RESULTS FROM THE CLIC TEST FACILITY

H.H. Braun, K. Aulenbacher, R. Bossart, F. Chautard, R. Corsini, J.P. Delahaye, J.C. Godot, S. Hutchins, I. Kamber, J.H.B. Madsen, L. Rinolfi, G. Rossat, S. Schreiber, G. Suberlucq, L. Thorndahl, I. Wilson, W. Wuensch, CERN, Geneva, Switzerland

Abstract

In order to study the principle of the Compact Linear Collider (CLIC) based on the Two Beam Acceleration (TBA) scheme at high frequency, a CLIC Test Facility (CTF) has been set-up at CERN. After four years of successful running, the experimental programme is now fully completed and all its objectives reached, particularly the generation of a high intensity drive beam with short bunches by a photo-injector, the production of 30 GHz RF power and the acceleration of a probe beam by 30 GHz structures. A summary of the CTF results and their impact on linear collider design is given. This covers 30 GHz high power testing, study of intense, short single bunches; as well as RF-Gun, photocathode and beam diagnostic developments. A second phase of the test facility (CTF2) is presently being installed to demonstrate the feasibility of the TBA scheme by constructing a fully engineered, 10 m long, test section very similar to the CLIC drive and main linacs, producing up to 480 MW of peak RF power at 30 GHz and accelerating the beam up to 320 MeV. The present status of CTF2 is reported.

1. HISTORY AND OVERVIEW

The construction of the CTF accelerator experiment was launched in 1988 aiming to study CLIC [1] drive beam generation by means of a RF photo-injectors, to act as a source of 30 GHz RF pulses of 60 MW for CLIC prototype testing and to have a test bench for beam diagnostic instruments of various types. After first beam was obtained at the end of 1990, the CTF was gradually improved and reached its design performance in 1994. While during the first years of operation the work on CTF was focused on achieving the design performance in terms of accelerated charge and RF power the 1994/95 programme emphasized testing the high power behaviour of various 30 GHz CLIC prototype components, beam monitors of various kinds, bunch compression experiments and photocathode work. The CTF experimental programme finished at the end of 1995 and the CTF was completely dismantled to make space for the successor experiment CTF2. The progress of CTF is documented in numerous conference reports [2-7].

Figure 1 shows a scheme of the CTF installation as it was in 1995. For simplicity magnetic focusing elements and beam diagnostic elements are omitted. An S-band RF-gun [8] produces single bunches or trains of up to 48 bunches from a photocathode illuminated by a short pulse, high power laser system [9]. A magnetic chicane, together with a longitudinal correlation introduced by the RF-gun phasing, is used for longitudinal bunch compression [10]. After compression a 1 m long S-band section boosts the electron energy to 65 MeV. This section is borrowed from LAL/Orsay where it was built and used for high gradient experiments [11]. The RF-gun and the structure are powered by two klystrons, one of them equipped with RF pulse compression. With typical power levels of 18 MW for the first and 27 MW for the second klystron we run well below their maximum power of 35 MW each. A drift space between the S-band section and a magnetic spectrometer is used to test beam-monitor and 30 GHz RF structure prototypes with beam. The sections CAS1 and CAS2 are identical prototypes of CLIC 30 GHz accelerating structures. While CAS1 is used to produce 30 GHz power due to the beamloading from the electron beam, CAS2 reaccelerates the electrons. The achieved accelerating gradients in CAS2 can be readily computed from the

