been tested in the ASSET Test Facility at SLAC, the measured wakefield levels shown in Fig. 8 are in excellent agreement with the theoretical predictions [10].

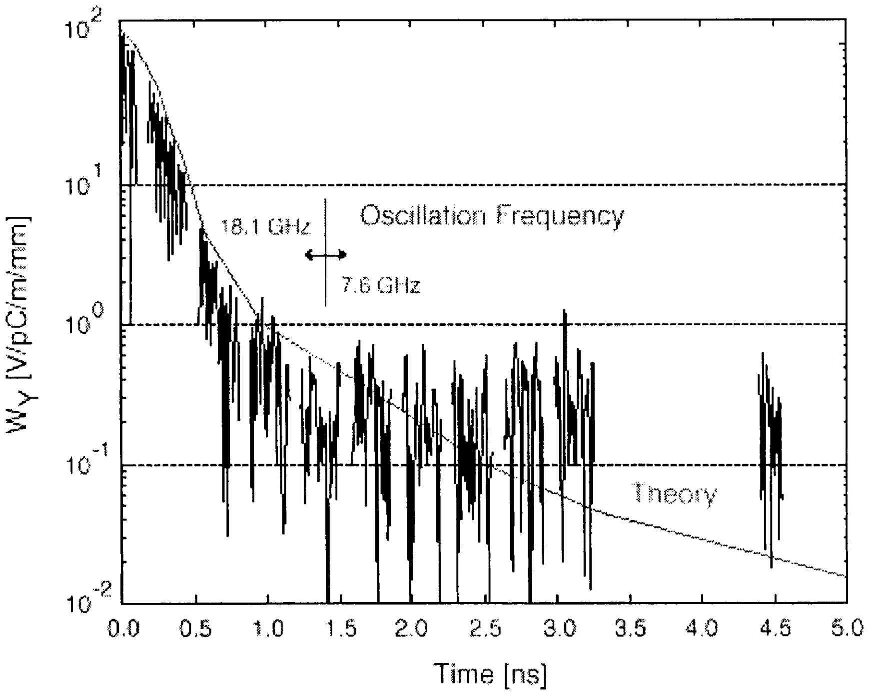

Fig.8 : Comparison of measured ASSET wakefield levels and theory.

The 7.6 GHz signal at the 1% level is not related to the structure but to the beam pipe / structure transition.

4 THE RF POWER SOURCE

The overall layout of the CLIC RF power source scheme for a 3 TeV centre-of-mass collider is shown in Fig.9. The RF power for each 624 m section of the main linac is provided by a secondary low-energy high-intensity electron beam which runs parallel to the main linac. The power is generated by passing this electron beam through energy-extracting RF structures (transfer structures) in the so-called "Drive Beam Decelerator".

