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DEMONSTRATION OF TWO-BEAM ACCELERATION IN CTF II

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Abstract

The second phase of the Compact LInear Collider (CLIC) Test Facility (CTF II) at CERN has demon-strated the feasibility of two-beam acceleration at 30 GHz using a high-charge drive beam, running parallel to the main beam, as the RF power source. To date accelerating gradients of 59 MV/m at 30 GHz have been achieved. In CTF II, the two beams are generated by 3 GHz RF photo-injectors and are accelerated in 3 GHz linacs, before injection into the 30 GHz modules. The drive beam linac has to accelerate a 16 ns long train of 48 bunches, each with a nominal charge of 13.4 nC. To cope with the very substantial beam-loading special accelerating structures are used (running slightly off the bunch repetition frequency). A magnetic chicane compresses the bunches to less than 5 ps fwhm, this is needed for efficient 30 GHz power generation. The 30 GHz modules are fully-engineered representative sections of CLIC, they include a 30 GHz decelerator for the drive beam, a 30 GHz accelerator for the main beam, high resolution BPM's and a wire-based active align-ment system. The performance achieved so far, as well as the operational experience with the first accelerator of this type, are reported.

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Abstract

The second phase of the Compact LInear Collider (CLIC) Test Facility (CTF II) at CERN has demonstrated the feasibility of two-beam acceleration at 30 GHz using a high-charge drive beam, running parallel to the main beam, as the RF power source. To date accelerating gradients of 59 MV/m at 30 GHz have been achieved. In CTF II, the two beams are generated by 3 GHz RF photo-injectors and are accelerated in 3 GHz linacs, before injection into the 30 GHz modules. The drive beam linac has to accelerate a 16 ns long train of 48 bunches, each with a nominal charge of 13.4 nC. To cope with the very substantial beam-loading special accelerating structures are used (running slightly off the bunch repetition frequency). A magnetic chicane compresses the bunches to less than 5 ps fwhm, this is needed for efficient 30 GHz power generation. The 30 GHz modules are fully-engineered representative sections of CLIC, they include a 30 GHz decelerator for the drive beam, a 30 GHz accelerator for the main beam, high resolution BPM's and a wire-based active alignment system. The performance achieved so far, as well as the operational experience with the first accelerator of this type, are reported.

1 INTRODUCTION

After successfully completing the first phase of CTF in 1995 [1], the construction of CTF II was launched in 1996 with the following goals:

1. To demonstrate the feasibility of the CLIC two-beam accelerator scheme [2] and its associated 30 GHz technology.
2. To build and test prototypes of the 30 GHz modules
3. To study the dynamics of a high-charge, multibunch drive beam.
4. To test the active alignment system in a realistic accelerator environment.
5. To test CLIC beam monitoring equipment.

The layout of CTF II with its two beam lines is shown in figure 1. 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. The RF-photo-injectors have photo-cathodes illuminated by a common short pulse (8 ps fwhm) laser. The cathodes and the laser system are described in [3].

The main beam operates with a single bunch of 1 nC charge. A second bunch, with a variable delay relative to the first, can be added later to allow wakefield studies in the 30 GHz structures. Before being injected into the 30 GHz accelerator the main beam is accelerated to 46 MeV in an S-band travelling wave structure. This is necessary to obtain a small enough geometric emittance 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 beam energy. The details of the 30 GHz accelerator are described in [4].

The drive beam RF-photo-injector is a 3-cell design optimised for high charge acceleration [5]. The nominal charge is 640 nC in 48 bunches with a bunch spacing of 10 cm. The photo-injector accelerates these bunches to 6 MeV. The photo-injector is followed by two short travelling wave S-band structures optimised for high-charge acceleration [6]. These structures are also used

