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**PRESENT STATUS AND FUTURE OF THE
CERN LINEAR COLLIDER TEST FACILITY (CTF)**

J.P. Delahaye, J.H.B. Madsen, A. Riche, L. Rinolfi

Abstract

The CLIC Test Facility (CTF) consists of an RF gun equipped with a laser driven photocathode and operated at 3 GHz. The RF and the picosecond laser pulse are synchronised with a timing jitter of less than 1 ps. The 4.5 MeV/c electron beam at the gun exit is accelerated to 60 MeV/c and then passes a prototype CLIC structure which generates 30 GHz power. A train of eight bunches with 333 ps intervals is used for high power generation. Results, improvements to and extensions of the CTF are described.

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PRESENT STATUS AND FUTURE OF THE CERN LINEAR COLLIDER TEST FACILITY (CTF)

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The CLIC Test Facility (CTF) consists of an RF gun equipped with a laser driven photocathode and operated at 3 GHz. The RF and the picosecond laser pulse are synchronised with a timing jitter of less than 1 ps. The 4.5 MeV/c electron beam at the gun exit is accelerated to 60 MeV/c and then passes a prototype CLIC structure which generates 30 GHz power. A train of eight bunches with 333 ps intervals is used for high power generation. Results, improvements to and extensions of the CTF are described.

INTRODUCTION

The main objective of the CTF is to generate the 30 GHz power (60 MW) required to produce in a CLIC structure a field of 80 MV/m. Due to the high charge a single bunch does not fulfil the requirement and a train of bunches at 333 ps intervals is used. For proper excitation of the CLIC travelling wave structure at 30 GHz, the e- pulse length should be equal to or less than 12 ps (FWHH). To get such short pulses, either the laser pulse has to be as short as 12 ps or a magnetic bunch compressor has to be inserted.

1. THE CTF

A general description of the CTF is given in reference [1]. Beam dynamics simulations in the RF gun, based on PARMELA code, has been performed [2]. Studies of the dynamics in the line are given in [3]. The results and experience with the facility using a 8 ns long laser pulse are reported in [4].

1.1 The laser system

The work discussed here was done with a laser system [5] giving pulses synchronised with the RF in the gun. The main laser parameters are:

- wavelength 209 nm
- pulse width $15 \text{ ps} \pm 2 \text{ ps}$ FWHH
- energy on cathode 1 to 10 μJ max.
- energy jitter at best $\pm 10\%$, often worse
- repetition rate 10Hz

1.2 The train generator

In order to reach the requested charge for CTF, it is necessary to create a train of bunches. The aim is to get 72 nC into the CLIC structure. For this reason a train of 8 bunches was generated. In a first test in December 1992, an optical set-up allowed the creation of eight laser pulses with different trajectories, all of them focused on the photo-cathode. The results are presented below. A second type of pulse generator was tested in May 1993 [6]. An optical set-up based on the polarised light allows the creation of eight laser pulses on the same trajectory. The laser transmission efficiency is around 40% between the output of the pulse train generator and the photo-cathode.

1.3 The RF gun

The 1 1/2 cell gun [7] is essentially the BNL gun design adapted to 2.99855 GHz. The main gun parameters are :

Cathode gradient:	100 MV/m.
RF input pulse:	2.5 μs at 10 Hz
Momentum:	4.5 MeV/c
Temperature:	30°C
Vacuum:	in the gun with RF of the order of 10^{-9} Torr.

1.4 The photo-cathodes

Several types of photo-cathodes have been tested on a dedicated test line with a DC gun [8]. In the CTF, only three types are used :

- a) Caesium iodide (CsI). For a longer life time and installation in ambient air, this type of alkaline cathode is well suited for our experiment. Due to its high work function ($\phi_S = 6.4$ eV), this cathode requires a short laser wavelength. We use a fifth harmonic at 209 nm. The quantum efficiency is roughly 3%.
- b) Copper (Cu). It provides the relation e- bunch charge versus RF phase as expected and avoids all complicated phenomena related to CsI. Unfortunately the quantum efficiency is only $3 \cdot 10^{-4}$.
- c) At the end of 1992, Caesium telluride (Cs_2Te) a new type of photo-cathode was tried. The equipment for transferring the photo-cathode under vacuum from the preparation chamber to the RF gun was not yet available and the photo-cathode was exposed to air briefly. As expected a factor twenty was lost for the quantum efficiency. From 6% in the cathode laboratory, the quantum efficiency falls to 0.3% in the CTF.

