THE CLIC TEST FACILITY 3 INSTRUMENTATION

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Abstract

Built at CERN by an international collaboration, the CLIC Test Facility 3 (CTF3) aims at demonstrating the feasibility of a high luminosity 3TeV e^+-e^- collider by the year 2010. The CLIC project is based on the so called 'two-beam acceleration scheme' where the RF accelerating power is provided by a high current high frequency electron beam. The required performances put high demands on the diagnostic equipment and innovative monitors have been developed during the past years. This paper gives an overview of the instrumentation developed at CTF3 with a special emphasis on short bunch length measurements, nanometer beam position monitors, femtosecond synchronization technique and high dynamic range beam imaging system.

INTRODUCTION

In the framework of the Compact Linear Collider (CLIC) project [1], a test facility named CTF3 [2] is constructed at CERN by an international collaboration. It shall demonstrate by 2010 the key technological challenges for the construction of a high luminosity 3TeV e^+-e^- collider. The two main issues to be addressed on CTF3 are the development of 100MV/m 12GHz accelerating structures and the generation of the CLIC RF power source which is based on the production of a high frequency high current electron beam, called Drive Beam. The layout of the CTF3 machine is depicted in Figure 1.

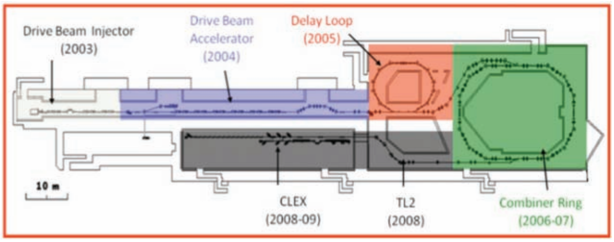

Figure 1: Overview of the CTF3 complex

In the present scheme, a long train of bunches with a bunch spacing of 20cm is converted into an eight times shorter train with a 2.5cm bunch spacing. The complex starts with a 3GHz linac (twice the bunch frequency) that produces a pulsed electron beam with a present maximum energy of 150MeV. By means of RF manipulation in the Delay Loop (DL), the beam is converted of four consecutive bunch trains, each of them having 7.5A average current and 10cm bunch spacing. The electrons are then injected into the Combiner Ring (CR) using a 3GHz RF deflector [3]. After the 4th turn, the bunch trains are combined into a single one with a current of 30A and a 2.5cm distance between bunches.

The beam is finally extracted and sent to the CLIC experimental area (CLEX) where several beam lines are under construction at the moment. A 'Test Beam Line' [4] will study the reliability and the stability of the Drive Beam decelerator which must operate with a low level of beam losses. A 'Two-Beam Test Stand' is devoted to the test of a relevant CLIC module [5] with Power Extraction and Transfer Structures (PETS) on the Drive Beam side and 12GHz accelerating structures on the Probe Beam side [6].

This paper presents an overview of the CLIC Test Facility 3 instrumentation. The first paragraph is dedicated to essential beam diagnostic to measure position, intensity and size. The second paragraph presents the beam diagnostics specifically developed for the need of CTF3. The third and final paragraph discusses some CLIC specific instruments which are currently tested on CTF3.

ESSENTIAL INSTRUMENTS

Beam Position and Intensity Monitors

Beam position and intensity monitors are the first instruments used when the accelerator is turned on. An overview of the different types of pick-up developed for CTF3 is shown in Figure 2.

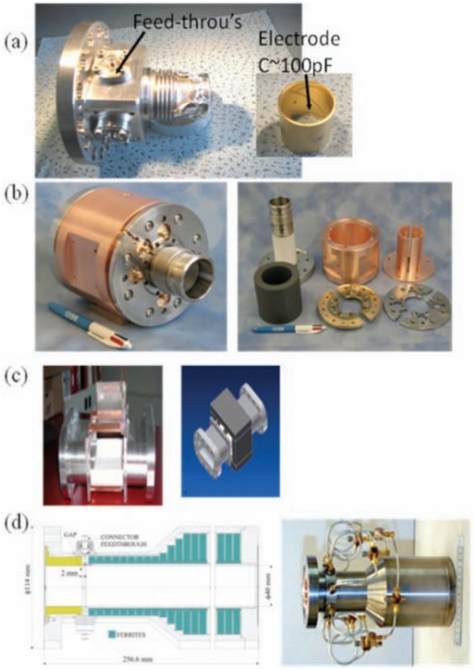

Figure 2: CTF3 Beam position and intensity monitors (a) BPE, (b) BPM, (c) BPI, (d) WCM

