CERN – European Organization for Nuclear Research
European Laboratory for Particle Physics

CTF3 Note 022 (Tech.)
(RF Deflectors)
PS/AE Note 2001-007

RF POWER TESTING OF THE TWO RF DEFLECTORS FOR THE PRELIMINARY PHASE OF THE NEW CLIC TEST FACILITY (CTF3)

R. Corsini, G. Rossat, P. Royer

Abstract

In this note, we describe the recent RF power tests performed on the two RF deflectors which will be used for injection during the Preliminary Phase of the new CLIC Test Facility (CTF3). The injection principle for the bunch frequency multiplication is presented, as well as the RF deflectors requirements for the Preliminary Phase. The conditioning process and the high-power testing of the two cavities are described, and the performances are reported.

Geneva, Switzerland
18 June 2001

1 INTRODUCTION

The new Compact Linear Collider (CLIC) Test Facility (CTF3) [1, 2] is being built at CERN in the area of the former LEP Pre-Injector (LPI) complex. The aim of this facility is to demonstrate the feasibility of the CLIC RF power source, based on electron pulse compression and frequency multiplication, by generating a 30 GHz RF source [3]. The construction of CTF3 is scheduled in stages over five years. As a preliminary phase [4], to begin in September 2001, it is planned to test the bunch combination scheme at low charge [5], making use of the existing LPI components.

In order to achieve frequency multiplication, the bunch trains are injected into the isochronous ring using two RF deflectors instead of fast injection kickers. The RF deflectors are travelling wave iris-loaded structures. One of them has been used in the past to measure the bunch length in LIL [6], but both needed to be tested at the required power of about 7 MW to allow a nominal deflection angle of 4.5 mrad at injection.

For that purpose, an experimental set-up was installed inside the CLIC Test Facility 2 (CTF2) area. The experiment allowed to test the two cavities beyond the required level of power, and to check some crucial operational parameters such as the transmission band in frequency and the temperature dependence on the repetition rate.

This note describes the RF deflectors requirements for the CTF3 Preliminary Phase and gives the results obtained for the various tests performed on the two cavities.

2 RF DEFLECTORS REQUIREMENTS FOR THE CTF3 PRELIMINARY PHASE

2.1 Injection Principle

The frequency multiplication process, which will be demonstrated during the Preliminary Phase of CTF3, relies on the use of two RF deflectors to inject bunch trains into an isochronous ring. The two RF deflectors are placed in the ring with a betatron phase advance of π between them, so that they produce a time-dependent closed bump. For the CTF3 experiment, the goal is to interleave three to five pulses (each pulse is composed of 20 bunches), thus achieving a frequency multiplication by a factor three to five. Figure 1 shows the case of a bunch combination factor four. The incoming bunch trains experience the maximum transverse deflection to be injected onto the equilibrium orbit, whereas the circulating bunch trains are either not kicked (zero crossing of the deflecting field at the second turn) or kicked on the opposite side of the injection septum (third turn).

2.2 RF deflectors requirements

The required angle for injection is given by both the geometry of the injection region and the optics. If μ_x is the horizontal phase advance between the deflector and the septum, if β_s and β_d are the values of the horizontal β-function at the septum and the deflector locations, then the angular kick is

$$\theta = \frac{x}{\sqrt{\beta_s \beta_d} \sin \mu_x} \tag{1}$$

where x is the distance between the centre of the injected beam and the centre of the machine aperture at the location of the septum. Given the geometry of the vacuum chamber in this region, and taking into account the radius of the chamber (around 47 mm) and the septum thickness (around 10 mm), the distance x must be larger than 57 mm. Using equation (1) for the reference optics of the isochronous ring [4], the required deflection angle is of the order of 4-5 mrad.

