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Demonstration of Two-Beam and 30 GHz Power Production in the CLIC Test Facility

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Abstract

The Compact Linear Collider (CLIC) Test Facility (CTF II) at CERN has recently demonstrated Two-Beam power production and acceleration at 30 GHz. With 41 MW of 30 GHz power produced in 14 ns pulses at a repetition rate of 5 Hz, the main beam has been accelerated by 28 MeV with fields of 59 MV/m. The 30 GHz RF power is extracted in low impedance decelerating structures from a low-energy, high-current "drive beam" which runs parallel to the main beam. The average current in the drive-beam train is 25 A, while the peak current exceeds 2 kA. Crosschecks between measured drive-beam charge, 30 GHz power and main-beam energy gain are in good agreement. In this paper, some relevant experimental and technical issues on drive-beam generation, two-beam power production and acceleration are presented.

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Abstract. The Compact Linear Collider (CLIC) Test Facility (CTF II) at CERN has recently demonstrated Two-Beam power production and acceleration at 30 GHz. With 41 MW of 30 GHz power produced in 14 ns pulses at a repetition rate of 5 Hz, the main beam has been accelerated by 28 MeV with fields of 59 MV/m. The 30 GHz RF power is extracted in low impedance decelerating structures from a low-energy, high-current "drive beam" which runs parallel to the main beam. The average current in the drive-beam train is 25 A, while the peak current exceeds 2 kA. Crosschecks between measured drive-beam charge, 30 GHz power and main-beam energy gain are in good agreement. In this paper, some relevant experimental and technical issues on drive-beam generation, two-beam power production and acceleration are presented.

1. INTRODUCTION

CTF II is the experimental facility of the Compact LInear Collider (CLIC) study dedicated to demonstrate the feasibility of the CLIC two-beam accelerator scheme (1) and its associated 30 GHz technology. In the frame of the CLIC studies, CERN has built two facilities: CTF I (2), which has been operated from 1990 to 1995, and CTF II (3), which is presently in operation.

CTF I was mainly dedicated to drive-beam and 30 GHz power production studies. A high impedance, disk-loaded, 30 GHz accelerating structure was employed as the drive beam power extracting structure and produced 76 MW at 30 GHz. This power was used to establish an accelerating field of 94 MV/m in an identical 30 GHz accelerating structure. The first bunch of the drive beam was used to probe the accelerating field.

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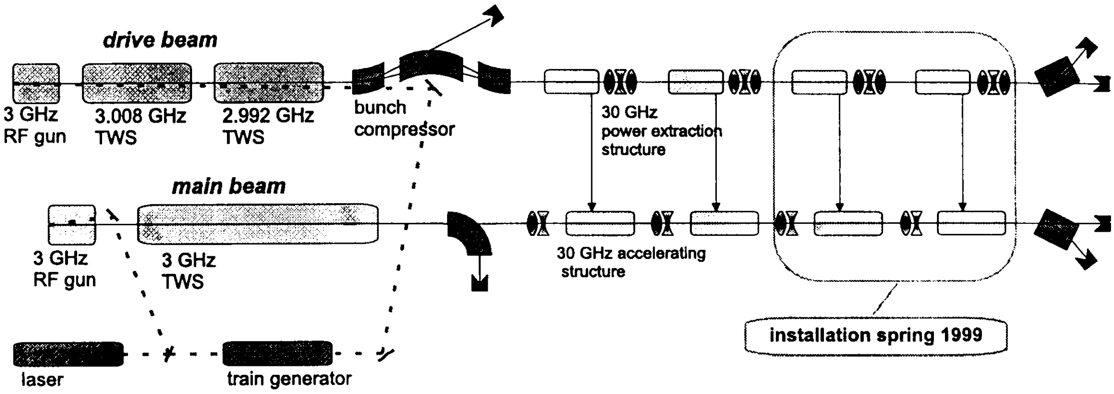

FIGURE 1. Layout of CTF II (TWS = travelling wave structure).

CTF II is the prototype of a two-beam accelerator. The layout of CTF II with its two beam lines is shown in Figure 1 and it is described in detail in (4). The drive beam generates 30 GHz power, while the main beam probes the accelerating field in the 30 GHz accelerator. Both beams are generated by S-band RF-photo-injectors whose photo-cathodes are illuminated by a common short pulse (8 ps FWHM), UV laser (5). Before injection in the 30 GHz two-beam accelerator, both beams are accelerated in S-band, disk-loaded structures and the drive-beam bunches are compressed in a magnetic chicane. The latter is essential for efficient power production at 30 GHz. The two-beam test accelerator consists of two fully-engineered CLIC building blocks, i.e. the modules, for a total length of 3 m (6). The layout of each module follows that currently foreseen for CLIC, but has a higher density of quadrupoles due to the lower beam energies. The test accelerator is equipped with a prototype active-alignment system in order to gain experience in a real accelerator environment.