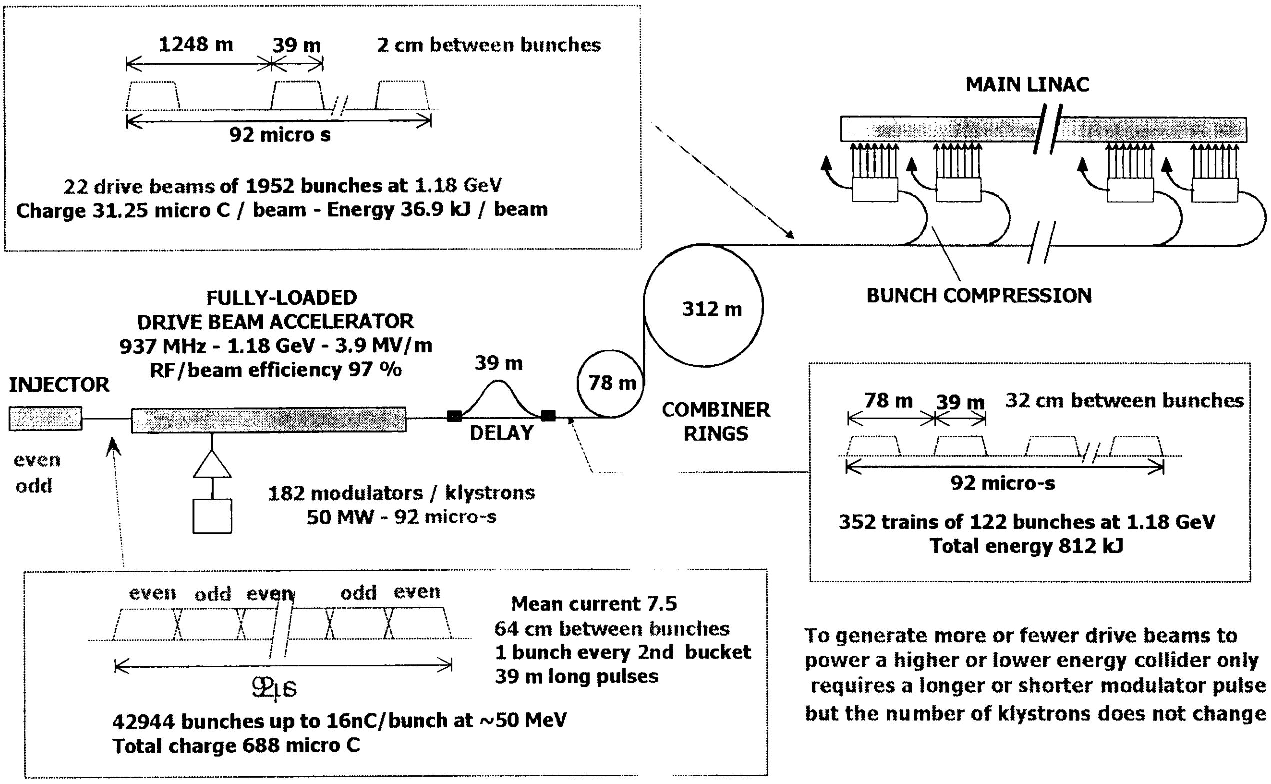

Fig 9 : Overall layout of the CLIC RF power source for a 3 TeV centre-of-mass collider.

For the 3 TeV c.m. collider there are 44 drive beams (22 per linac). Each drive beam has an energy of 1.18 GeV and consists of 1952 bunches with a spacing of 2 cm and a maximum charge per bunch of 16 nC. These 22 drive beams, spaced at intervals of 1.248 km, are produced as one long pulse by one of the two drive beam generators. By sending this drive beam train towards the on-coming main beam, different time slices of the pulse can be used to power separate sections of the main linac (see Fig. 1). This drive beam is generated as follows [11]. All the bunches (for 22 drive beams) are first generated and accelerated with a spacing of 64 cm as one long continuous train in a normal-conducting fully-loaded 937 MHz linac operating at a gradient of 3.9 MV/m. This 7.5 A 92 µs continuous beam can be accelerated with an RF/beam efficiency ≈ 97%. After acceleration the continuous train of 42944 bunches is split up into 352 trains of 122 bunches using the combined action of a delay line and a grouping of bunches in odd and even RF buckets. These trains are then combined in a 78 m circumference ring by interleaving four successive bunch trains over four turns to obtain a distance between bunches at this stage of 8 cm. A second combination using the same mechanism is subsequently made in a similar, larger 312 m circumference ring, yielding a final distance between bunches of 2 cm. The power-extracting and transfer structures (PETS) consist of 4 periodically-loaded rectangular waveguides coupled to a circular beam pipe. Each 80 cm long structure provides 458 MW of 30 GHz RF power, enough to feed two accelerating structures. For stability in the drive beam decelerator, these structures have to be damped to reduce long-range transverse wakefield effect. A cross-sectional view of a model of one of these PETS structures is shown in Fig.10.