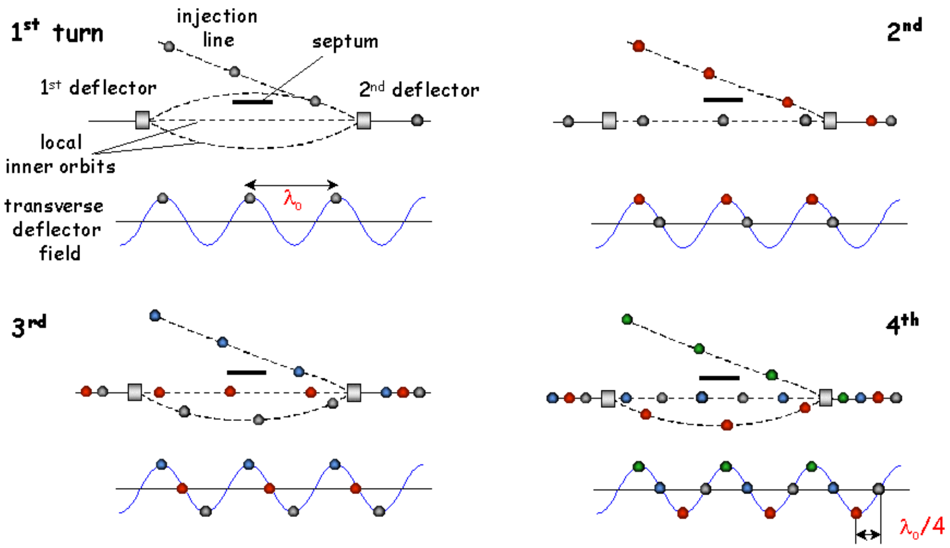

Figure 1: Schematic description of the injection process using RF deflectors, for a combination factor four.

For a frequency multiplication factor five, the pulse train is composed of five pulses spaced by 420 ns (corresponding to the ring circumference) and with a maximum length of 10 ns for each pulse. The whole electron pulse train is injected using a single RF pulse. The filling time of the cavities being of the order of 3 ns, the total RF pulse length needed in the deflectors to inject the whole pulse train using a single RF pulse is about 2.5 μs.

For the CTF3 Preliminary Phase, the RF deflectors are short, travelling wave, iris-loaded structures for which the fundamental mode is a deflecting mode, with a phase advance of $\pi/2$ per cell and a negative group velocity [7]. Each deflector has an overall length of 27 cm, with six regular cells (and the two couplers) and an iris diameter of 2.3 cm (2.1 cm in the coupler cells). In this type of cavity, the deflecting force is uniform in strength and direction over the aperture [8]. The voltage attenuation along the structure is characterized by the constant α and the deflection angle is given by

$$\phi = \frac{\sqrt{ZP}}{E}\left(\frac{1-e^{-\alpha L}}{\alpha}\right) \tag{2}$$

where P is the input power (in MW), L the total active length (in m), E the electron beam momentum (in MeV/c), and Z the series impedance (in Ω.m^{-2}) defined as

$$Z = \frac{R}{Q}\frac{2\pi}{\lambda_0}\frac{1}{\beta_g} \tag{3}$$

where R is the shunt impedance, λ_0 the RF wavelength, Q the quality factor, and β_g the normalized group velocity.

Using the set of parameters of Table 1, Equation (2) gives the simple law for the deflection angle ϕ in mrad

$$\phi = 585.5\frac{\sqrt{P}}{E} \tag{4}$$

where P is the input power in MW and E the beam momentum in MeV/c (the two couplers are considered as two active cells for the transverse deflection). At the nominal beam momentum of 350 MeV/c, a reference injection angle of 4.5 mrad is then found for an input power of 7 MW.

Parameter	Symbol	Value	Unit
Frequency	ν	2.998	GHz
Number of cells	N_c	6+2	
Dephasing/cell		$\pi/2$	
Opening	$2a$	2.3	cm
Diameter	$2b$	11.9	cm
Cell length	d	2.5	cm
Active length	L	20	cm
Overall length	L_d	27	cm
Normalized group velocity	β_g	-0.0189	
Quality-factor	Q	1.281×10^4	
Shunt impedance	R	3.389×10^7	$\Omega.\mathrm{m}^{-1}$
Series impedance	Z	8.797×10^6	$\Omega.\mathrm{m}^{-2}$
Voltage attenuation	α	0.13	m^{-1}
Beam energy	E	350	MeV
Input power	P	7	MW
Deflection angle	ϕ	4.5	mrad

Table 1: Main parameters of the RF deflectors [9].