In the first part of the accelerator, electrostatic beam position and intensity monitors (BPE) have been installed. They present the advantage of functioning inside the magnetic of the solenoids. Along the linac, inductive pick-ups (BPM) [7] have been developed. They detect the beam image current circulating on the vacuum chamber using eight electrodes. Similarly, inductive pick-ups (BPI) are used in the rings. Their design is slightly modified compared to the BPM, with a racetrack vacuum chamber and a reduced number of electrodes (4). The spatial resolution of the position measurements is better than 100µm, and with a frequency bandwidth ranging from 1kHz up to 200MHz they are sensitive to fast signal fluctuations and can observe the 1.2µs long pulse without any signal droop.

In addition to these pick-ups, Wall Current Monitors (WCM) [8] have been installed all along the machine in order to provide intensity measurements with an absolute precision better than 1%. Their high frequency bandwidth of 7GHz allows them to measure bunch to bunch intensity variations. A preliminary design of the CTF3 machine protection system was based on the measurement and the comparison of consecutives WCM signals [9].

Several acquisition systems have been developed and tested during the last few years. In the linac and in the combiner ring, a front-end electronic system is installed close to the monitors. It combines the signals from the BPM electrodes to generate the intensity and position signals, which are then amplified and sent via long cables onto 100MS/s digitizers located in a nearby technical gallery. In the Delay Loop, the four signals from the BPI's electrodes are directly sent to the digitizers via long cables. The beam position and intensity are computed numerically afterwards. In CLEX, a third choice has been made. The front-end electronic is kept in order to increase the signal to noise ratio but the signals are digitalized in the tunnel using a radiation compatible electronic system developed by LAPP [10]. It has the advantage to reduce by a large amount the cable cost but cannot be used without a control and software interface.

With a total of 104 devices installed in 2008, CTF3 is becoming one of the largest test facility ever built.

Beam Size for Emittance and Energy Measurements

In the list of essential beam diagnostics, the beam profile monitors would come in second. In a linac they are classically used to check the beam optics and measure the beam emittance. Beam profile monitors are also used in spectrometer lines to measure the beam energy and its energy spread.

In CTF3 ten TV stations have been distributed all along the machine for emittance measurements [11] and seven additional units are installed in spectrometer lines. All of them are based on the observation of Optical Transition Radiation. The most recent designs of CTF3 TV stations are presented in Figure 3.

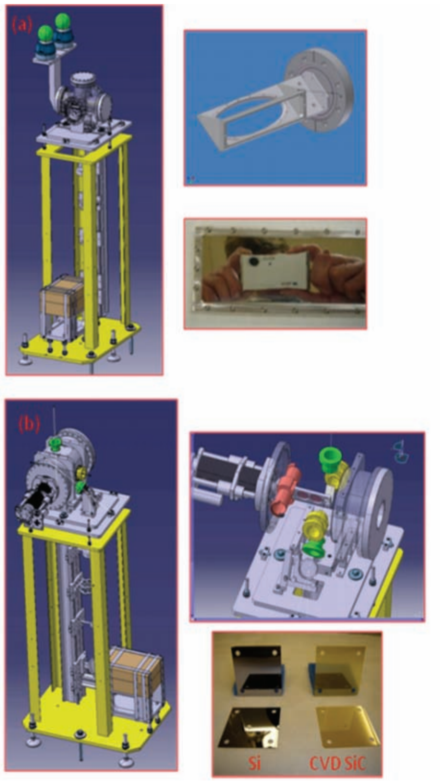

Figure 3: Beam profile monitors based on OTR screens. (a) Designed for energy measurement, (b) Designed for emittance measurement

In the case of emittance measurement, OTR screens are mounted on a 4 positions remotely controlled moving support. The system is designed to provide a spatial resolution that can be adjustable between 20 to 100µm. The 15° tilt angle between the OTR screen and the beam trajectory has been chosen to minimize field depth errors. A high reflectivity silicon screen coated with a thin aluminium layer is used to observe the lowest beam intensity. Higher beam charges are imaged using a CVD Silicon Carbide screen. When the screens are not used, a replacement chamber is put in place to ensure the continuity of the beam line. It suppresses wakefield effects that would become problematic, specially at the exit of the combiner ring, where the beam current increases up to 30A. A calibration plate can be inserted as well to quantify the resolution of the optical system.