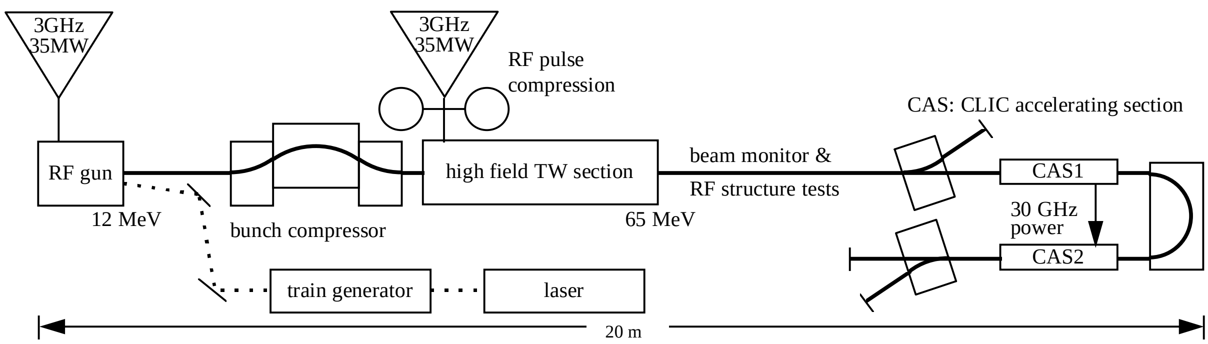

Figure 1. Schematic layout of CTF as it was in 1995

magnetic field values in the 180° bend and in the second beam spectrometer. The 30 GHz output from CAS1 is also used for high power tests of other CLIC 30 GHz components. Apart from conventional beam diagnostics like pick-ups and scintillating screens, a streak camera in conjuction with transition and Cerenkov radiators is used to measure the time structure of single bunches and bunch trains [12].

2. LASER SYSTEM

The laser system [9] consists of a 250 MHz active mode locked cw laser (from LightWave) seeding a regenerative amplifier and two single pass amplifiers (from Quanta System). Nd:YLF is the active material in all laser stages. The seed laser uses diode pumping, while the amplifiers are flashlamp pumped. The synchronization with the RF is achieved by using the 250 MHz Oscillator of the mode locker as the master oscillator for the RF. The main parameters of the laser system are given in table 1.

Table 1. Parameters of the laser system

Energy per pulse at laser output for λ=1048 nm λ=524 nm λ=262 nm λ=209 nm	 10 mJ 5 mJ 1 mJ 0.2 mJ
pulse length	8 ps fwhm
pulse to pulse energy jitter	3% rms
pulse to pulse timing jitter	1 ps rms
rep. rate	10 Hz

Depending on the switching of the selector pockel cells of the regenerative amplifier, either one or two pulses from the seed laser can be amplified. These pulses can be split into a train of up to 48 pulses with 10 cm spacing with an optical splitting system of semi-transparent mirrors and polarizing splitters. Other train generating methods using only polarizing splitters have also been tried [13].

3. PHOTO CATHODES

The photocathode materials mainly used in the CTF RF-gun were CsI [14] and Cs_2Te [15]. Typical quantum efficiency of CsI is 3% at a wavelength of 209 nm; due to CsI's high work function of 6.4 eV the QE is decreasing rapidly for longer wavelength. Cathode lifetimes are of the order of weeks. CsI has the advantage that it can be exposed to air.

However, for reasons of laser stability, laser energy and quality of optical beamline elements it is much more favourable to operate at longer wavelength. Cs_2Te was found as a cathode material which gives initial QE values of the order of 10% at a wavelength of 262 nm, corresponding to the 4th harmonic of the laser. The sensitivity of Cs_2Te to air exposure necessitated the construction of a load lock system for the RF-gun which became operational in 1993. Figure. 2 shows a lifetime plot of a Cs_2Te cathode used during several weeks in the RF-gun. After a fast drop of QE over the first 30 h of operation the QE stays at a level of about 2% over several weeks with very little additional degradation. It was further found that only the time with RF on affects the lifetime; however, it is not yet clear if the RF fields or the vacuum conditions with RF on are causing this. Typical vacuum values in the RF-gun are $2 \cdot 10^{-10}$ Torr with RF off and $4 \cdot 10^{-10}$ Torr with RF on. It was found to be advantageous for the lifetimes and quantum efficiency of Cs_2Te to have a thin layer of molybdenum or magnesium between the cathode and the copper substrate and to keep strict interlock conditions on the RF-gun klystron with respect to sparking. Since the bunch length measurements for the RF-Gun are usually in good agreement with beam dynamics predictions a response time of Cs_2Te well below 10 ps can be assumed.

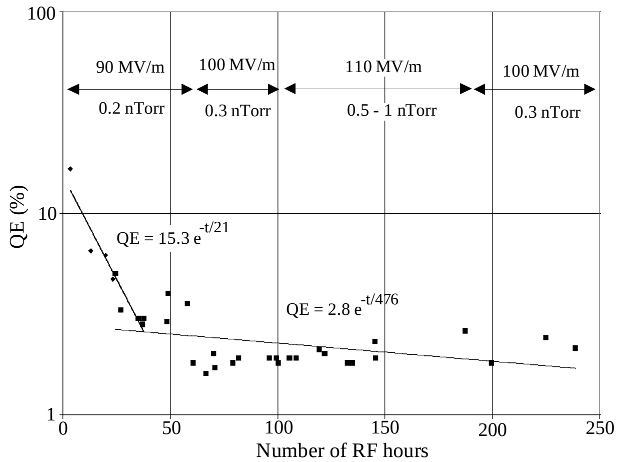

Figure 2. Quantum efficiency of Cs_2Te cathodes as a function of RF hours. During the use of this cathode different RF field levels were applied as indicated.