However, for the cavity used in 1985 to make bunch length measurements in LIL [6] (this cavity is referred to as the first cavity in the rest of the note, the other one being the second cavity), the deflection has been calibrated and the following experimental law was found

$$\phi = 813.6\frac{\sqrt{P}}{E} \tag{5}$$

with the same conventions as before. In that case, the required power to achieve the same deflection angle is reduced to 3.7 MW. The difference is rather important and a new calibration will have to be made with the beam during the commissioning of CTF3. The theoretical values, based on the geometry of the cavity, are more pessimistic than the experimental ones and are chosen as the reference values in this note: an input power of 7 MW is needed for a nominal deflection angle of 4.5 mrad for 350 MeV/c electrons. The resonant frequency is 2.99855 GHz and the RF pulse length is 2.5 μs.

3 EXPERIMENTAL SET-UP

The experimental set-up shown in Figure 2 was installed inside the CTF2 tunnel for the RF conditioning of the two cavities. Figure 3 is a picture of the test stand.

The 30 MW klystron-modulator MDK29, operating at 3 GHz, is used to feed the cavity. It is located in the gallery upstairs the test stand and around 60 meters of wave guides are necessary to bring the RF power from the klystron exit to the cavity. The wave guides are filled with SF_6 gas up to the entrance of the cavity, where a water-cooled window separates the gas in the wave guides from the vacuum in the cavity. The temperature in the wave guides is stabilized by a water cooling system along the guides. However, no such cooling equipment is available on the cavity itself.

The bake-out process uses thermal strips winded around the cavity. The temperature follows a programmed ramp up to 150° C. The pressure in the baked cavity, without RF power, is kept to a level close to 1.10^{-8} mbar using primary, turbo and ion pumps. The vacuum level is constantly recorded to monitor the breakdowns in the cavity.

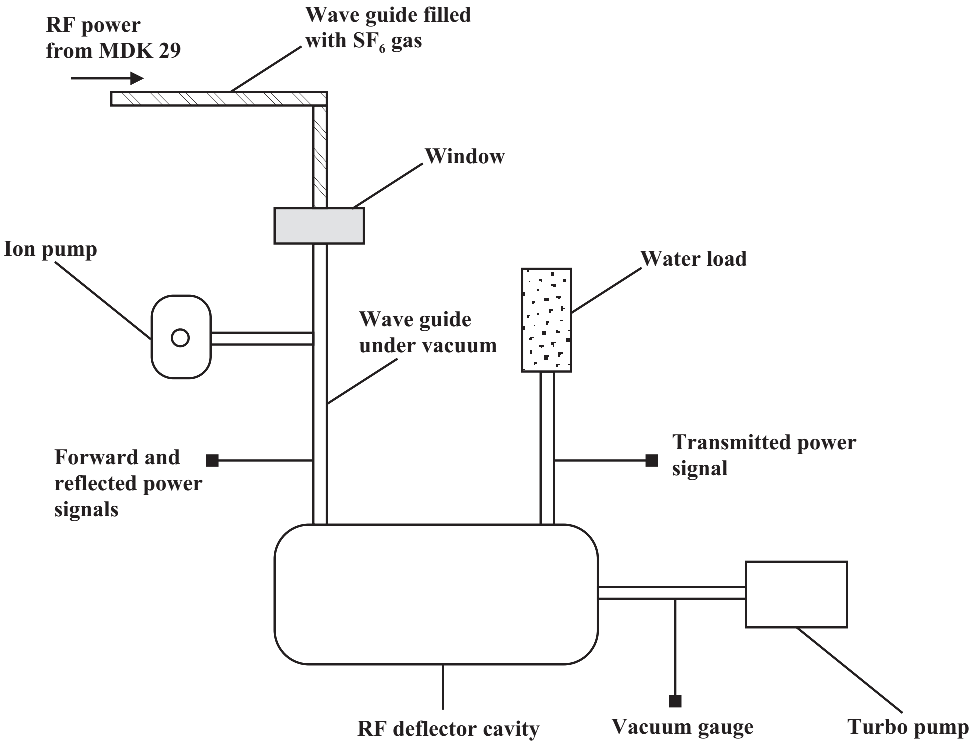

Figure 2: Schematic layout of the test stand.