The first demonstration of two-beam acceleration was obtained in autumn 1997, during the commissioning at low drive-beam charge of the 30 GHz two-beam accelerator. Experiments on two-beam acceleration and power production continued during 1998 and substantial two-beam acceleration and power production started in June 1998.

The CLIC Test Facility (CTF II) is described in Section 2 and, in Section 3, results on the operation of the two-frequency drive-beam beamloading compensation scheme are presented. Results on two-beam acceleration and power production are presented in Section 4.

2. THE CLIC TEST FACILITY

A major challenge of CTF II is the production and transport of the drive-beam train of intense (13.4 nC) and short (5 ps FWHM) bunches, which is needed to produce the required microwave power for the main-beam acceleration. Some relevant design parameters of drive and main beam are presented in Table 1.

TABLE 1. Design Parameters of the Drive and Main Beams in the CLIC Test Facility

	Drive Beam	Main Beam
Number of bunches	48	1 - 2
Bunch charge	13.4 nC	1 nC
Bunch repetition frequency	3 GHz	1.5 GHz
Energy at gun exit	7 MeV	4 MeV
Energy at injection into 30 GHz two-beam accelerator	60 MeV	45 MeV
Bunch length at injection into 30 GHz two-beam accelerator	5 ps (FWHM)	6 ps (FWHM)
Drive-beam decelerating field in 30 GHz two-beam accelerator	7.6 MV/m	
Main-beam accelerating field in 30 GHz two-beam accelerator		95 MV/m

The main beam is generated in a 2-cell RF-photo-injector and operates with a single bunch of 1 nC charge. A second bunch, with a variable delay relative to the first, can be switched on to allow wakefield studies in the 30 GHz structures. Before being injected into the 30 GHz accelerator the main beam is accelerated to about 46 MeV in an S-band travelling wave structure. This is necessary to obtain a geometric emittance that is sufficiently small to fit into the small acceptance of the 30 GHz accelerating structures, which have a beam aperture of only 4 mm diameter. Magnetic spectrometers before and after the 30 GHz accelerator are used to measure the main beam energy.

The drive beam is generated in a 3-cell RF-photo-injector specially designed for high-charge acceleration (7). At the design specifications, the photo-injector operates at a field of 100 MV/m and generates a train of total charge of 640 nC in 48 bunches with a bunch spacing of 10 cm. The train energy at the photo-injector exit is about 7 MeV and the total energy spread due to beam loading is about 20%. The photo-injector is followed by two short travelling wave S-band structures optimised for high-charge acceleration (8). In order to provide approximate compensation of the beam loading, the two accelerators are operated at $\pm$ 7.81 MHz with respect to the bunch repetition frequency. The chosen accelerator frequencies set the residual train energy spread to about 7%. Since the acceptance of the S-band beam line in terms of energy spread is about 14%, the system allows for a single-bunch correlated energy spread high enough for magnetic bunch compression. A small train energy spread is essential also to limit the bunch-to-bunch desynchronisation caused by the energy spread and by the different path length of each bunch in the magnetic bunch compressor.

As a result of the laser pulse length on the photocathode (8 ps FWHM), focusing longitudinal RF forces and defocusing space-charge forces, the bunch length after acceleration is about 8 ps FWHM at the nominal charge. Since efficient 30 GHz power production requires short bunch lengths, a magnetic chicane, together with optimised phasing in the accelerating structures, is used to compress the bunches to 5 ps FWHM. After bunch compression, the beam is injected into the 30 GHz decelerator (6) where a part of its energy is converted into 30 GHz power. A downstream spectrometer magnet measures the energy spectrum of the beam after power extraction.

The CTF II 30 GHz two-beam accelerator consists of prototypes of CLIC modules, equipped with 30 GHz Power Extraction and Transfer Structures (PETS), 30 GHz disk-loaded accelerating structures and 30 GHz beam monitoring equipment. Since operation at high frequency involves tight alignment tolerances, each module of the 30 GHz two-beam accelerator is equipped with a micron-precision active alignment system, consisting of position monitors and actuators. In each module, the drive-beam power extracting structures, the main-beam accelerating structures and the beam position monitors sit on two girders, one per linac. The position of the girder ends can be adjusted both in the vertical and horizontal plane. The quadrupoles sit above each girder on independent, moveable supports. Sensors are used to measure the position of each element with respect to a wire positioning system and to actively align girder and quadrupoles with respect to the reference wire.