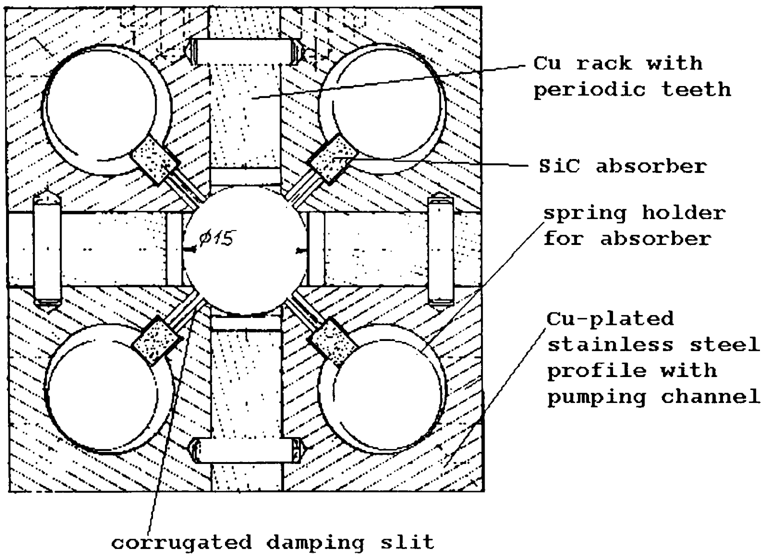

Fig.10 : Cross-sectional view of a model CLIC PETS structure

5 INJECTOR OF MAIN BEAMS

The layout of the centrally-located injector complex of the main beams [12] is shown in Fig.11. To reduce costs the same linacs accelerate both electrons and positrons on consecutive RF pulses. The positrons are produced by standard technology already in use at the SLC but with improved performance due to the larger acceptance of the L-band capture linac. A specific design to damp the particles for a 3 TeV collider is underway but has not yet been completed. The aim is to provide normalised emittances of 5×10^{-7} and 1×10^{-8} rad.m. in the horizontal and vertical planes respectively, at the entrance to the main linac. The basic approach is as follows. The electron and positron beams are damped transversely in specially designed damping rings for low emittances [13]. The damping rings are made up of arcs based on a Theoretical Minimum Emittance (TME) lattice and straight sections equipped with wigglers. The positrons are pre-damped in a pre-damping ring. The bunches are compressed in two stages in magnetic chicanes [14], the first one after the damping ring using 3 GHz structures, the second one just before injection into the main linac with 30 GHz structures.

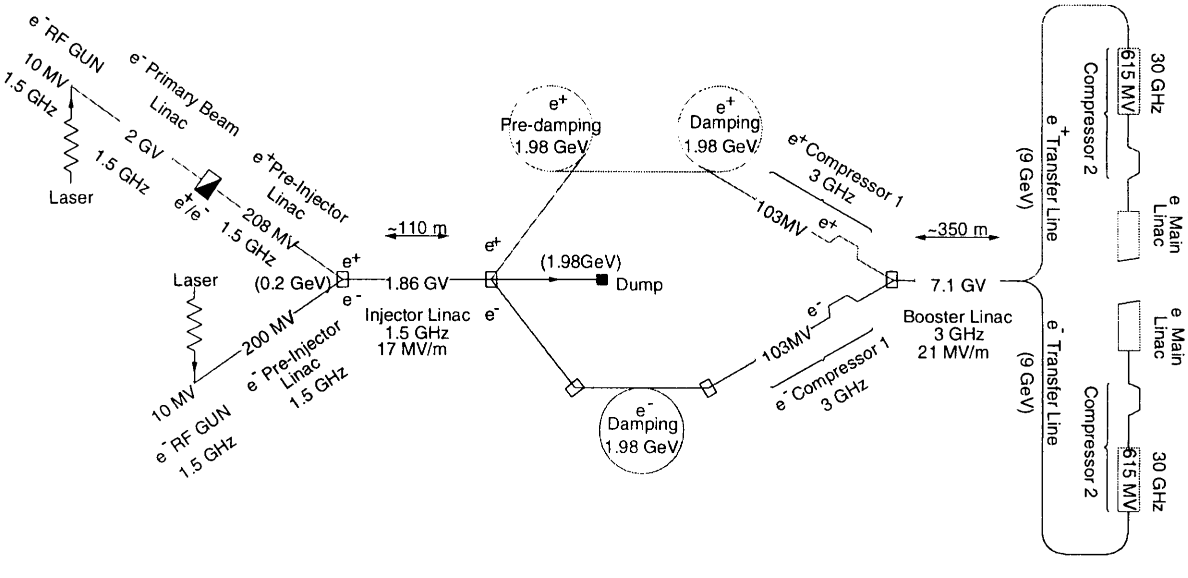

Fig.11: Layout of the injector complex of the main beams.