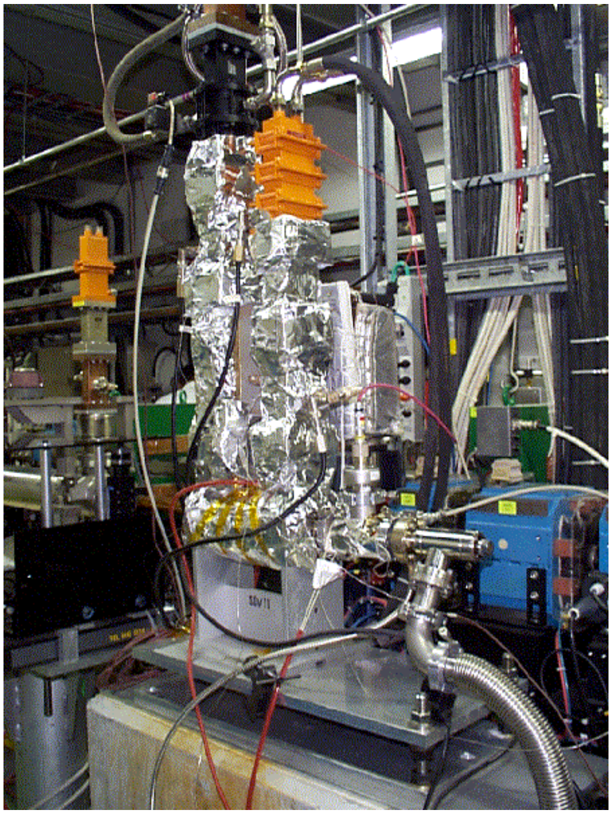

Figure 3: Picture of the test stand inside the CTF2 tunnel.

There are two measurement points for the forward and reflected power: the signals can be read either directly at the entrance of the cavity or at the exit of the klystron. Attention must be paid to the fact that the amount of forward power read on the peak power meter at the exit of the klystron is much higher than than amount of power effectively received at the entrance of the cavity, because of the attenuation along the 60 meters of wave guides. The typical attenuation in the wave guides is of the order of 0.02 dB per meter. The overall absolute error on the power is estimated to be less than 10%.

Fast interlocks for the gas pressure in the wave guides, for the vacuum pressure and for the klystron reflected power are added to the usual interlocks for protection of equipment and personnel.

At the exit of the cavity, the transmitted power is measured and then absorbed into a water-cooled load.

4 EXPERIMENTAL PROCESS AND RESULTS

4.1 High power tests

For the high power tests, the repetition rate is fixed to 5 Hz and the klystron-modulator frequency is 2998.5 MHz. The pulse length is first set to 1.2 μs and the forward RF power is manually increased from a few mega-watts to more than 10 MW. A few RF breakdowns are observed. If the pressure goes above a reasonable level, or in case of many consecutive breakdowns, the input power is reduced so that the vacuum can recover. Then, the pulse length is set to its nominal value of 2.5 μs and the process is repeated. Figure 4 shows a typical recording of the vacuum level where each spike results from a sudden rise of pressure due to RF breakdowns.

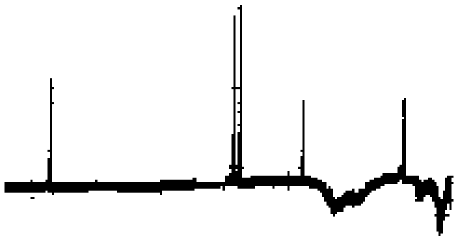

Figure 4: Typical vacuum recording showing RF breakdowns.