The 30 GHz accelerating sections are fully-engineered CLIC prototype accelerating sections optimised for single-bunch acceleration (i.e. they are not detuned or damped to suppress wakefields). The sections are manufactured to micron tolerances using parts made on ultra-precision diamond-tool lathes. A prototype was extensively tested in CTF I at an average accelerating gradient of 94 MV/m without any sign of electrical breakdown. The maximum gradient was limited only by the available power. For focusing the beam, a doublet lattice has been chosen, with a period which is equal to the nominal length of a CLIC girder (i.e. 1.4 m).

The 30 GHz Power Extraction and Transfer Structures consist of a 15 mm diameter circular tube coupled by 4 slots to the broad sides of four corrugated rectangular waveguides. In order to selectively damp the transverse modes, lossy longitudinal slits terminated with resistive materials are cut in symmetry planes of the main decelerating mode. The presently-adopted structures have an effective length of 0.6 m and a design r'/Q of 1080 Ω/m. The extracted power depends quadratically on the charge per bunch and, for operation at the design specifications, each structure produces about 71 MW. The decelerating field increases along the structure and reaches 7.6 MV/m at the end, corresponding to a drive-beam deceleration of about 2.3 MeV per structure. The suppression of transverse modes has been experimentally demonstrated.

3. DRIVE-BEAM ACCELERATION AND BEAM-LOADING COMPENSATION

An important issue, which must be overcome when accelerating a relatively short train of high-intensity bunches, is the compensation of the beam loading in the accelerator. For short trains, when the beam loading is a transient process, it is not possible to compensate it by injecting the train before the structure is completely filled by the RF wave or by regulating the power from the klystrons within the bunch train.

The nominal CTF drive-beam train of 640 nC during 16 ns extracts 1.8 GW/m of power from the two 3 GHz accelerating structures. The related energy has to be provided by the energy stored in the accelerating structures. For this reason, the structures are operated at a high field (design 60 MV/m, achieved 36 MV/m) and their geometry is optimised for a low r'/Q (2200 Ω/m) to maximise the stored energy. Nevertheless the energy drop due to transient beam loading would be 17.5 MeV (i.e.

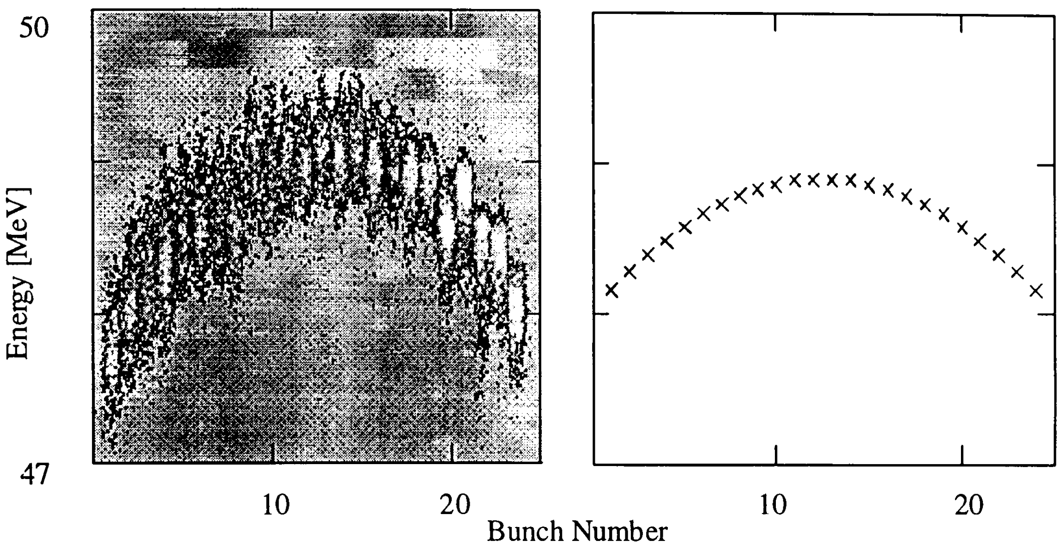

FIGURE 2. Longitudinal phase space with beam-loading compensation. Left side: measured; right side: predicted.