In our spectrometer line, a bending magnet kicks the beam horizontally onto an OTR screen where the beam position and its transverse width are monitored. Because the electrons are dumped just after the TV station, the system has been simplified compared to the OTR system developed for emittance measurement. A 45° tilt angle OTR screen is mounted on a fixed support. The dimension of the screen, 100x50mm, fits the large horizontal beam size induced by dispersion. The spatial resolution of the system is typically 250µm. For electron energies higher than 100MeV, the intensity of the synchrotron radiation emitted in the dipole magnet becomes comparable to the OTR light level and perturbs the measurement. Therefore, in order to suppress this effect, a carbon foil has been implemented just in front of the screen and acts as a SR shielding. Moreover, the OTR screen surface is parabolic along the x axis [12,13]. It refocuses the OTR photons onto our camera and improves the linearity of the measurement with respect to the beam position.

In addition to OTR-based monitors, seven TV stations are installed in the machine observing the synchrotron radiation emitted from dipole magnets in the magnetic chicane, the delay loop and the combiner ring.

For all systems, the light is sent onto a CCD Camera via a 1.5m long optical line. Optical density filters mounted on a remotely controlled wheel adjusts the light intensity if necessary. The camera itself is surrounded by a lead shielding but nevertheless due to the high radiation level generated in the machine, cameras must be replaced in average every two years.

These 24 TV stations are controlled by CERN made VME cards [14] which can switch on and off the camera, move the screens in and out of the beam tube, turn on and off a lamp and digitize the image.

CTF3 SPECIFIC INSTRUMENTS

Time resolved spectrometry

In order to optimize the overall efficiency of the Drive Beam generation, the accelerating structures [15] are operated in fully beam-loaded condition, meaning that all the RF power, except for ohmic losses, is transferred into beam energy. In this mode of operation, the RF-to-beam transfer efficiency has been measured at 96 % [16]. The resulting energy spectrum shows a strong time dependency with higher energies in the first 10-50 nanoseconds of the pulse. Time-resolved spectrometry is therefore an essential beam diagnostic to correctly tune the phase of the accelerating structures.

Time resolved beam diagnostics have been developed with the aim of measuring beam energy spread with 50MHz bandwidth. Three spectrometer beam lines are now routinely used along the linac as shown in Figure 4. For low and intermediate beam energies as they are in the first two spectrometer lines, segmented beam dumps are used as detector [17]. They consist of 32 parallel metallic plates designed to stop the incident particles. By measuring the deposited charge in each segment, the horizontal beam profile can be reconstructed. The material and the dimension of the segments must be chosen correctly to provide the required spatial resolution. With our beam parameters, 2mm thick 40mm long tungsten plates have been chosen. Because of the high power carried by the beam, thermal changes represent a crucial issue and radiation effects influence the long term behavior the detector. Therefore, a multi-slit collimator has been installed just upstream of the segmented dump. Its role is to capture as much beam power as necessary to ensure a good signal to noise ratio, but to keep the deposited power in the plates low enough so that they do not need water cooling. Radiation hard ceramics have been chosen as insulating material in between each segment.

For electron energies higher than 100MeV, the input collimator does not work as efficiently and multiple scattering inside the segments degrades the resolution of the monitor [17]. At the end of the linac, an alternative solution has been proposed and uses a 32 channels linear multi-anode photomultiplier (MAPMT) [18]. The latter is installed on the OTR screen of the spectrometer line, where an optical beam splitter has been added and divides the OTR light intensity in two parts, guiding 70% of the photons onto the MAPMT and the remaining 30% onto the camera.