At nominal pulse length, the first cavity was conditioned up to 18 MW at the exit of the klystron (roughly 13.5 MW at the entrance of the cavity) and the second cavity up to 17 MW at the exit of the klystron (roughly 13 MW at the entrance of the cavity). Both cavities have a common behaviour, although more breakdowns are observed on the second cavity at high power (beyond 10 MW). However, the frequency of gas bursts rapidly decreases with the running time. The conditioning process is stopped when the cavity has run for at least a few hours with very few breakdowns. This process typically takes a few days for each cavity. Reliability is expected to be further increased during operation in the machine. These levels of power are far beyond the requirements for the use of these deflectors in the CTF3 Preliminary Phase and provide us with a large safety margin for operation.

The forward, transmitted and reflected power signals are as expected for this type of cavity. Figure 5 shows the forward and reflected power signals measured at the entrance of the cavity for the nominal pulse length and power. The spikes at both ends of the reflected signals appear during the rising and falling time of the forward power because a large band of frequencies is covered and some of these frequencies are not in the transmission band of the cavity. The asymmetry in the height of these spikes between the beginning and the end of the reflected signal could result from an asymmetry in the behaviour of the forward power signal during rising and falling time.

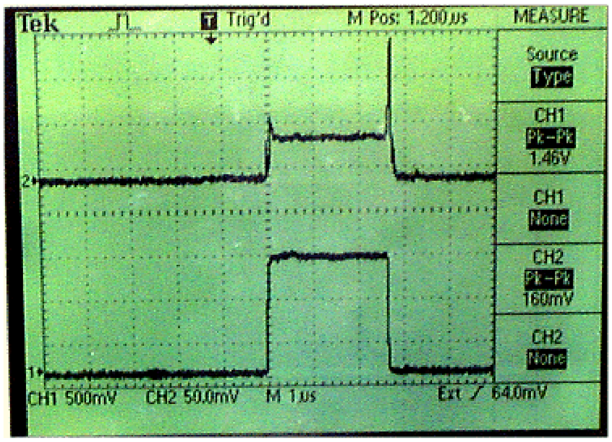

Figure 5: Forward power signal (bottom) and reflected power signal (top) at the entrance of the cavity for the nominal pulse length and power.

Figure 6 shows the forward and transmitted power signals measured at the entrance of the cavity for the nominal pulse length and power. As expected, the shape of the transmitted signal is the same as the forward signal.

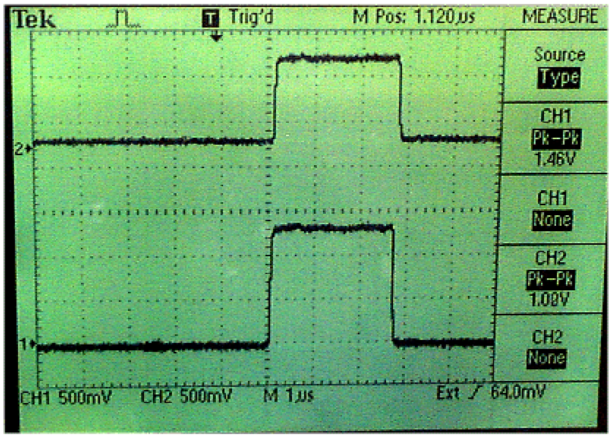

Figure 6: Forward power signal (bottom) and transmitted power signal (top) at the entrance of the cavity for the nominal pulse length and power.

To be noticed is the difference between the reflected power signals measured at the entrance of the cavity or at the exit of the klystron. The signal read at the entrance of the cavity is much cleaner, though attenuated by 60 meter long cables, than the signal read at the exit of the klystron where reflections and delays occur in the directional couplers along the wave guides. Figure 7 illustrates this difference between the reflected power signals measured at the entrance of the cavity and at the exit of the klystron for the nominal pulse length and power.