30%) at nominal charge. Since such an energy spread is neither acceptable for the bunch compression nor for the transverse matching into the 30 GHz decelerator, a two-frequency beam-loading compensation is used.

The two accelerating structures operate at 7.81 MHz above and below the drive-beam bunch repetition frequency of 2998.55 MHz. This introduces a change of RF phase from bunch to bunch which leads to compensation (to the first order in the bunch number with respect to the train centre) of the beam loading. Due to the curvature of the RF wave, a residual energy spread remains, leading to somewhat lower energies of the early and late bunches compared with bunches at the centre of the train. This effect is visible in Figure 2, which shows a longitudinal phase-space image of a 24 bunch train with a total charge of 120 nC. This is taken with a streak camera from a transition radiation screen in the first drive-beam spectrometer. A plot of the calculated energy distribution (not including the single-bunch energy spread) is also shown for comparison. For a 48 bunch train the total energy variation from bunch to bunch due to this effect is 7%. Without beam-loading compensation it would be 30% for the nominal charge. By running the two accelerators at the same field amplitude and injecting the train at the same phase, the single-bunch energy spread introduced in the first structure is compensated by the second structure. However, by using the correct phasing and a reduction of the field amplitude in the second structure, it is possible to introduce a correlated energy spread in the individual bunches which is approximately equal for all bunches. This is essential for bunch compression in the magnetic chicane. When adding a correlated energy spread to allow for magnetic bunch compression, the energy spread with beam-loading compensation increases to 14%.

Thanks to the successful operation of the beam loading compensation scheme, the performance of the drive-beam accelerator exceeded the design specifications in terms

TABLE 2. Design and Achieved Performance

	Design	Achieved
Maximum drive-beam accelerated charge	640 nC	755 nC
Drive-beam charge during two-beam acceleration experiments	640 nC	475 nC
Maximum Drive beam charge through decelerator	640 nC	374 nC
Number of drive-beam bunches	48	48
Drive-beam bunch length (FWHM)	5 ps	5 ps
30 GHz power from Power Extraction Structure	71 MW	27 MW
30 GHz power pulse length	14 ns	14 ns
Mean accelerating field in 30 GHz acc. structure	95 MV/m	59 MV/m
Maximum probe beam acceleration	47 MeV	28 MeV

of accelerated drive-beam charge. To date, the maximum accelerated charge was 755 nC in a 48 bunch train.

4. TWO-BEAM ACCELERATION AND POWER PRODUCTION AT 30 GHZ

Recently, the CTF II demonstrated two-beam acceleration and power production at 30 GHz by simultaneously passing the drive beam through the 30 GHz decelerator and the main beam through the 30 GHz accelerator.

At present two power extraction structures are installed in the 30 GHz decelerator. Each power extraction structure is connected to one 30 GHz accelerating structure of the main beam. One of the power extraction structures is an older prototype (soon to be replaced) and gives about half the power of the other. The numbers given in Table 2 for power and accelerating field refer to those measured with the newer structure. The following quantities were measured: drive-beam charge in front of and behind the decelerator, drive-beam bunch length (9), main-beam charge and bunch length, drive-beam spectrum in front of and behind the decelerator, 30 GHz power (input, reflected and transmitted) for each of the two accelerating structures and main-beam spectrum.

Table 2 summarises the performance achieved in comparison with the design goals. To date 27 MW at 30 GHz is produced in the PETS and used to establish a mean accelerating field of 59 MV/m in the 30 GHz accelerator. The total 30 GHz power was 41 MW and the total main-beam acceleration was 28 MeV. As already experienced in CTF I (at higher power levels), no RF breakdowns were observed in either the 30 GHz waveguide networks or the accelerating structures. The 30 GHz power production is limited for the moment by the drive-beam charge that can be transported through the decelerator. Although the maximum accelerated charge exceeds the design target, the drive-beam transmission through the 30 GHz decelerator is still unsatisfactory. Full transmission is presently achieved up to a drive beam charge of 340 nC. Above this charge level, the drive beam transmission progressively deteriorates and the maximum charge transported is 374 nC. Possible reasons for the unsatisfactory transmission at high charge level include the gradient in the drive-beam accelerator, which is still below