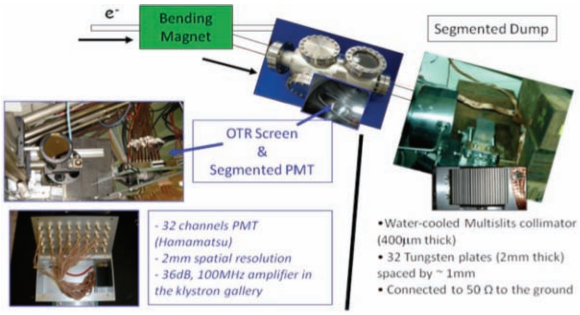

Figure 4 : Spectrometer line equipped with time resolved monitors

An example of the beam spectrum measured on the first spectrometer is shown in Figure 5. The time resolution is better than 10ns, limited in the present set-up by the bandwidth of the digitizers (100MS/s).

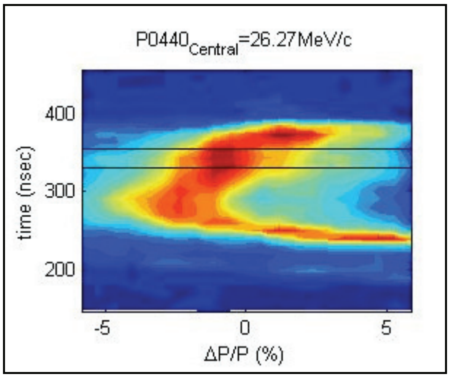

Figure 5: Time resolved energy profile measured at the exit of the CTF3 injector.

Bunch frequency multiplication

The Drive Beam generation relies on the production of high current high frequency electron beam based on a flexible bunch multiplication frequency technique. This is currently performed by means of RF manipulation and RF injection in a delay loop and a combiner ring.

The role of the delay loop is to rearrange the 1.2μs beam-pulse from the drive-beam linac into four 140ns long pulses, separated by 140ns gaps, increasing at the same time by a factor 2 both the current and the bunch repetition frequency. The procedure is schematized in Figure 6.

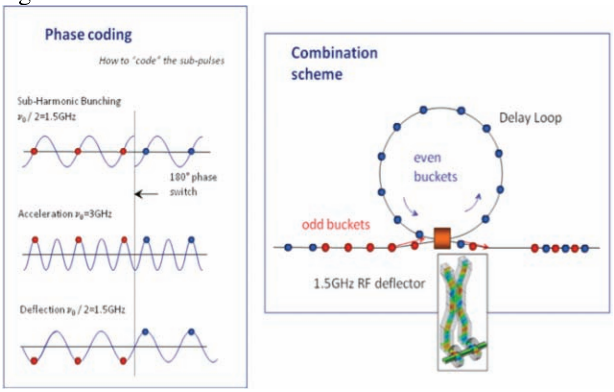

Figure 6 : Operation of the Delay Loop

A transverse RF deflector working at 1.5 GHz sends the first phase-coded sub-pulse (labeled as "even buckets" in the figure) into the delay loop. The loop length of 42 m corresponds to the sub-pulse length of 140ns, thus the "even" bunches are coming back at the deflector at the same time as the "odd" bunches of the next sub-pulse from the linac. The delay loop length can be precisely tuned to be an integer number of the RF wavelength, thus odd and even bunches arrive with opposite phases and receive opposite kicks. However their incoming angles are also opposite, so they are interleaved and combined into the same orbit. The bunch spacing is halved to 10cm and the beam current is doubled. The process also naturally produces a gap of 140ns, essential in the next stage for clean injection in the combiner ring.

The four 140ns pulses are then combined in the ring using a similar principle as depicted in Figure 7. The combiner ring length is equal to the distance between pulses (280ns) and for a four-fold bunch interleaving it is precisely tuned to (*n* + ¼) λ, where *n* is a (large) integer.

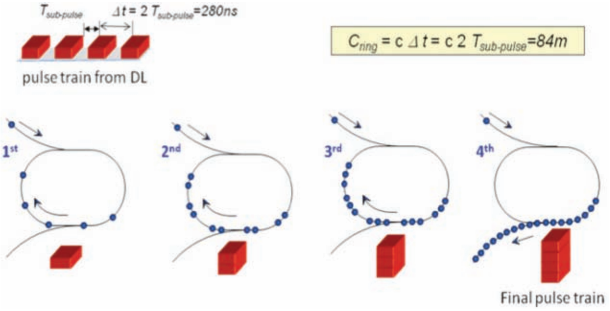

Figure 7 : Schematic operation of the Combiner Ring

A 3GHz RF deflector located after the injection septa kicks each incoming pulse into the closed orbit. Another deflector before the septa is synchronized with the first one to generate a closed bump, such that whenever the injected pulses come round they are kept on the closed orbit. After four turns, the first injected pulse would experience the maximum kick and hit the septum from the inside. Before this happens, the four pulses combined into one are extracted by the kicker on the other side of the ring to be sent to the CLEX area. The beam current is now eight times the initial one and the bunch distance is 2.5 cm, i.e., 12 GHz.