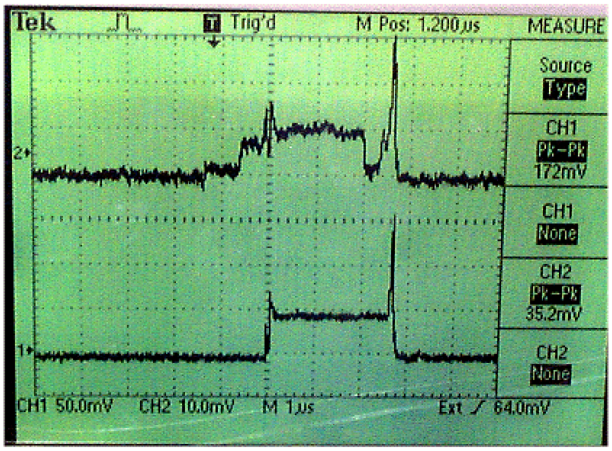

Figure 7: reflected power signals measured at the entrance of the cavity (bottom) and at the exit of the klystron (top) for the nominal pulse length and power.

During the experiment, the pressure increased from the 10^{-8} mbar scale to the 10^{-7} mbar scale. However, for those tests, no optimization of the experimental set-up was carried out from the point of view of the vacuum assembly.

4.2 Temperature dependence on the repetition rate

During the operation of the CTF3 Preliminary Phase, the repetition rate can vary from 5 Hz to 50 Hz, but some beam diagnostics require a given repetition rate. For instance, the streak camera used to monitor the synchrotron light emission can only run at 5 Hz, whereas the use of the wire beam scanners in the ring would rather need a higher frequency. It is therefore expected to vary the repetition rate during the commissioning phase of CTF3. To ensure a constant resonant frequency at various repetition rates, some water cooling is needed to stabilize the temperature of the cavity. Therefore, monitoring the temperature at various repetition rates helps better estimate the cooling requirements.

For that purpose, a thermo-couple was installed on the second cavity to monitor the temperature of the surface of the cavity. At rest, without any cooling, the temperature of the surface of the cavity is 24.4° C. The repetition rate is first set to 5 Hz and the nominal power of 7 MW at the entrance of the cavity is reached. After a few hours, the temperature stabilizes around 27° C. Then the repetition rate is doubled to 10 Hz and the temperature raises to around 30° C after a few hours of run. Eventually, the repetition rate is set to its maximum value of 50 Hz and the surface temperature then climbs up to 45° C after three hours. The experiment is stopped at that temperature to avoid any permanent detuning of the cavity.

During all these tests, the signals of the forward and reflected power stay the same as before and no breakdowns are observed.

4.3 Transmission band

During CTF3 Preliminary Phase, it is planned to change the frequency multiplication factor from three to five. If N is the combination factor, λ_0 the RF wave length in the deflectors (and in the linac), and C the circumference of the ring, the combination process requires

$$C = n\lambda_0 \pm \frac{\lambda_0}{N} \tag{6}$$

where n is any integer. The circumference of the ring is fixed to the average value of $1256.73\lambda_0$, corresponding to a combination factor four at the reference frequency of 2998.5 MHz [4].

In order to cover the whole range of combination factors from three to five, the RF frequency will have to be varied by ± 150 kHz around its reference value. Assuming the expansion coefficient for copper is $\alpha_T = 1.65 \times 10^{-5}$ per degree, the change in the diameter D of the cavity per degree is given by

$$\Delta D = \alpha_T D \tag{7}$$

and the corresponding change in frequency is

$$\Delta f = -f_0 \frac{\Delta D}{D} \tag{8}$$

where f_0 is the reference frequency. Consequently, a temperature variation of one degree implies a frequency shift of about 50 kHz. It is therefore foreseen to tune the RF deflectors to the needed frequency by changing their temperature by $\pm 3^\circ$ C, thus covering the needed ± 150 kHz range. However, if the transmission band is large enough, the whole frequency range could be covered inside the band without changing the temperature.