6 THE BEAM DELIVERY AND INTERACTION POINT

Studies of the beam delivery section consisting of a final-focus chromatic correction section and a collimation section for the 3 TeV collider have only just started and for the moment there is no consistent design. A large crossing angle (10 mrad total) is required [15] to suppress the multi-bunch kink instability created by parasitic collisions away from the main interaction point (IP). This however means that crab-cavities will have to be used to avoid a reduction in luminosity.

Although the final-focus design is at a very preliminary stage, an optics has been found (see Fig.12) which already looks quite promising [16]. 80% of the ideal luminosity is obtained for a 1% full-width flat energy spread of the beams. The luminosity is calculated by convoluting two tracked distributions. The rms spot sizes in both planes are 20-30% larger than expected from the simple calculation using the emittance and the beta function at the IP. Peak beta functions reach 1000 km. The length per side is 3.1 km.

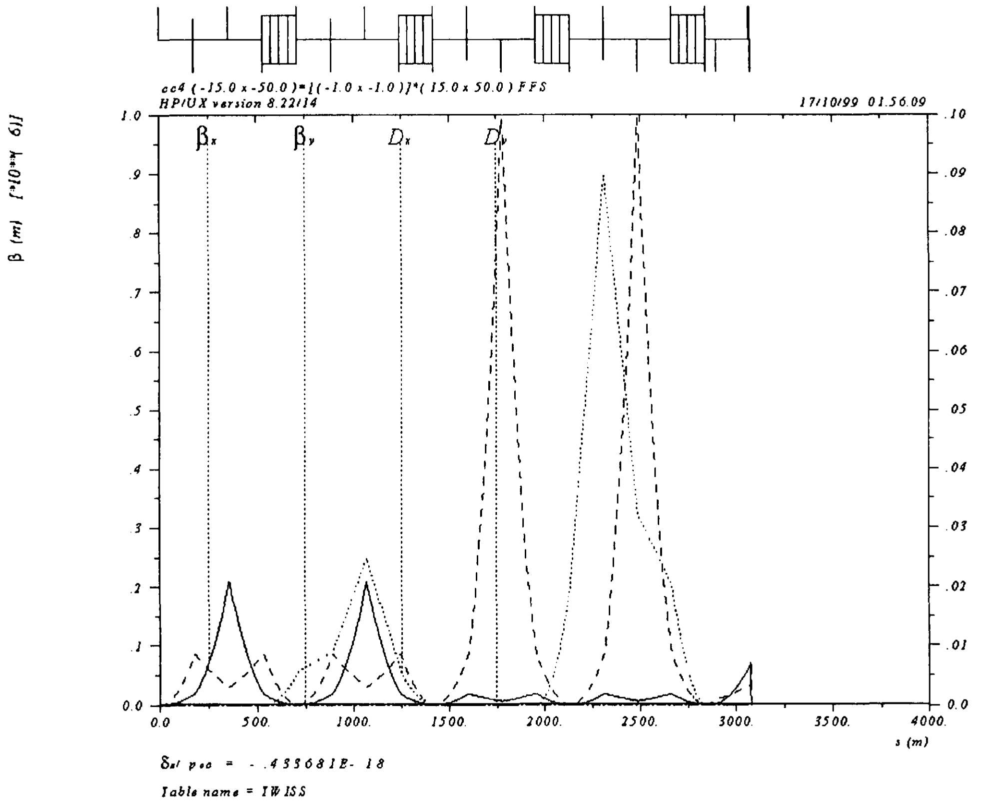

Fig.12: Final focus optics for a 3 TeV collider.

The feasibility of maintaining 1nm beam sizes in collision in the presence of ground movement and component jitter has to be investigated. The use of position feedback systems within the 130 ns pulse are being considered.

The consequences of the large mean energy loss (31%) and energy spread (100%) which are produced by the very strong beam-beam forces at the IP in the vertical plane (even when the beams miss each other by 10-20σ) must be carefully studied. Extraction of a spent beam with 100% energy spread and with a large beam divergence is a concern and will make bending and focussing without beam losses particularly challenging.