Streak cameras combined with OTR or synchrotron radiation have been used for decades for longitudinal profile measurements. In CTF3 long optical lines have been implemented to connect the OTR screen in the linac and the synchrotron radiation emitted in the rings to the streak camera laboratories [19].

The sub-harmonic bunching (SHB) system is responsible for the phase coding of 'even' and 'odd' RF bucket introducing a 180° phase switch every 140ns. Successfully operated since 2006, the results on the SHB performances can be found in [20]. Streak cameras images have been acquired in order to study the phase coding as presented in Figure 8. The phase switch is performed in 6ns and the presence of 8% satellite bunches at 3GHz that will be lost in the combiner ring gives an indication of the 1.5GHz SHB system efficiency.

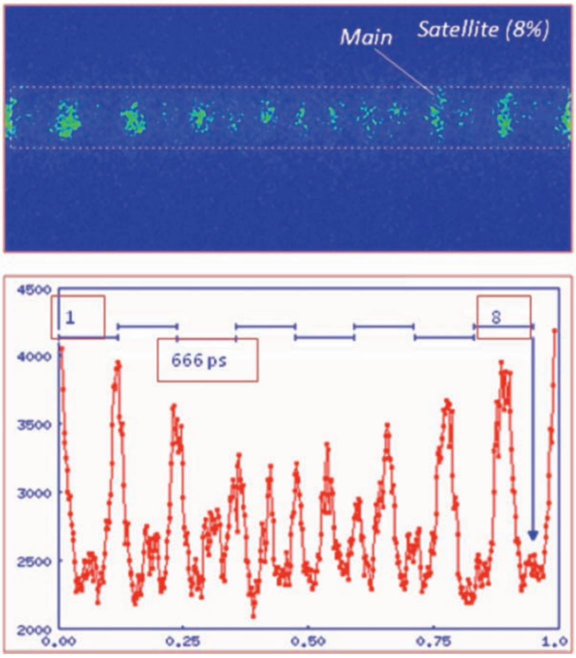

Figure 8 : Observation of the SHB 180° phase switch with a streak camera

The first commissioning of the delay loop was done in 2006 [21] and a bunch multiplication frequency by a factor of two was measured as presented in Figure 9.

In order to control the bunch interleaving, the beam time-of-flight in the ring must be precisely equal to an integer number of RF deflector periods. This is adjusted using an undulator installed in the delay loop, which tunes the path length of the electrons accordingly as shown in Figure 10.

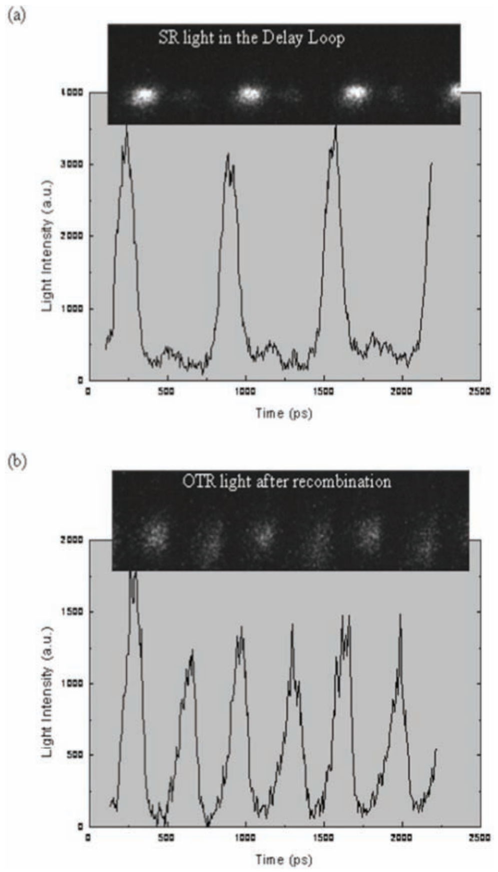

Figure 9 : Streak camera image taken with a sweep speed of 250ps/mm. (a) Bunch spacing of 20cm measured using SR in the delay loop (b) Bunch spacing of 10cm measured after recombination using OTR light.

