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EXPERIMENTAL RESULTS AND TECHNICAL RESULTS AND DEVELOPMENT AT CTFII

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Abstract

The second phase of the Compact Linear Collider Test Facility (CTF II) has demonstrated the feasibility of two key ingredients of the Compact Linear Collider scheme (CLIC) [1], namely the acceleration with a 30 GHz normal conducting linac and the 30 GHz RF power production by a tightly-bunched, high-charge drive beam running parallel to the main beam. This beam is produced and accelerated with a 3 GHz linac using an RF-photo-injector and two travelling-wave sections, all specially developed for handling very high charges. A magnetic chicane compresses the micro-bunches to their nominal length. A mm-wave spectrometer, coupled to the beam pipe, allows non-destructive measurements of bunch length. So far a total acceleration of 60 MeV has been obtained using a string of five accelerating structures with a total active length of 1.4 m. The corresponding drive-beam deceleration is 6 MeV. The flexibility and extensive beam instrumentation allows a variety of other experiments, such as measurements of emittance growth and energy loss in bunch compressors due to coherent synchrotron radiation, high-gradient tests in single-cell 30 GHz cavities, high-power tests of a planar 30 GHz RF structure and tests of beam position monitor prototypes.

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Experimental Results and Technical Research and Development at CTF II

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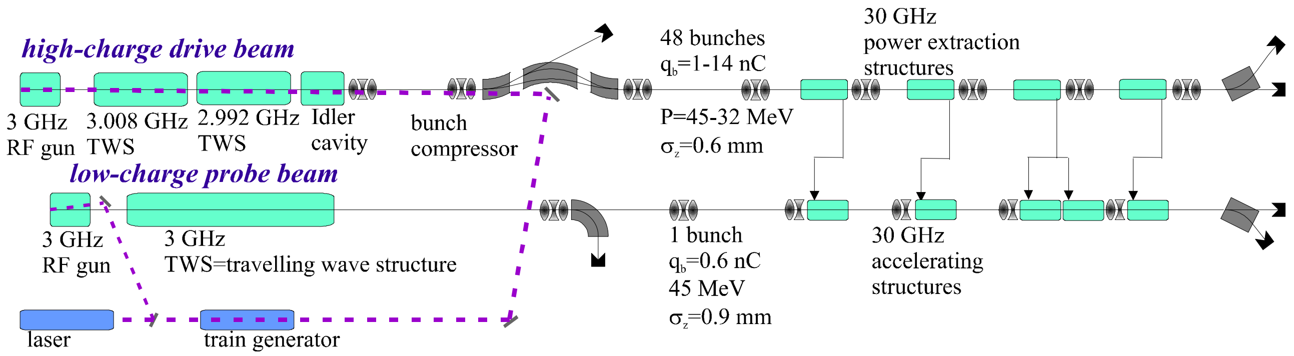

Figure 1: Configuration of CTF II during the 1999 run

Abstract

The second phase of the Compact Linear Collider Test Facility (CTF II) has demonstrated the feasibility of two key ingredients of the Compact Linear Collider scheme (CLIC) [1], namely the acceleration with a 30 GHz normal conducting linac and the 30 GHz RF power production by a tightly-bunched, high-charge drive beam running parallel to the main beam. This beam is produced and accelerated with a 3 GHz linac using an RF-photo-injector and two travelling-wave sections, all specially developed for handling very high charges. A magnetic chicane compresses the micro-bunches to their nominal length. A mm-wave spectrometer, coupled to the beam pipe, allows non-destructive measurements of bunch length. So far a total acceleration of 60 MeV has been obtained using a string of five accelerating structures with a total active length of 1.4 m. The corresponding drive-beam deceleration is 6 MeV. The flexibility and extensive beam instrumentation allows a variety of other experiments, such as measurements of emittance growth and energy loss in bunch compressors due to coherent synchrotron radiation, high-gradient tests in single-cell 30 GHz cavities, high-power tests of a planar 30 GHz RF structure and tests of beam position monitor prototypes.