The large number of coherent pairs produced at 3 TeV (6.8×10^8) is also a concern. The total energy carried by the pairs is about 40 Joules per bunch crossing and extracting the particles without producing losses in the detector will be a challenge. The worry is also that background levels in the detector may dramatically increase due to the sheer number of pairs produced.

7 TEST FACILITIES

The first CLIC Test Facility (CTF1) operated from 1990 to 1995 and demonstrated the feasibility of two-beam power generation. It produced 76 MW of 30 GHz RF power from a low-energy high-intensity beam and generated on-axis gradients in the 30 GHz structures of 125 MV/m.

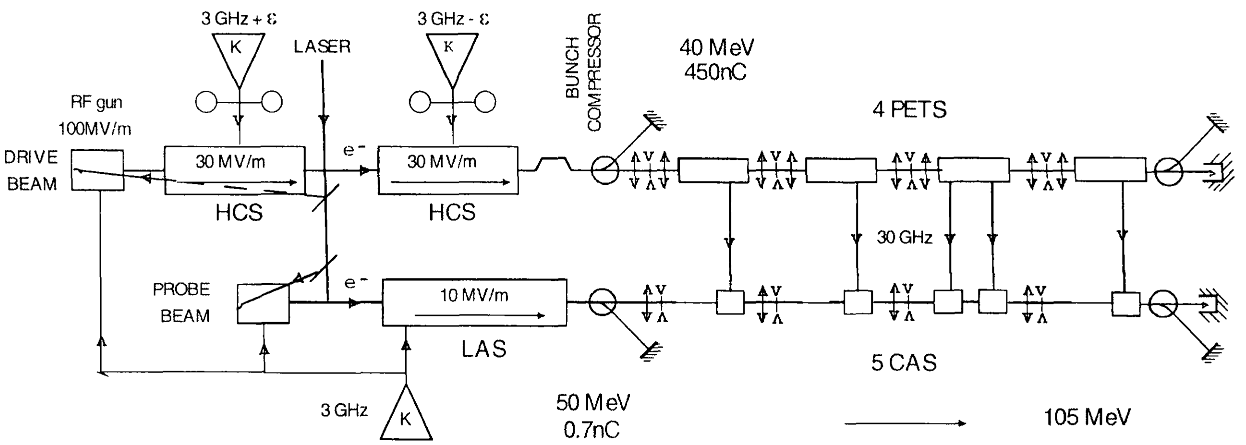

Fig.13 : Layout of CTF2

A new test facility (CTF2) [17] is now being operated (see Fig.13). The 30 GHz part of this facility is equipped with a few-microns precision active-alignment system. The 48-bunch 450 nC drive beam train is generated by a laser-driven S-band RF gun with a Cs$_2$Te photocathode (PC). It is accelerated to 40 MeV by two travelling-wave sections (HCS) operating at two slightly different frequencies to provide beam loading compensation along the train. After bunch compression in a magnetic chicane, the bunch train passes through four power extraction and transfer structures (PETS) each of which powers one 30 GHz accelerating section (CAS) (except the third which powers two) with 16 ns long pulses. The single probe beam bunch is generated by an RF gun with a CsI+Ge PC. It is pre-accelerated to 50 MeV at S-band before being injected into the 30 GHz accelerating linac. The drive beam RF gun has produced a single bunch charge of 112 nC and a maximum charge of 755 nC in 48 bunches. The maximum charge transmitted through the 30 GHz modules is 450 nC. A series of cross-checks between drive beam charge, generated RF power, and main beam energy gain have shown excellent agreement. A consistent set of values are given in Table 2 for two 30 GHz modules with one PETS feeding one CAS. The highest accelerating gradient obtained is 59 MV/m and the energy of an 0.7 nC probe beam has been increased by 55 MeV.

Table 2 : A consistent set of measured values from two 30 GHz modules in CTF2.