1.5 The beam line and RF layouts

The CTF beam line has been modified in 1992 by placing the gun on-axis 1.3 m upstream of the accelerating section. The laser beam is deflected with a mirror in the vacuum chamber to the photo - cathode.

A manipulator for exchanging the gun cathodes under vacuum facilitates the use of the gun by avoiding bakeouts at 150°C. The electron bunch from the gun is accelerated with a travelling wave structure which is a spare for the LEP Injector Linac (LIL). The LIL Accelerating Structure (LAS) is fed from the same modulator as the gun and accelerates the beam up to 60 MeV/c. The RF gun, the beam focusing elements, the CLIC 30 GHz structure (TRS) and the beam diagnostics are presented on a schematic layout in Fig. 1.

The beam instrumentation is the following:

- UMA's: beam intensity and position detectors.
- TCM's: transition and Cerenkov light monitors coupled with a streak camera.
- MTV's: scintillator screens show the presence of the beam and the spot sizes. The dark current is visible when the laser beam is switched off.
- FCM: Faraday cup measures the whole beam charge.

The focusing elements are one solenoid (SNF 350) upstream from LAS and three quadrupoles downstream from LAS. The triplet allows us to focus the beam into TRS. The spectrometer (BHZ 430) drives the beam onto the screen (MTV 440) and onto the detector (TCM 435). Reference [9] gives the parameter list of the CTF.

2. SIMULATIONS

Since the main objective is to generate the 30 GHz power in a CLIC structure, an analysis of the 30 GHz generation has been performed [10] [11]. The requested beam characteristics at the TRS are 9 nC per pulse and 12 ps (FWHH). Assuming a transmission efficiency of 82% between the gun and the TRS, implies a charge of 11 nC at the gun exit.

Simulations show that the bunch is compressed between the photo-cathode and the gun exit. In order to be close to the experimental laser pulse length, a value of 19 ps (FWHH) was taken for simulations. It corresponds to a $\sigma_t = 8$ ps. The PARMELA code was used to simulate beam dynamics in the RF gun. Table 1 provides typical CTF conditions.

Fig. 2 gives the variations of γ , the energy spread, the bunch length, the emittance and the peak current versus the RF phase for both electric fields 60 MV/m and 100 MV/m.

Simulations [12] show that the bunch parameters depend on the RF phase ϕ_0 . The latter is defined as the phase the centre of the laser pulse hits the cathode minus the phase the electric field is zero on the cathode. For an accelerating field of 100 MV/m, the maximum energy is obtained at $\phi_0 = 45^\circ$. It provides a bunch compression in the gun of $15 \text{ ps} / 19 \text{ ps} = 0.8$. Nevertheless a greater bunch compression can be achieved with $\phi_0 = 20^\circ$ which gives a factor 0.64. The bunch

is compressed from 19 ps down to 12 ps (FWHH). The beam dynamics downstream from the RF gun is simulated with a TRANSPORT code where the space charge is included. Fig. 3 gives the beam envelopes from the gun to the TRS for a charge of 3.5 nC . Initial conditions are given in Table 1 at the gun exit, except for the charge. As shown on the figure, the beam is well focalised into the TRS (ϕ 4 mm).

Another simulation without space charge, but taking into account the beam loading in the gun exit and in the LAS is given on Fig. 4 for a bunch charge of 10 nC .

3. RESULTS

3.1. Single bunch

To produce short, high intensity e-bunches, CsI cathodes are used. The e-emission of CsI depends on the laser energy density on the cathode surface and we cannot assume - as is done in the simulations - that the electrons are emitted promptly. Therefore, copper (Cu) cathodes were used for comparing measurements with simulations.