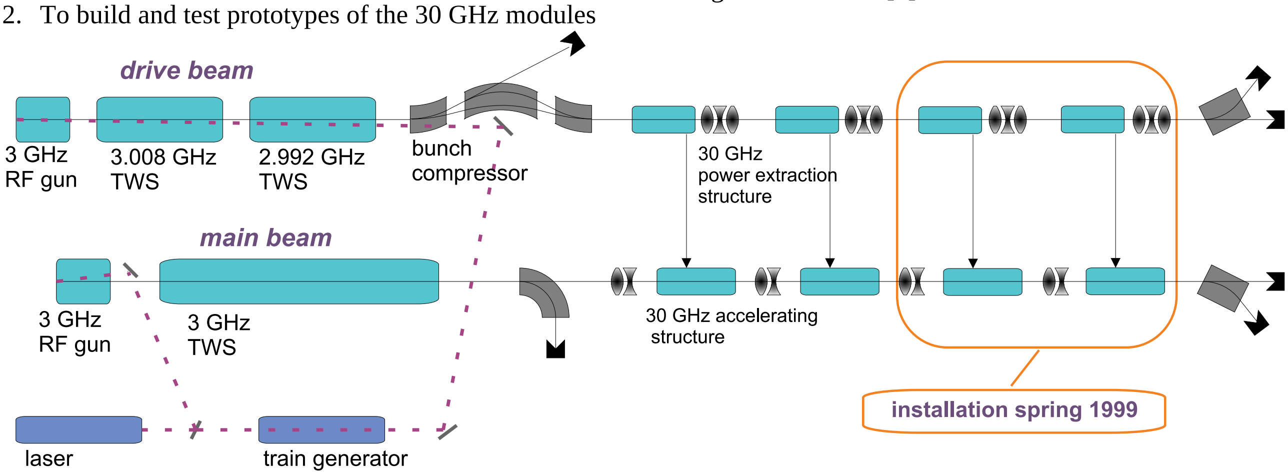

Figure 1: Layout of CTF II (TWS=travelling wave structure)

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for beam-loading compensation, as described in below. As a result of the counteracting longitudinal RF focusing and space-charge defocusing forces, the bunch length after acceleration is about 8 ps fwhm for the nominal charge. A magnetic chicane, together with proper phasing in the accelerating structures, compresses the bunches to ≤ 5 ps; this is needed for efficient 30 GHz power production. The first magnet of the chicane is also used as a spectrometer magnet. After bunch compression, the beam is injected into the 30 GHz decelerator [4] where a part of its energy is converted into 30 GHz power. A downstream spectrometer magnet measures the energy of the beam after power extraction.

2 DRIVE BEAM ACCELERATION AND BEAM LOADING COMPENSATION

The nominal drive beam train of 640 nC during 16 ns extracts 2.2 GW of power from the two 3 GHz accelerating sections. 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 (2.2 kΩ/m) to maximise the stored energy. Nevertheless the energy drop due to transient beam-loading would be 17.5 MeV 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 7.8 MHz below and above the drive-beam bunch repetition frequency of 2998.6 MHz. This introduces a change of RF phase from bunch to bunch which allows an approximate compensation 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 center 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 is 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 using two frequencies, the single bunch energy spread introduced in the 1st structure is compensated by the 2nd structure. However, using correct phasing and a slight reduction of the field amplitude in the 2nd 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. Adding a correlated energy spread to allow for bunch compression, the energy spread with beam loading compensation increases to 14%.

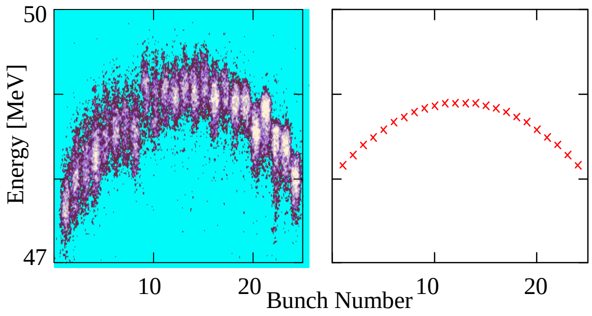

Figure 2: Longitudinal phase space with beam loading compensation. Left side: measured; right side: predicted.