Qtrain	375 nC
Qbunch	7.8 nC
Power out of PETS1 and PETS2	27 MW and 22MW
Power into CAS1 and CAS2	21 MW and 17 MW
Field in CAS1 and CAS2	57 MV/m and 51 MV/m
Total probe beam acceleration	30.5 MeV

A new facility (CTF3) is under study [18] (see Fig.14), which would test all major parts of the CLIC RF power scheme. To reduce costs, it is based on the use of 3 GHz klystrons and modulators from the LEP injector Linac (LIL). The drive beam is generated by a thermionic gun and is accelerated by twenty 1.3 m long fully-loaded 3 GHz structures operating at 7 MV/m with an RF to beam efficiency of 96%. The power is supplied by ten 30 MW klystrons and compressed by a factor 2.3 to give a peak power at each structure of 69 MW. The beam pulse is 1.4 μs long with an average current of 3.5 A. The bunches are initially spaced by 20 cm (two 3 GHz buckets) but after two stages of frequency multiplication they have a final spacing of 2 cm. This bunch train with a maximum charge of 2.3 nC per bunch is then decelerated by four 0.8 m long transfer structures in the 30 GHz drive beam decelerator from an initial energy of 184 MeV to a final energy of 125 MeV. Each transfer structure provides 458 MW. The main beam is accelerated from 150 MeV to 510 MeV by eight 30 GHz accelerating structures operating at a gradient of 150 MV/m. CTF3 and CLIC parameters are compared in Table 3.

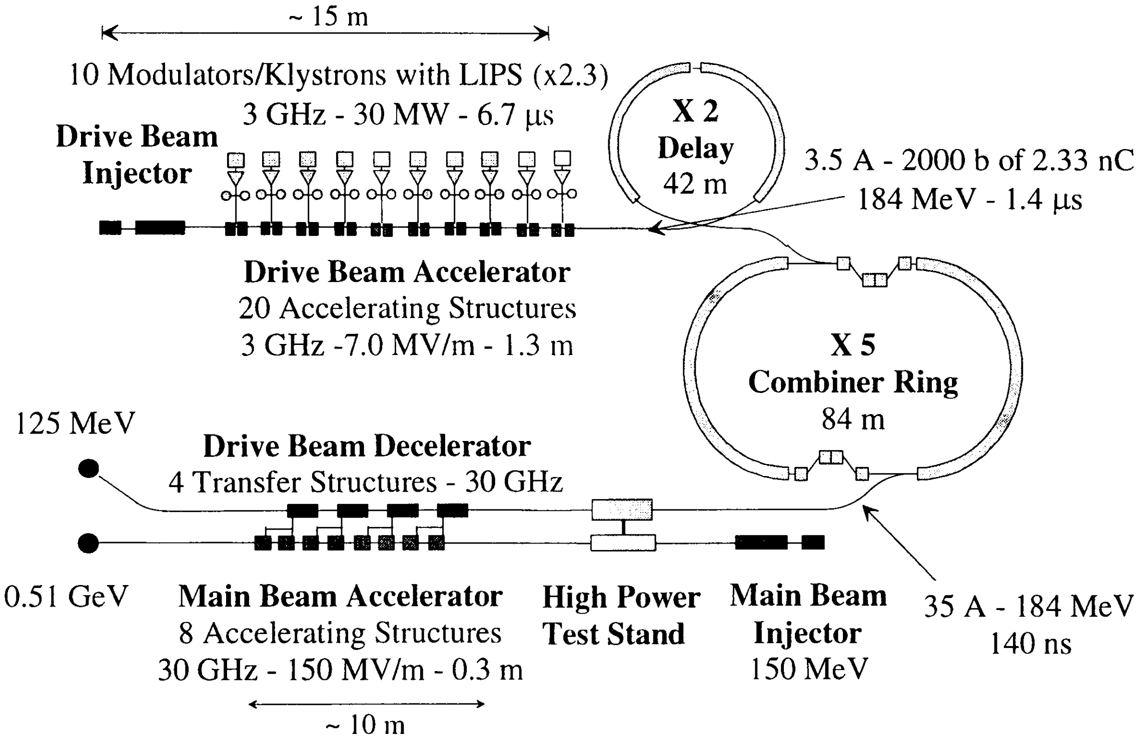

Figure 14: CTF3 schematic layout.

Table 3: A comparison of CTF3 and CLIC parameters.