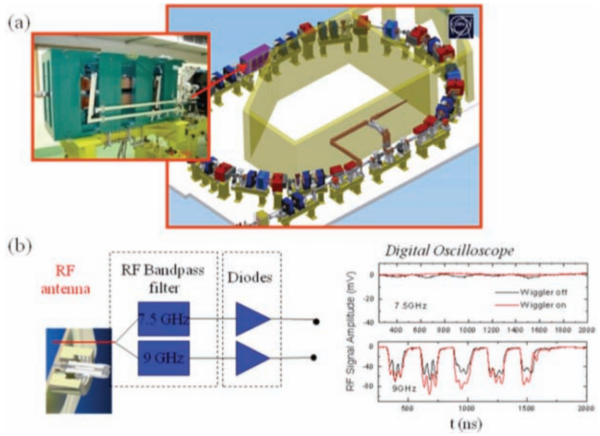

Figure 10 : (a) Picture of the delay loop undulator (b) Principle of the phase monitor with some measured signals taken during the optimization of the bunch train combination in the delay loop.

For the same purpose, a non-intercepting monitor, called ‘Phase monitor’ [22], was installed at the exit of the delay loop. The detector is an RF antenna as shown in Figure 10, which was already tested several years ago at a previous test facility [23]. It measures the amplitude of the electromagnetic field emitted by the particles at harmonic frequencies of 1.5 and 3GHz. In the case of a perfect frequency multiplication from 1.5 to 3GHz, the signal at 7.5GHz would completely disappear whereas the signal at 9GHz would increase accordingly. A typical measurement is presented in Figure 10, where the signal at 7.5GHz is strongly reduced for an optimized tuning of the delay loop length.

Bunch Length Monitors

The bunch length needs to be controlled precisely in the CTF3 complex [24]. In the linac the bunches must remain short to keep the energy spread as low as possible, but need to be stretched before the rings to minimize emittance dilution due to coherent synchrotron radiation. Two magnetic chicanes have been implemented in the machine. The first one, located after the injector, is used to adjust the bunch length before the beam enters in the linac. A second magnetic chicane, installed at the end of the linac, is currently used as a stretcher before the electrons enter in the rings. Typical streak camera measurements are presented in Figure 11.

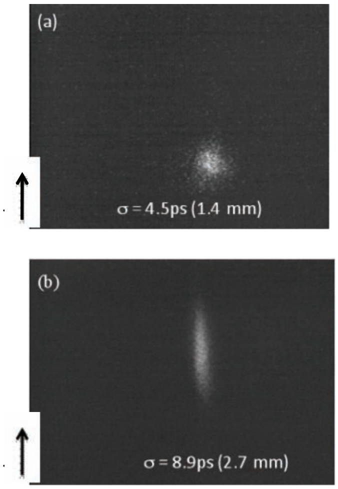

Figure 11 : Streak cameras images taken with a sweep speed of 10ps/mm: (a) Short bunch length from the linac. (b) Stretched bunches at the entrance of the Delay Loop.

In addition to the streak camera, other techniques to measure short bunch lengths have been studied. One of the most promising alternative techniques is based on the use of RF deflecting cavities. As the bunch is passing through the cavity, it experiences a time dependent deflection which converts time into spatial information. By measuring the beam size at a downstream location, the longitudinal profile can be extracted. The time resolution depends on the deflecting power, the beam optics at the location of both the deflector and the beam profile monitor, and finally on the spatial resolution of this monitor. With this method time resolutions of 10fs have already been obtained [25]. In CTF3 RF deflectors are already used for injection in the rings and bunch length measurements can be performed using the same hardware; see Figure 12.