Fig. 5 shows the charge measured at the gun exit (UMA385) versus the RF phase for $E_0 = 70$ MV/m. The result of a simulation is also plotted. The simulations done with PARMELA are in good agreement with the charge measured at the gun exit.

There are no beam diagnostics to measure the beam parameters at the gun exit except the bunch charge. The gun was put as near as possible to the accelerating section (LAS) in order to have limited bunch blow up due to space charge forces. Bunch length and transverse dimensions are measured after acceleration to 60 MeV/c. Low bunch charges are accelerated by LAS with small losses.

Example of an experimental result for a single bunch :

- downstream gun (UMA385) 3.3 nC (100%)
- downstream LAS (UMA406) 3.1 nC (94%)
- downstream TRS (UMA455) 2.7 nC (82%)

The beam transmission as function of the RF phase in the gun for low charges is shown on Fig. 6. In this case the transmission is 86 % for the highest charge transmitted - 1.9 nC -. The sharp drop in transmission at phases above 60° (on the graph) is probably due to the increase in energy spread and emittance as

can be inferred from the simulation . If the laser energy on the photo-cathode is increased, more charge is produced but the transmission becomes lower. The highest transmission efficiency is : 74 % to UMA 406 and 41 % to UMA 455 (Fig. 7) .

Fig. 7 also shows the increase of the bunch length with RF phase. PARMELA simulations predict a bunch shortening at low phases at the gun exit. However, this has not been measured at this place (lack of instrumentation) but an effect of bunch shortening has been observed at 60 MeV/c.

Fig. 8 shows the laser pulse measured with a streak camera. The lasers were optimized to obtain 16 ps (FWHH).

Fig. 9 shows the electron pulse measured with a streak camera, using the transition detector at 60 MeV/c. The length is 14 ps (FWHH) at low phase. Pulse lengths are measured with the maximum camera sensitivity. Then the full scale is 493 ps and the resolution of the streak camera is ± 2 ps.

3.2 Train of 8 bunches

The required single bunch charge cannot be obtained from the gun and therefore a train of eight bunches was prepared in December 1992. The train was created by splitting one laser pulse into eight pulses separated by 333 ps. The total laser energy on the photo-cathode was 10 μ J. However, CsI saturates and consequently the train charge is roughly 2/3 of the sum of the charge of each bunch alone. The best result for the transmission efficiency was:

UMA 385: 14.3 nC (100 %).

UMA 406: 13.7 nC (96 %)

UMA 455: 11.3 nC (79 %)

Fig. 10 shows the train of bunches upstream from the TRS measured with the streak camera. The highest charge does not generate the maximum 30 GHz power. By decreasing the RF phase, i.e. providing shorter bunches, more power was obtained. The transmission efficiency was:

UMA 385: 12.9 nC (100%).

UMA 406: 12.6 nC (98%)

UMA 455: 6.8 nC (53%)

The result was 2 MW at 30 GHz.

Finally, the laser energy was pushed up to 16 μJ on the photo-cathode for the eight bunches. The transmission efficiency became :

UMA 385: 20.6 nC (100%).

UMA 406: 18.2 nC (88%)

UMA 455: 12.1 nC (59%)

The result was 2.7 MW at 30 GHz.

4. FUTURE

To obtain more 30 GHz power the aim is to shorten the laser pulse length to 7 ps FWHH and to increase the energy per pulse.

Shortening the e- bunch from the gun with a magnetic compressor is under study.

Later this year we expect to complete a system for transferring the cathode under vacuum from the preparation chamber to the gun. We can then use Cs_2Te cathodes and use the laser at 262 nm. With this wavelength, it will be easy to obtain more energy on the cathode and a better laser stability. It would then be possible to work with a laser train of sixteen pulses.

To improve the beam quality four more accelerating cells (Fig. 11) will be attached to the present 1 1/2 cell gun [13].