	CTF3	CLIC	
Accelerating frequency	30	30	GHz
Main linac accelerating gradient	150	150	MV/m
Number of accelerating structures per linac	8	22 x 1000	
RF pulse length	140	130	ns
Main beam acceleration per drive beam	0.36	75	GeV
Number of transfer structures per linac	4	22 x 500	
Number of drive beams / linac	1	22	
Frequency of drive-beam accelerator	3000	937	MHz
Drive-beam energy	0.184	1.18	GeV
Average drive-beam current before compression	3.5	7.5	A
Number of klystrons	10	182	
Number of RF power compressors	10	0	
Drive-beam pulse length before compression	1.40	92	μs
Interval between bunches before compression	20	64	cm

Table 3 Continued: A comparison of CTF3 and CLIC parameters.

	CTF3	CLIC	
Delay line combiner	42m (x2)	39m (x2)	
Combiner ring	84m (x5)	78m (x4)	
Combiner ring (x 4)	NO	312m (x4)	
Overall frequency multiplication	10	32	
Final average drive-beam current after compression	35	244	A
Interval between bunches	2	2	cm
Drive-beam energy per pulse	0.8	812	kJ
Repetition frequency	5	100	Hz
Average beam power	4.1	81.2×10^3	kW
Drive-beam energy on beam dump	125	118	MeV

8 CONCLUSION

The CLIC Two-Beam scheme is an ideal candidate for extending the energy reach of a future high-luminosity linear collider from 0.5 TeV up to 5 TeV c.m. The high operating frequency (30 GHz) allows the use of high accelerating gradients (150 MV/m) which shorten the linacs (27.5 km for 3 TeV) and reduce the cost. The effects of the high transverse wakefields have been compensated by a judicial choice of bunch length, charge and focusing strength such that the emittance blow-up is made independent of the frequency of the accelerating system for equivalent beam trajectory correction techniques. The two-beam RF power source based on a fully-loaded normal-conducting low-frequency linac and frequency multiplication in combiner rings is an efficient, cost effective and flexible way of producing 30 GHz power. The feasibility of Two-Beam power production has been demonstrated in the CLIC Test Facilities (CTF1 and CTF2). A third test facility is being studied to demonstrate the newly-proposed drive beam generation and frequency multiplication schemes.

REFERENCES

[1] J.P.Delahaye and 26 co-authors, Proc. PAC'99, New York, and CERN/PS 99-05, 1999.
[2] Int. Linear Collider Technical Review Committee Report, ed. G. Loew, SLAC-R-95-471, 1995.
[3] J. Ellis, E. Keil, G. Rolandi, CERN-EP/98-03, 1998.
[4] W. Schnell, CERN-LEP-RF/86-06, 1986.
[5] J.P.Delahaye and 3 co-authors,CERN/PS/97-51,1997.
[6] D. Schulte, Proc. EPAC'98, Stockholm, Sweden, and CERN/PS 98-018(LP), 1998.
[7] D. Schulte and T. Raubenheimer, Proc. PAC'99, New York, and CERN/PS 99-24, 1999.
[8] M.Dehler, I. Wilson and W. Wuensch, Proc. XIX Linac Conf. Chicago, August 1998, and CERN/PS 98-040.
[9] M. Luong, I. Wilson and W. Wuensch, , Proc. PAC'99, New York, and CERN/PS 99-20, 1999.
[10] C. Adolphsen and M. Ross, SLAC, Private communication.
[11] H.Braun and 16 co-authors, CLIC Note 364 and CERN Yellow report 99-06 (Sept).
[12] L. Rinolfi, CLIC note 354, 1997.
[13] J.P. Potier, L. Rivkin, CLIC note 337 and Proc. PAC'97, Vancouver, B.C., Canada, 1997.
[14] E. D'Amico and 2 co-authors, CLIC Note 372 and Proc. EPAC'98, Stockholm, Sweden.
[15] O. Napoly, CLIC Note 414, CERN-SL-99-054 AP (Aug. 99).
[16] F. Zimmermann, Proc. LC99 (Frascati) October 1999.
[17] R. Bossart and 15 co-authors, CERN/PS 98-60, 1998.
[18] The CLIC Study Team, CLIC Note 402 and CERN/PS 99-47 LP (July 99).