To estimate the transmission band, the frequency range is explored by steps of 100 kHz while monitoring the reflected signal at a low level of forward power. Qualitatively, the central frequency corresponds to the minimum of the reflected signal and the lower and higher limits of the bandwidth corresponds to twice the minimum value of the reflected signal. Once the temperature is stabilized at 27° C with a repetition rate of 5 Hz, the bandwidth goes from 2997.5 MHz to 2999.9 MHz, where this upper value is the klystron hardware limit. Although the temperature follow-up might still be needed when changing the frequency, this bandwidth is large enough to avoid the need of a very precise temperature stabilization system. The central frequency is estimated to be close to 2998.9 MHz which is higher to the expected value at this temperature, the design frequency being 2998.5 MHz at 30° C. This small shift in the central frequency confirms other previous measurements [10].

5 Conclusion

The feasibility of the CLIC RF power power source relies on the frequency multiplication scheme, which requires the use of RF deflectors to inject pulse trains into an isochronous ring. This scheme is to be tested during the Preliminary Phase of the new CLIC test facility CTF3. Two existing travelling wave deflecting structures, operating at 3 GHz, are going to be used to produce a time-dependent closed bump. The required deflecting angle for injection is 4.5 mrad for 350 MeV/c electrons. To inject a five pulse train during one single RF pulse, the required RF pulse length is 2.5 μs. With these parameters, the calculations based on the deflector geometry lead to a power of 7 MW at the entrance of the RF deflectors.

The RF power tests described in this note allowed to check that two RF deflectors can cope with a much higher amount of power than required, thus leaving a comfortable margin for the commissioning of the machine. The cavities were conditioned up to 13.5 MW for the first cavity (already used at lower power for bunch length measurements), and 13 MW for the second one, with the nominal pulse length. In addition, the bandwidth of the cavities was found to be of the order of 2-3 MHz, thus allowing some flexibility for frequency tuning and temperature stabilization. The tests also showed that a cooling device is needed for operation at high repetition rate in order to guarantee a constant resonant frequency, the design and reference frequency being 2998.5 MHz at 30° C.

Acknowledgements

The authors would like to thank the technical and support staff who made these tests possible by assisting in the cavity assembly and processing inside the CTF2 area, and specially D. Allard and G. Yvon. We are also grateful to the CTF2 team, who allowed us to use part of their equipment for those tests.

References

[1] G. Guignard (Ed.), ”A 3 TeV e^+/e^- Linear Collider Based on CLIC Technology”, CERN 2000-008 (2000).

[2] CLIC Study Team, ”Proposals for Future CLIC Studies and a New CLIC Test Facility (CTF3)”, CERN/PS 99-047 (LP) and CLIC Note 402 (1999).

[3] H.H. Braun, R. Corsini, T.E. D’Amico, J.P. Delahaye, G. Guignard, C.D. Johnson, A. Millich, P. Pearce, L. Rinolfi, A.J. Riche, R.D. Ruth, D. Schulte, L. Thorndal, M. Valentini, I. Wilson, W. Wünsch, ”The CLIC RF power source: a novel scheme of two beam acceleration for electron-positron linear colliders”, CERN 99-06 (1999).

[4] R. Corsini, A. Ferrari, L. Rinolfi, T. Risselada, P. Royer, F. Tecker, ”Beam Dynamics for the CTF3 Preliminary Phase”, CLIC Note 470 (2001).

[5] R. Corsini, A. Ferrari, J.P. Potier, L. Rinolfi, T. Risselada, P. Royer, ”A Low Charge Demonstration of Electron Pulse Compression for the CLIC RF Power Source”, CERN/PS 2000-055 (AE) and CLIC Note 457, *Presented at* 20th International Linear Accelerator Conference, Monterey, USA, 2000.

[6] R. Belbeoch, ”Pouvoir de Résolution dans la mesure de la distribution longitudinale des paquets a la sortie du groupeur du linac pre-injecteur de LEP”, LAL PI 85-06/T.

[7] R. Belbeoch, ”Utilisation d’une section accélératrice pour la mesure du profil longitudinal des micro-paquets à la sortie du groupeur de la station d’essais du LAL”, SERA Note 89-09.

[8] Ph. Bernard, H. Langeler and V. Vaghin ”On the design of disk-loaded waveguides for RF separators”, CERN 68-30 (1968).

[9] I. Syratchev, private communication.

[10] P. Brown, private communication.