1 HISTORY AND OVERVIEW

Soon after the successful completion of the experimental program of the 1st phase of CTF at the end of 1995 [2], the construction of CTF II was launched. The goals of CTF II are

- To demonstrate the feasibility of the CLIC two-beam accelerator scheme and its 30 GHz technology.
- 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.
- To study the dynamics of a high-charge, multi-bunch drive beam.
- To test the active alignment system within a realistic accelerator environment.
- 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 probe beam measures 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 probe beam operates with a single bunch of 1 nC charge. Before being injected into the 30 GHz accelerator, the probe 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 nominal drive beam charge is 640 nC in 48 bunches with a bunch spacing of 10 cm. As a result of the counteracting longitudinal RF focusing and space-charge defocusing forces, the bunch length after acceleration is 8-10 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. The bunch length after the compressor can be measured either with the help of a Cherenkov radiator and a streak camera [3] or with a mm-wave pick-up connected to a mm-wave spectrometer sensitive in the range 28.5-88.5GHz [4]. The latter method allows a non-destructive measurement with good resolution down to about 2 ps

FWHM. After bunch compression, the beam is injected into the 30 GHz decelerator, 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 ACCELERATOR

The drive beam is generated in a 3-cell RF-gun with a laser-driven photo-cathode. The design of this gun is optimised to cope with the substantial beam-loading [5]. The gun is fed by a 20 MW pulse of 2 μs duration, providing a peak electric field of 105 MV/m on the photo-cathode. For this field level, the gun accelerates the 1st bunch of the train to 6.9 MeV, while beam-loading reduces the energy of the 48th bunch to 5.6 MeV. Magnetic focusing is provided by two solenoids downstream of the gun. The output emittance of this gun is dominated by chromatic effects in these solenoids due to the beam-loading along the 48-bunch train. The laser beam is injected on axis, through a vacuum window in the magnetic chicane of the bunch compressor. This injection method allows to keep the space between the RF gun and the accelerating structures to be kept short, thus minimising bunch lengthening and emittance growth due to space charge forces.

Further acceleration is achieved by two constant impedance, travelling wave, S-band structures, each with a length of 69 cm. These structures operate with a phase advance of $11/12\,\pi$ and have an iris aperture diameter of 30.5 mm [6]. The large iris reduces beam loading and transverse wakefields, while the high phase advance close to π keeps the group velocity at a reasonable value of $0.003\ c_0$. However, this mode shows a transient power reflection similar to what happens in a standing wave cavity. To protect the klystrons, an amplitude ramp at the beginning and end of the RF pulse had to be introduced to reduce the reflected power. Moreover, it turned out that tuning of the $11/12\,\pi$ mode is difficult, in particular for the couplers. One of the consequences is a considerable overvoltage in the coupling cells, limiting the average accelerating field to 35 MV/m. This is substantially less than the 60 MV/m foreseen in the design.

Beam loading compensation is achieved by running the 1st structure 7.8 MHz higher than the bunch repetition frequency and the 2nd structure lower by the same amount [7]. This introduces a phase shift from bunch to bunch of slightly less than 1°, which compensates for the transient beam-loading along the bunch train. Due to the use of two frequencies, intra-bunch energy/phase correlation varying from bunch to bunch is avoided. A residual 2nd order energy spread is reduced by a 6-cell idler cavity with 3 cells tuned to a resonant frequency, 31 MHz above the bunch repetition frequency, and 3 cells to a frequency 31 MHz below [8]. In operation, the beam-loading compensation works very well and in accordance with the design.

A magnetic bunch compressor [9] is used to compress the bunches from the accelerator with a bunch length of 8-10 ps FWHM to a length of 5 ps FWHM. This is necessary to achieve efficient 30 GHz power production.

So far trains of 48 bunches with up to 750 nC have been generated in the RF gun and accelerated with the S-band structures. In single-bunch mode, bunch charges of more than 100 nC have been produced and accelerated.

A new 3-cell RF gun has been constructed and high-power tested. The main improvements of this gun compared to the one presently installed are the 1st cell operating in TM_{020} mode to increase the stored RF energy, and a symmetric two-port power coupler on the 3rd cell to improve the symmetry of the RF field [10]. It is foreseen to install this gun in early 2001 in CTF II.