The beam momentum at the gun exit will become about 11 MeV/c if the required 3 GHz power is provided. Since the beam will be accelerated to a higher energy by LAS then , the energy spread from beam loading will be smaller. A second klystron / modulator set is under construction but it will become available next year only. In the mean time we will use an RF pulse compressor to enhance the RF power.

To test the acceleration in a 30 GHz CLIC structure a probe beam is under construction .

The 30 GHz from the TRS 1 is fed into a similar structure - TRS 2 - located in parallel and at 66 cm. When the first bunch of the train , after a 180° bend, arrives at TRS 2 then the 30 GHz electric field has built up and the bunch is accelerated. The energy gain is measured with the downstream spectrometer. The running-in of this extension to the CTF is foreseen at the end of 1993.

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TABLE 1
Typical CTF operating conditions

<u>Laser pulse at the gun</u>		
Wavelength	λ_l (nm)	209
Energy	E_l (μ J)	4
Spot size	σ_{ro} (mm)	3
Duration	σ_{to} (ps)	8
Nb of micropulses	n_p	8
<u>Photo-cathode</u>		
Quantum efficiency	QE (%)	2
Emitted charge	Q_o (nC)	12
Peak current density	J_o (A/cm ²)	1060
Diameter	d (mm)	8
<u>RF gun</u>		
Max. cathode E field	E_o (MV/m)	100
Initial phase	ϕ_o (deg)	45
RF power	P_{rf} (MW)	5.85
<u>Bunch at the gun exit</u>		
Momentum	p (Mev/c)	4.5
Energy dispersion	σ_E (%)	0.8
Length	σ_z (mm)	1.91
Size	σ_r (mm)	4.4
Charge	Q_f (nC)	11
Peak current	$\hat{I}$ (A)	630
Norm. emittance	ϵ_n (mm.mrad)	53
Divergence	$\sigma_{r'}$ (mrad)	28
Number of bunches	n_b	8

FIGURE CAPTIONS

Fig. 1. Layout of CTF beam line

Fig. 2. Beam characteristics at the gun exit

Fig. 3. Beam envelopes from the gun to the TRS ($Q = 3.5 \text{ nC}$)
(With space charge and without beam loading)

Fig. 4. Beam envelopes from the gun to the TRS ($Q = 10 \text{ nC}$)
(Without space charge and with beam loading)

Fig. 5. Charge versus RF phase (Cu) (1 nC)— simulations measurements

Fig. 6. Charge versus RF phase (CsI) [low charge]

Fig. 7. Charge and pulse length versus RF phase (CsI)[high charge].

Fig. 8. Laser pulse ($\lambda = 209 \text{ nm}$ $W = 20 \text{ }\mu\text{J}$)

Fig. 9. Electron pulse ($Q = 2 \text{ nC}$)

Fig. 10. Train of 8 bunches (TCM 445)

Fig. 11. New gun assembly

Figure 1 Layout of CTF beam

Beam characteristics at the gun exit

Figure 2 a

Initial phase [deg.]

Beam characteristics at the gun exit

Initial phase [deg]

Figure 2 b

Beam characteristics at the gun exit

Figure 2 c

Beam characteristics at the gun exit

Beam characteristics at the gun exit

Figure 2. a

Beam envelopes from the gun to the TRS ($Q = 3.5$ nC)
(With space charge and without beam loading)

Figure 3

Beam envelopes from the gun to the TRS ($Q = 10$ nC)
(Without space charge and with beam loading)

Figure 4

Charge versus RF phase — simulations measurements
(Cu) (1nC)

Figure 5

Charge versus RF phase ($C_s I$) (low charge)

Figure 6

+UMA 385 +UMA 406 *UMA 455 -TCM 445 (FWHH)

Charge and pulse length versus RF phase
(C.L.) (high charge)

Laser pulse $\lambda = 209 \text{ nm}$; $W = 20 \mu\text{J}$

Figure 8

Electron pulse ($Q = 2 \text{ nC}$)

Figure 9

Figure 10 Train of 8 bunches (TCM 445)

New gun assembly

Figure 11