Another cathode type tested is CsI with a thin layer of Germanium. The QE of this cathode was found to be about 0.1% at 262 nm. The peak field on this cathode is limited by breakdown to about 70 MV/m. Nevertheless, this cathode is attractive for certain applications, since it can be exposed to air and has reasonable QE at 262 nm.

In the fall of 1995 the CTF was used to test for the first time GaAs-photocathodes in an RF-gun [16]. This semiconductor cathode material is a potential candidate for producing a polarized electron beam out of an RF-gun. The two samples used were 0.3 mm thick crystals of highly doped ($5 \cdot 10^{18} cm^{-3}$) bulk-GaAs. Those crystals were provided by SLAC, where they were glued with indium into the standard cathode support structure of the CTF RF-gun. After transfer to CERN the samples were

mounted in the RF-gun and tested at high power. The tests revealed that the RF-detuning of the gun due to the use of GaAs instead of Cs_2Te is negligible. Operation of the gun at fields up to 85 MV/m was possible after several hours of RF-conditioning. Due to the absence of a cleaning technique for the GaAs surface the negative electron affinity (NEA) state was not achieved. However, a single bunch of 2 nC was produced at a laser wavelength of 262 nm and accelerated. Streak camera measurements revealed an electron bunch length of 16 ps fwhm in agreement with simulation predictions. This indicates that the response time of the cathode for this wavelength is short compared to this value.
To prove the feasibility of a polarized RF-gun it remains to be shown that a GaAs cathode with a NEA surface can also be operated at high fields and that photo-emission at the GaAs bandgap (850 nm) can be achieved and maintained in an RF-gun enviroment .

4. RF GUN

The RF gun setup used from 1994 on consisted of a 1½-cell RF gun similar to the gun developed at BNL [17] and a 4-cell booster cavity [8]. With this gun in combination with Cs_2Te cathodes a peak cathode field of 110 MV/m can routinely be maintained . Operation at 120 MV/m is also possible but leads to frequent RF-breakdowns. The onset of beam losses at the gun aperture occurs for bunch charges higher than 12 nC. This leads to a less-than-linear growth of the bunch charge with respect to the laser energy for charges higher than this. Nevertheless, single-bunch charges of up to 35 nC were measured at the output of the gun. This charge was achieved with an increased laser pulse length of 16 ps fwhm.
The emittances from this gun were measured over a wide range of bunch charges and conditions [6,10]. For example normalized rms emittances of 29 π·mm·mrad have been measured for a single bunch charge of 1.2 nC and 118 π·mm·mrad for 16 nC.

5. ACCELERATED CHARGE

The maximum measured charges in single and multibunch operation are listed in Table 2. The charge limitations for the gun are space-charge forces in single-bunch and laser energy in multibunch operation. In the 3 GHz section the beam loading limits the multibunch charge and single-bunch charge is limited again by space charge. The limits of transmission through the CAS are due to emittance growth caused by space-charge forces, transverse wakefields and chromatic effects in focusing quadrupoles due to beam loading (the CAS aperture radius is only 2 mm!).

Table 2. Maximum measured charges

position in beamline	single bunch [nC]	48 bunches [nC]
RF Gun exit	35	450
Exit 3 GHz section	20	160
Exit CAS1	7	81