3 PHOTO-CATHODES AND LASERS

Since 1993 the drive beam gun has used laser-illuminated tellurium alkali photo-cathodes. These cathodes have been produced and tested in our photo-emission laboratory [11] and transported under vacuum to the CTF. They are used in the gun with an electric field > 100 MV/m to produce a train of 48 bunches, each of up to 13.4 nC charge and 10 ps length when they are illuminated with UV light (λ=262 nm). The photo-cathode consists of a 10 nm tellurium layer over a copper substrate covered by a layer of approximately the same thickness of alkali (usually caesium). The amount of the alkali is optimised by measuring in situ the quantum efficiency (QE) of the photo-cathode. In 1999, the drive beam gun has used 8 Cs_2Te photo-cathodes with a mean initial QE of 10 % and with a mean lifetime of 200 hours of working time with RF and laser. The lifetime is defined here as a time to decrease from the starting QE down to 1.5 %, which is the minimum QE able to produce the nominal charge with the nominal laser energy.

The probe beam gun has used air-transportable photo-cathodes, which produce a single, 10 ps bunch of 1 nC charge. This cathode consists of a copper substrate covered by 100 nm of aluminium, 350 nm of caesium-iodide and 2 nm of germanium. At λ=262 nm the starting QE is about 0.2 % and the laser energy is high enough to use the cathode with a QE of 0.05 %. The time constant (time to decrease QE by a factoe 1/*e*) is more than 2000 hours.

The laser [12] is a “Master Oscillator-Power Amplifier” (MOPA) system in which 2 pulses are selected from a 250 MHz Nd:YLF mode-locked oscillator. The pulses are 8 ps long and have an energy of 0.5 nJ per pulse. They are amplified in a regenerative amplifier (RA), followed by power amplifiers to 7 mJ per pulse. The wavelength is converted from 1047 nm to 262 nm (the 4th harmonic). The 2 UV pulses are then progressively “split” with appropriate delays in a “Pulse Train Generator” (PTG) to produce the drive beam train of 48 pulses with 333 ps separation. The timing for the laser and the 3 GHz RF generator are synchronised. The residual green light from the 4th harmonic crystal which used to generate the UV light for the drive beam, is passed to another 4th harmonic generator to produce a pulse for the probe beam. This pulse has to be delayed with respect to the drive beam pulse, so that the probe beam arrives in the accelerating structures of the 30 GHz linac when the RF power from the drive beam has filled the structures.

The laser energy on the photo-cathodes is 48×4.5 µJ at 262 nm for the drive beam, and a single pulse of 25 µJ with the same wavelength for the probe beam.

4 TWO BEAM ACCELERATOR

4.1 Description

The 30 GHz drive beam decelerator/probe beam accelerator consists of 4 so-called “CLIC modules” [13]. Each module is 141 cm long and, for the decelerator contains a 55 cm long 30 GHz power extraction and transfer structure (PETS) [14], a 4 button beam position monitor (BPM) and a quadrupole triplet. The aperture available for the beam is 15 mm in diameter in the PETS and 20 mm in the triplet. Each module of the accelerator has a quadrupole doublet, a 30 GHz TM_{110} mode RF BPM [15], and space for two 28.5 cm long 30 GHz CLIC accelerating structures (CAS) [16]. However, at present, only the third module is equipped with two structures, while the other modules have one CAS. The beam aperture in the probe beam is 4 mm in diameter. Each 30 GHz waveguide transferring 30 GHz power from a PETS to a CAS is equipped with a high-power phase shifter and a directional coupler for measuring forward and reflected RF power. RF windows are only used in the low-power arms of the directional couplers.

4.2 Two-beam acceleration experiments

Many experiments were dedicated to the comparison between theoretical and measured parameters relevant for two-beam acceleration. These parameters are: drive beam charge; bunch-length; drive beam deceleration; 30 GHz power levels; probe beam acceleration. After some temporary confusion about the results of deceleration measurements, an error in the theoretical treatment of the PETS was found [17,18]. Afterwards, the agreement between measurements and theoretical predictions was very good. Fig. 2 shows an example of a measurement of the drive beam energy spectra before and after the 30 GHz decelerator in comparison with the prediction from a simulation program. This measurement has been performed with a total drive beam charge of 300 nC and two PETS.