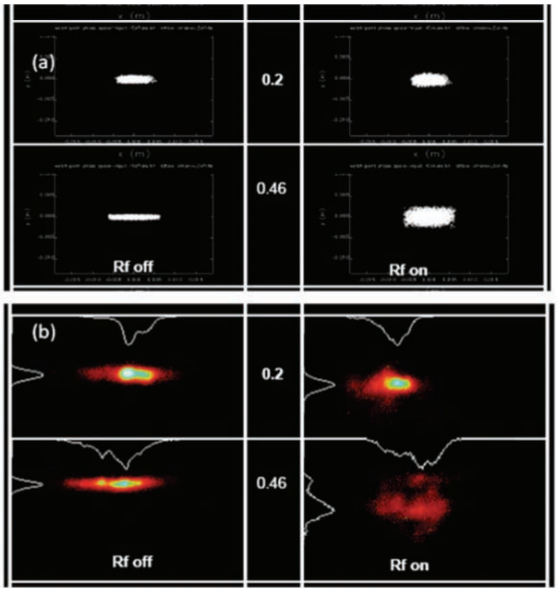

Figure 12 : RF deflector measurements at CTF3 performed for two different bunch compression factors in the magnetic chicane: (a) Estimated beam sizes from simulations (b) Corresponding measured beam sizes.

The deflection is done using the 3 GHz cavity installed just after the 'stretching' magnetic chicane and the beam size is then monitored by an OTR screen. The bunch length is obtained by comparing the measured beam sizes with and without RF power in the deflector. Bunch lengths of 1.2 and 6ps were measured in these cases.

At the same time, non-intercepting bunch length monitors have been developed, in particular through the use of an RF pick-up. The device picks-up and analyzes the power spectrum of the electromagnetic field emitted by the electrons. A simple version, called BPR, has been implemented in the machine since 2003 in order to tune the bunch compression in the first magnetic chicane. Pictures of the BPR components are depicted in Figure 13. The monitor relies on the detection of beam emitted power at 30GHz. The signal from the WR28 waveguide is strongly attenuated using two horns deliberately off centered the one with respect to the other. The RF signal is then bandpass filtered at 30GHz and measured using a schottky diode. The signal is finally digitalized using 100MS/s ADC's.

Three additional BPR's have been installed after the stretcher chicane and in the rings. Reliable and robust, this device gives a signal proportional to the bunch length but cannot provide any absolute measurement.

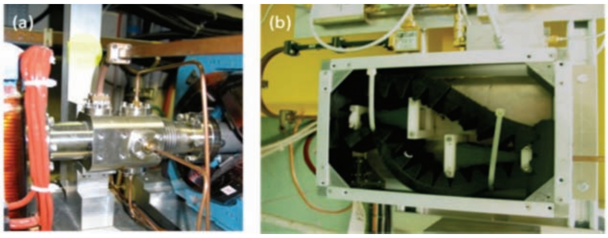

Figure 13: BPR monitor (a) Vacuum assembly installed on the beam line (b) WR28 waveguide components used for the measurement.

A more sophisticated detection system has been developed recently in order to get single shot non intercepting sub-picosecond bunch length measurements [26]. The vacuum assembly of the BPR remains the same but the RF window in alumina is replaced by a thin diamond window, which improves the transmission for high frequencies. Using a series of down-converting mixing stages and filters (see Figure 14), the signal amplitude and phase are measured simultaneously in four different frequency bands: 30-39GHz, 45-69GHz, 78-90GHz and 157-171GHz. Each signal is then digitized using ADCs with a bandwidth of 2 GHz. The system is capable of performing single shot bunch length measurements with a 300fs time resolution.

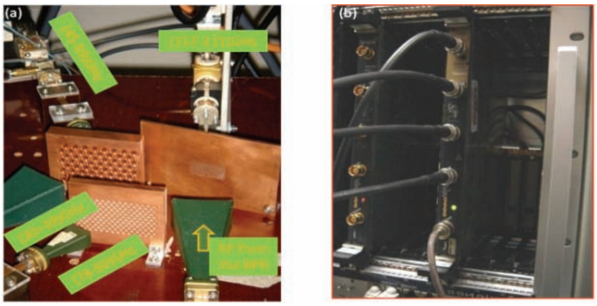

Figure 14 : Bunch length measurement with an RF Pick-up: (a) Waveguide assembly using reflecting brass filters and two consecutives down mixing stages in four different frequency bands (b) 4 channels, 2GHz, 8GS/s digitizer.

The pick-up is installed close to the 1.5GHz RF deflector such that cross-calibrations can be obtained easily. Detailed results of the recent commissioning of the detector are presented in [26].