6. 30 GHZ HIGH POWER TESTING

One of the major concern about the CLIC acceleration scheme using 30 GHz was the lack of experimental data about power handling capabilities of accelerating structures and RF network components. Although scaling laws [18] indicate that high frequencies are favourable for high electric fields by the sheer appearance of a 7.11×3.56 mm waveguide it is remarkable that such a device can transport MWs of power.
By decelerating a train of 48 bunches of 3 nC each, pulses of up to 76 MW peak power with a 3 dB width of 12 ns were achieved at the output of CAS1 (see fig. 1). This power corresponds to a mean accelerating field of 94 MV/m in CAS2 and a peak decelerating field of 123 MV/m in CAS1. The design field of the CLIC accelerating sections at the time those tests started was 80 MV/m. The power level during the tests was limited by the maximum charge which could be transported through CAS1 (see above) but not by RF breakdown. It is remarkable that neither in the structures nor in the connecting waveguides was any sign of RF breakdown observed. Further high power tests of flexible waveguides, waveguide loads, phase shifters and a piece of waveguide with a silver plated surface were performed, always revealing the same result. To provoke a breakdown a nailtip was mounted in a piece of waveguide but no decrease of transmission as a function of power could be observed. Thus it has been proved that the CLIC structures can handle field levels in excess of the design values. Moreover, it seems that in the field-strength/pulse-length regime we have investigated, breakdown is not at all a severe issue. Based on these results a recent reoptimization of CLIC parameters gave an increase of the nominal accelerating gradient from 80 MV/m to 100 MV/m.

7. BEAM MONITORS

The flexibility of CTF with respect to the accelerated charge and the number of bunches made it an ideal test-bed for beam monitors. Several types of beam position and intensity monitors were tested, among them BPM prototypes for the CLIC main linac [19] and the TESLA Test Facility [20].
As an alternative to the streak camera measurements the bunch length was also determined by measuring the distribution of the coherent part of a transition radiation spectrum [21]. For this measurement the radiation from a sheet of aluminium was observed with a bolometric

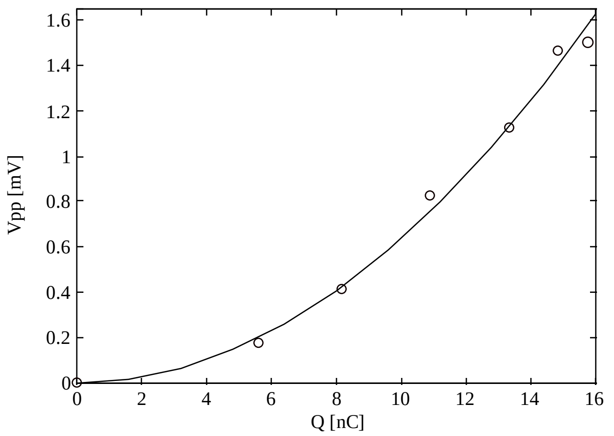

Figure 3. Bolometer output signal as a function of the total charge in the train.

detector foreseen as a part of the Tesla Test Facility bunch length measurement system. To prove that the signal really stems from a coherent process the signal strength was measured as a function of the total charge in the train for a constant number of bunches. As expected the signal raised quadratically with the charge (see fig. 3). Grids consisting of arrays of circular apertures in a brass plate were mounted in front of the Bolometer. Those grids act as mm-wave high pass filters. Using an assortment of these grid filters radiation spectra were measured for two different settings of the bunch compressor and the bunch length was computed from the spectra by an appropriate fitting procedure. For the same beam conditions the bunch length was measured with the streak camera. The results from both methods are in reasonable agreement as shown in Table 3.

Table 3. comparison of bunch length measurements

bunch compressor setting	A	B
fwhm streak camera [ps]	7.1	5.2
fwhm coh. radiation [ps]	6.4	5.6

8. CTF2

Presently the successor of the CTF, CTF2 is in its installation phase at CERN [22]. The objectives of this experiment are:

1. To demonstrate the feasibility of the CLIC two-beam accelerator scheme and its 30 GHz technology.
2. To build and test prototypes of CLIC modules. A CLIC module, which is a building block for the CLIC accelerator, consists mainly of accelerating structures for the main beam, transfer structures to extract 30 GHz power from the drive beam, and the support girders with their active alignment system.
3. To study the dynamics of a high charge, multibunch drive beam.
4. To test the active alignment system with in a realistic accelerator environment.
5. To test CLIC beam monitoring.

A sketch of CTF Phase II is shown in Figure 4. The drive beam of 48 bunches with 10 cm bunch spacing and a total charge of 640 nC is generated in a 2½ cell RF-gun [23] and accelerated by two travelling-wave structures optimized for high charge acceleration (HCS1 and HCS2). The design and construction of these structures is conducted by LAL/Orsay [24]. To compensate for the very high beam loading, the structures run at frequencies slightly different from the bunch repetition frequency. The frequencies and phases are chosen so that