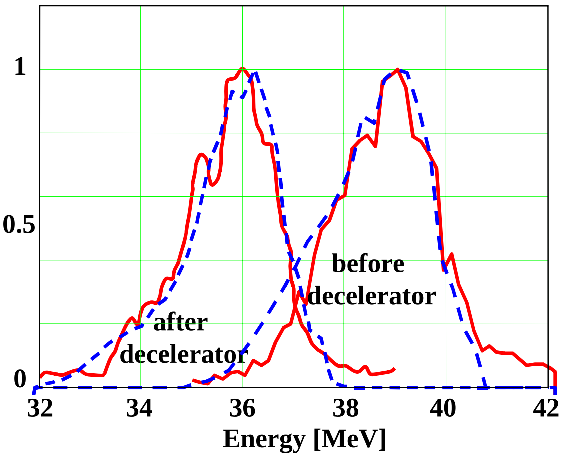

Figure 2: Measured (solid lines) and simulated (dashed lines) drive beam spectra before and after passage through the 30 GHz decelerator

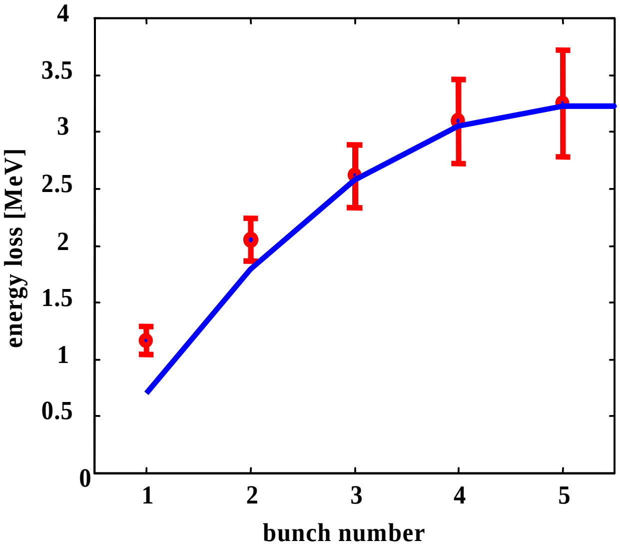

Figure 3: Measurement of transient voltage build up in the PETS. The circles show the measurements, the solid line the theoretical curve.

By measuring the beam energy spectra for a single bunch, and for trains of up to 5 bunches it is possible to detect the transient build-up of the decelerating field in the PETS. The result of such a measurement is shown in Fig. 3 for a bunch charge of 6.4 nC and two PETS. The error bars increase with the number of bunches, since the energy loss of bunch n has to be computed by subtracting the spectrum for $n-1$ bunches from the spectrum of n bunches. While the agreement for $n>2$ is very good, it seems that the 1st and 2nd bunch lose considerably more energy than predicted. This could be explained by higher order modes in the PETS with synchronous frequencies, which are not multiples of the bunch repetition frequency of 3 GHz. However, such modes have not been found in the MAFIA calculations of the PETS and the effect remains unexplained.

The measurement of the total acceleration in the probe beam 30 GHz accelerator gave a somewhat smaller value than expected. Although it is not possible in a two-beam accelerator to switch individual structures off and on, the acceleration in each CAS of the probe beam was measured by back-phasing of the CAS's one after the other. It was found that the discrepancy in the total acceleration was due to a lack of acceleration in the 2nd module. A post mortem inspection of the CAS which had been used in the 2nd module revealed considerable damage to the cell irises. This damage stems probably from an earlier use of this structure in the 1st phase of CTF 1.

4.3 best performance

The highest total acceleration in the 30 GHz probe beam accelerator amounts to 60 MeV. The corresponding mean accelerating gradient of the 1st CAS in the accelerator is 59 MV/m. The gradients in the downstream CAS's are somewhat lower, due to the different configuration of the RF network in module 3, a different type of PETS used in the 4th module, and the problem with the 2nd module mentioned above. The original design value for CTF II was 80 MV/m. The limitation of the acceleration is due to the maximum possible charge which can be transmitted through the decelerator. The transmission in the decelerator is limited by transverse wakefields and chromatic errors [19]. These effects are much more important than foreseen in the design of CTF II, since the drive beam energy for the design charge of 640 nC is only 35 MeV instead of the design value of 62 MeV. The reasons for this are the problems of the drive beam S-band accelerator structures mentioned above.