3 TWO BEAM ACCELERATION AT 30 GHZ

In June and July of this year two-beam acceleration was tested 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 quoted below for power and accelerating field refer to those measured with the newer structure. The following quantities were measured: drive beam charge before and after the decelerator, drive beam bunch length [7], main beam charge and bunch length, drive beam momentum before and after the decelerator, 30 GHz power (input, reflected and transmitted) for each of the two accelerating structures and main beam momentum. Table 1 summarises the performance achieved in comparison with the design goals. As already experienced in CTF I, no RF breakdowns were observed in either the 30 GHz waveguide networks or the structures. The 30 GHz power production is limited for the moment by the drive beam charge which can be transported through the decelerator.

		design	achieved
drive beam	maximum accelerated charge	640 nC	755 nC
	acc. charge giving max. 30 GHz power	640 nC	475 nC
	max. charge through decelerator	640 nC	374 nC
	number of bunches	48	48
	bunch length fwhm	5 ps	5 ps
30 GHz power at output of 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

Table 1: Nominal and achieved performance.

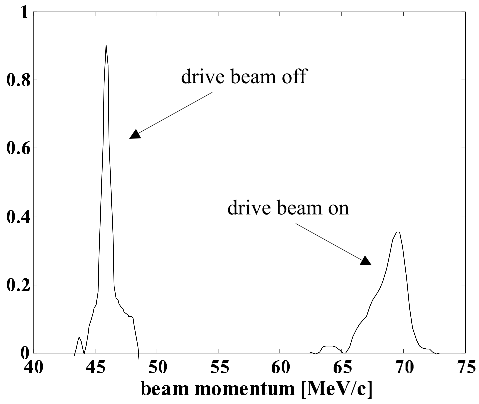

Figure 3: Momentum spectra of the main beam measured with drive beam on and off.

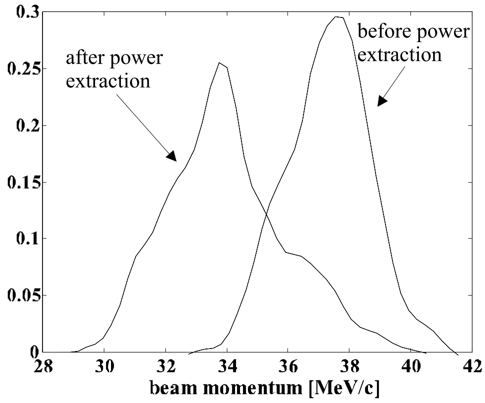

Figure 4: Drive beam momentum spectra measured before and after the 30 GHz power extraction structures.

Possible reasons for the still unsatisfactory transmission at high charges include the gradient in the drive beam accelerator which is still below the design value, transverse matching problems and various problems with the laser system.

Figure 3 shows energy spectra of the main beam 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 65o at 30 GHz. Figure 4 shows the drive beam energy spectra before and after passage through the 30 GHz decelerator. These spectra were measured with a drive beam charge of 400 nC and a transmission of 85% in the decelerator. The measured power and acceleration are compatible with the values expected from theory. However, the precision of this comparison is presently limited by the beam losses in the decelerator.

4 SINGLE BUNCH EXPERIMENTS

The drive beam accelerator of CTF II can also be operated in single bunch mode. This mode of operation allows the study of the dynamics of single bunches with high charges. Recently a single bunch of 112 nC was produced and accelerated. Effects leading to emittance growth in the magnetic bunch compressor were studied experimentally [8]. The single bunch mode of operation is also used for beam monitor testing [9].

5 CONCLUSION AND OUTLOOK

The CTF II has demonstrated the principle of two-beam acceleration at 30 GHz. Although not all the design specifications have been met until now, 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.

For the coming year it is planned to add two more power extraction and accelerating structures. A test with a special power extraction structure of considerably higher shunt impedance is foreseen, which will allow to generate even higher power than with the standard structures. This power will be used to explore the as yet unknown gradient limits of 30 GHz structures.

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

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