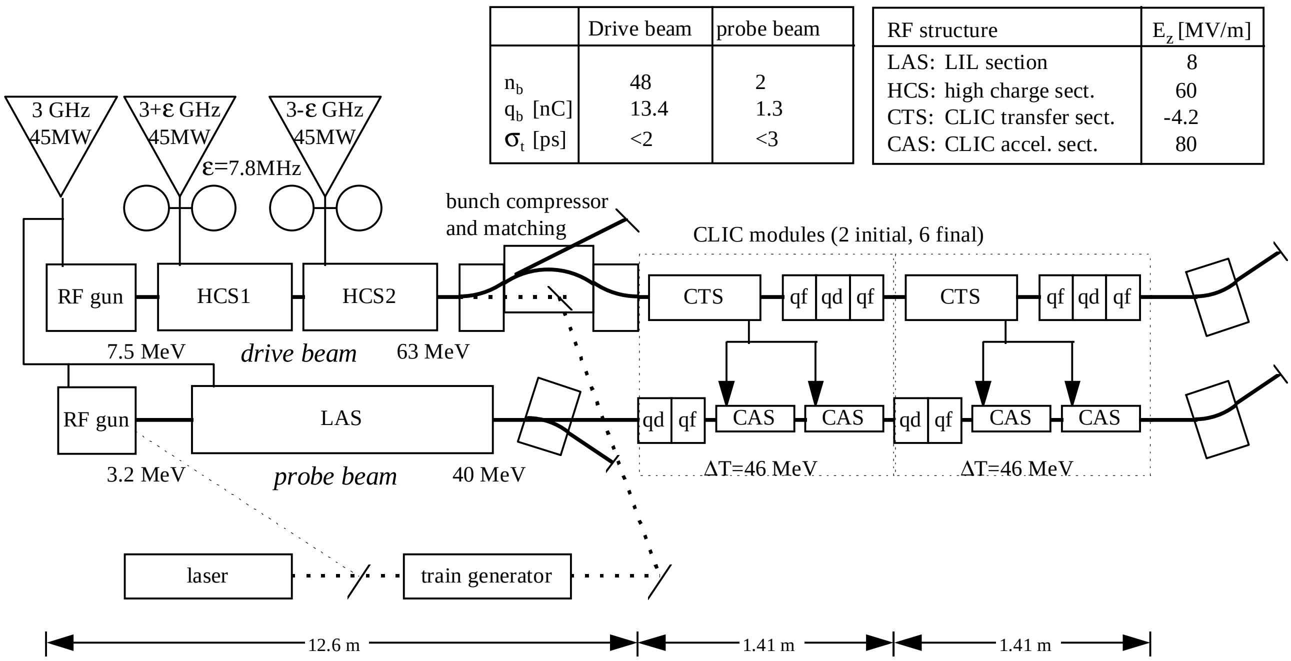

Figure 4. Sketch of CTF2. BPM's and focusing is omitted, except of the quadrupoles in the CLIC modules.

the phase change from bunch to bunch compensates for the field reduction due to beam loading. This scheme for beam loading compensation is similar to the one already tested at KEK [25]. After acceleration, the beam passes through a transverse matching section with a total of 12 quadrupoles (not shown in Figure 4) and the three bending magnets of the magnetic chicane for bunch compression, before it is injected into the string of CLIC modules. The probe beam is generated in the same 1½-cell RF Gun as used in CTF before, but without the 4-cell booster. Afterwards it is accelerated in a 4.5 m traveling-wave structure (LAS), which is of the same type as the structures used in the LEP injector linac. Downstream of this structure 6 quadrupoles (not shown) are used to match the beam into the CLIC modules. The probe beam charge will be very low in the beginning since no second load lock system for the probe beam gun will be available, thus prohibiting the use of high QE photocathodes. However, the main issues in the beginning will be the measurement of energy gain and stability, for which a single low charge bunch is sufficient. Later on the charge for the probe beam will be raised to 1.3nC (the nominal CLIC main beam bunch charge) and a second bunch will be introduced to study beamloading and wakefield effects in the CAS. The 30 GHz modules will be as similar as possible to those foreseen for CLIC. However, due to the low beam energies in CTF, the density of focusing elements has to be much higher than in CLIC.

The 3 GHz part of the probe beam and the drive beam gun are installed and ready for testing. The 3 GHz part of the drive beam is almost completed, except for the HCS structures which are expected to be ready later this year. The first 30 GHz module is planned to be installed at the end of 1996. It is foreseen to install a total of six 30 GHz modules until 1999, which will give a final probe beam energy of 320 MeV. The total 30 GHz RF power extracted from the drive beam will then be 480 MW. In order to improve the drive beam quality a new 2½ cell RF-Gun with reduced beam loading is presently under construction [26].