4.4 High power test of a planar structure

A 12.3 cm long 30 GHz accelerating structure with a planar geometry, designed and build by a group of the Technische Universität of Berlin, has been high-power tested in the 1st module, replacing the CAS. To our knowledge this is the first high power test of this type of RF structure. Although this prototype structure suffered from a considerable tuning error of about 250 MHz, it was possible to achieve an accelerating gradient of 23 MV/m for an input power of 30 MW. No signs of RF breakdown have been observed. More details about this experiment can be found in [18].

4.5 Active alignment system

The girders carrying the RF structures and the quadrupoles are mounted on actuators. The girder position is continuously measured relative to a stretched wire. A digital feedback system using the position information and controlling the actuators allows the position of the RF structures and quadrupoles to be kept with a accuracy of better than 1 μm [19,20].

In operation, this system works very satisfactory, except for an occasional malfunctioning when the drive beam is running. This problem is presently under investigation. The suspicion is that it is related to electronic interference between the return currents from the drive beam dump and the position read-out electronics.

5 HIGH GRADIENT EXPERIMENT

To explore the maximum field which can be achieved in 30 GHz cavities, a single cell resonant cavity was installed in the CTF II drive beam and excited with a train of 12 bunches passing through the cavity. RF breakdowns started to occur for surface fields larger than 540 MV/m and a maximum field on the copper surface of 750 MV/m has been achieved. More information can be found in [21].

6 COHERENT SYNCHROTRON RADIATION EXPERIMENTS

Two sets of experiments have been performed to measure the influence of coherent synchrotron radiation (CSR) in the bunch compressor magnet chicane on beam parameters. During the 1st set of experiments the emittance growth and bunch-length was measured as a function of deflecting angle and bunch charge. In the 2nd set, the energy loss and spectral distribution has been measured in addition. The results of the 1st set are reported in [22] and of the 2nd in [23].

7 SUMMARY AND OUTLOOK

The CTF II has already demonstrated:

- high-charge, tightly-bunched drive beams can be generated, accelerated and manipulated,
- two-beam acceleration at 30 GHz works,
- measured drive-beam deceleration, power transfer & main beam acceleration are consistent with the theoretical model,
- system integration of 30 GHz decelerator/ac-celerator and active alignment system.

The running of CTF II will continue until late 2001. During this time we plan to perform the following experiments and investigations:

1. High power testing of CAS structures using a PETS structure of double length. This should allow to reach gradients in excess of 100 MV/m in spite of the drive beam transmission limitations mentioned above.
2. High-gradient experiments using a set of single-cell cavities with resonant frequencies of 21 GHz, 30 GHz and 39 GHz in the drive-beam. These experiments will be similar to the first experiment of this kind mentioned above and will hopefully help in understanding the mechanisms and frequency scaling of RF break-down phenomena.
3. Another experiment on CSR-induced energy loss and emittance growth. This experiment will use a new magnet chicane optimised for this purpose, and a set

of vacuum chambers of various heights. The main goal is to investigate the suppression of CSR due to shielding by the vacuum chamber.

4. Resolve the remaining problems of the active alignment system.
5. Study the performance of the main-beam 30 GHz high-resolution BPM's

In spite of the very successful experimental program of CTF II, it has not been possible to keep up with the rapid development of the CLIC design in recent years. At the time the design parameters of CTF II were fixed, the main beam of CLIC was supposed to operate with an accelerating gradient of 80 MV/m, an RF pulse length of 12 ns and with either single bunches or trains of a maximum 10 bunches [24]. The present CLIC design, however, assumes for the main beam a 120 ns RF pulse length, an accelerating gradient of 150 MV/m and a train of 154 bunches [1]. To demonstrate some key aspects of this new design, namely the drive beam generation scheme and the nominal RF pulse length, a new test facility, baptised CTF 3, has been proposed and approved [25]. The construction of CTF 3 will start after the final shutdown of LEP, reusing buildings and equipment from the present LEP pre-injector.

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