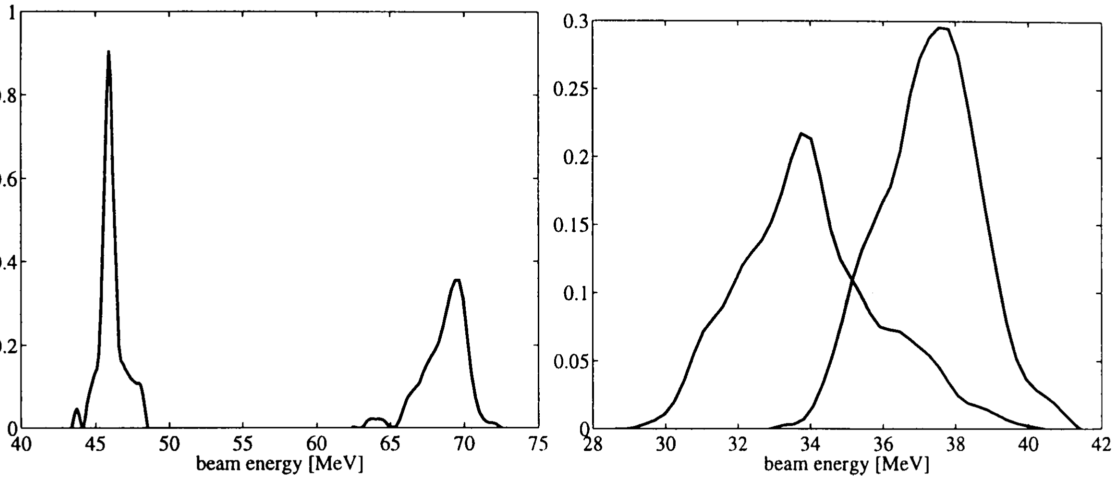

FIGURE 3. Momentum spectra of the main beam measured with drive beam on and off (left), and drive beam momentum spectra measured before and after the 30 GHz power extraction structures (right).

the design value, transverse matching problems and various problems with the laser system.

Figure 3 shows energy spectra of the main (left) and drive (right) beam for a drive beam charge of 400 nC and a transmission of 85% in the decelerator. The main beam spectra are measured downstream of the 30 GHz accelerator with and without 30 GHz acceleration. The larger energy spread of the accelerated beam is caused by laser energy jitters and by the bunch-length of the main beam, which is 6 ps FWHM corresponding to a phase extension of 65° at 30 GHz. The drive-beam spectra are measured before and after passage through the 30 GHz decelerator.

Table 3 presents the comparison of the measured and expected performance in the case of a drive-beam charge of 340 nC at 100% transmission. Within the stability of the drive-beam charge (at present +/- 2% rms due to laser energy jitters), the measured power and acceleration are consistent with the values expected from theory. However, the precision of this comparison at higher drive-beam charge is presently limited by the beam losses in the decelerator.

TABLE 3. Measured and Expected Performance in Case of 100% Drive Beam Transmission

	Expected	**Measured**
Drive-Beam Charge		340 nC
Drive-Beam Transmission		100%
30 GHz power	19.8 MW	17.5 MW
Main-beam acceleration	25 MeV	22 MeV
Measured / Expected acceleration from drive beam charge measurement	1	0.88
(Measured / Expected power) $^{1/2}$	1	0.92
Measured / Expected acceleration from 30 GHz power measurement	1	0.99

5. STATUS AND PERSPECTIVES

The CTF II has demonstrated the principle of two-beam acceleration at 30 GHz. Although the facility is still in the commissioning stage, the accelerating gradients achieved are already well above those in more conventional electron accelerators and the charge and beam current obtained from the drive-beam accelerator are unprecedented for RF-photo-injectors. Thanks to the two-frequency beam loading compensation scheme, a maximum drive-beam charge of 755 nC in 48 bunches has been accelerated by the system RF-Photo-Injector + 3 GHz accelerators. The top performance of the drive beam accelerator in terms of bunch charge in single-bunch operation is 112 nC, corresponding to a peak current of 5.5 kA. Regarding two-beam acceleration experiments, 41 MW at 30 GHz has been extracted from the drive beam and used to accelerate the main beam by 28 MeV. The.corresponding mean gradient in the 30 GHz accelerator was 59 MV/m.

It is planned to add two more CLIC modules to the 30 GHz, two-beam accelerator during the coming year (1999). A test with a special power extraction structure of considerably higher shunt impedance is foreseen to generate even higher power than with the standard structures and to explore the as yet unknown gradient limits of 30 GHz equipment.

To improve the quality of the drive beam a new RF-photo-injector (10) and an idler cavity are under construction. The photo-injector will improve the drive-beam quality while the idler cavity will reduce the residual energy spread of the beam loading compensation system.

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