REFERENCES

[1] H.H. Braun and 10 coauthors, “CLIC-a Compact and Efficient High Energy Linear Collider,” Proc. of the Part. Acc. Conf., Dallas 1995

[2] Y. Baconnier and 9 coauthors, “The CERN Linear Collider Test Facility,” Proc. of the Lin. Acc. Conf., Los Alamos 1990

[3] Y. Baconnier and 13 coauthors, “The CERN Linear Collider Test Facility,” Proc. of the Lin. Acc. Conf., Ottawa, 1992

[4] J.P. Delahaye, J.H.B. Madsen, A. Riche, L. Rinolfi, “Present Status and Future of the CTF,” Nucl. Inst. and Meth., A340, p.139, 1994

[5] R.Bossart and 12 coauthors, “Performances obtained with the CERN Linear Collider Test Facility,” Proc. of the European Part. Acc. Conf., London, 1994

[6] R. Bossart and 12 coauthors, “CTF Developments and Results,” Proc. of the Part. Acc. Conf., Dallas 1995

[7] H.H. Braun for the CTF-Team, “Recent Results of the CLIC Test Facility,” Proc. of Microbunches workshop, Brookhaven, 1995.

[8] R. Bossart, J.-C. Godot, S. Lütgert, “Modular Electron Gun Consisting of Two RF Sections and an Intermediate Focusing Solenoid,” Nucl. Inst. and Meth., A340, p.157, 1994

[9] S. Schreiber, “The Synchro Laser System for the CLIC Test Facility,” Proc. of the workshop Lasers for RF-Guns, Anaheim, 1994

[10] K. Aulenbacher, H.H. Braun, F. Chautard, R. Corsini, J.H.B. Madsen, L. Rinolfi, “Bunch Compressor Performances in the CLIC Test Facility,” this conference

[11] G. Bienvenu and P. Brunet, “Dark Current under Low and High Electric Field,” Proc. of the Europ. Part. Acc. Conf., London, 1994

[12] S. Battisti, “Measurement of Short Bunch Length in the CTF,” CLIC Note 211,1993

[13] P.M. Devlin-Hill, “Pulse Train Generation at 209 nm,” Nucl. Inst. and Meth., A340, p.164, 1994

[14] G. Suberlucq, "Photocathodes en Iodure de Césium utilisées à fort courant", CLIC Note 162, 1992

[15] G. Suberlucq, "Développement et Production de Photocathodes pour le CLIC Test Facility", CLIC Note 299, 1996

[16] K. Aulenbacher, R. Bossart, H.H. Braun, J. Clendenin, J.P. Delahaye, J.H.B. Madsen, G. Mulhollan, J. Sheppard, G. Suberlucq and H. Tang, “RF Guns and the Production of Polarized Electrons,” CLIC-Note 303 and NLC-Note 20, 1996

[17] K. Batchelor, H. Kirk, J. Sheehan and M.Woodle, “Development of a high brightness electron gun for the Accelerator Test Facility at BNL,” Proc. of the Europ. Part. Acc. Conf., Rome 1988

[18] P.B. Wilson, “Linear Accelerators for TeV Colliders,” Proc. of the Workshop on Laser Acc. of Part., Los Angeles, 1985

[19] J. Sladen, I. Wilson, W. Wuensch, “CLIC Beam Position Monitor Tests,” this conference

[20] R. Lorenz, “Beam Position Measurement in the TESLA Test Facility,” Proc. of the Part. Acc. Conf., Dallas 1995

[21] K. Hanke, V. Schlott, K. Aulenbacher, H.H. Braun, F. Chautard, “Beam Diagnostics using Coherent Transition Radiation at the CTF,” CLIC Note 298, 1996

[22] The CLIC Study Group, “CTF2 Design Report,” CLIC Note 304, 1996

[23] R. Bossart, H.H. Braun, M. Dehler, J.-C. Godot, “A 3 GHz Photoelectron Gun for High Beam Intensity,” Proc. FEL Conf., New York 1995

[24] G. Bienvenu, J. Gao, “A Double High Current, High Gradient Electrons Accelerating Structure,” this conference

[25] “ATF Design and Study Report,” KEK 1995

[26] R. Bossart, M. Dehler, “Design of a RF Gun for Heavy Beam Loading,” this conference