CLIC-RELATED DEVELOPMENTS

High Precision Beam Position Monitor

In CLIC, the beam position has to be controlled very precisely to minimize emittance growth along the main linac. Beam dynamic simulations have shown that to guarantee the performance of the collider, beam position measurements must be performed with an absolute precision of 10µm and a resolution of 100nm. One approach, which has already demonstrated good performance [27,28], is to develop cavity BPM's. Another alternative pursued at CERN is to scale down the inductive pick-up already developed for the CTF3 linac [7]. The beam tube diameter is reduced by a factor 10 compared to the initial design down to 4mm and the number of electrodes is reduced from 8 to 4 as shown in Figure 15.

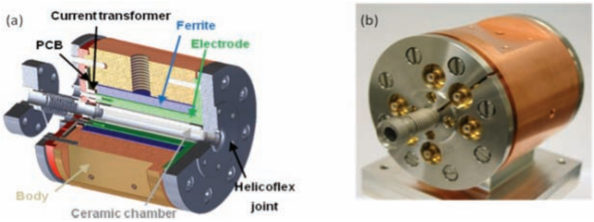

Figure 15 : Nanometer BPM: (a) 3D drawing (b) Pictures of the final assembly.

Three nanometer BPM's have already been build and tested on a vibration free stabilized bench. Calibration results are illustrated in Figure 16. Scaled to the CLIC beam parameter the achieved resolution corresponds to 200nm.

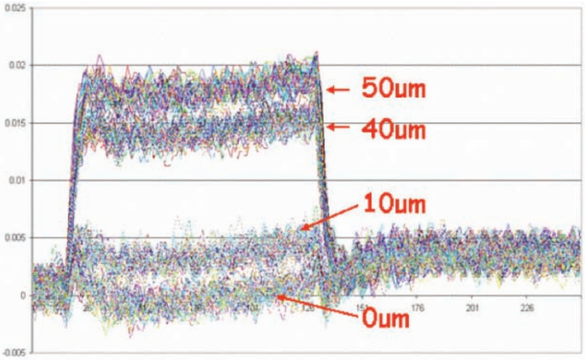

Figure 16: Calibration of the BPM using a stretched wire traversed by a 100mA pulsed current. Each curve represents a different transverse position of the wire.

The three BPM's have been installed at the end of the CTF3 linac (see Figure 17) and a beam test is planned sometime this year.

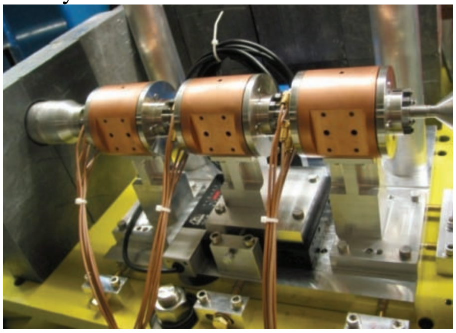

Figure 17: Picture of the nanometer-BPM test in CTF3.

Beam Halo Monitors

For future linear colliders, it must be ensured that particle losses are minimized, as activation of the vacuum chambers or other components makes maintenance and upgrade work time consuming and costly. It is imperative to have a clear understanding of the mechanisms that can lead to halo formation and to have the possibility to test available theoretical models with an adequate experimental set-up. Measurements based on optical transition radiation are a well-established technique for measurements of the transverse beam profile. However, in order to be suitable for halo measurements as well, the dynamic range of the final image acquisition system needs to be high, being able to cover at least five orders of magnitude in intensity changes. In CTF3, high dynamic imaging system has been investigated since 2004. Beam core suppression techniques were tested on CTF3 using a coronagraph [29]. The central part of the beam is masked so that the beam halo can be observed without saturating the camera. The performances at that time were limited to 10^4 dynamic range measurements because the mask had a fixed size which was not adaptable to the real beam size.

Innovative camera based on charge injection device (CID) technology [30], which potentially can reach dynamic ranges up to 10^6, as well as improved beam core suppression technique using adaptive optics [31] have been investigated since then. The latter is based on digital light processing technology using micro mirror arrays as depicted in Figure 18. Composed of individually controllable mirrors, they have the possibility to produce a mask of any geometrical form which can fit perfectly to the beam dimension.

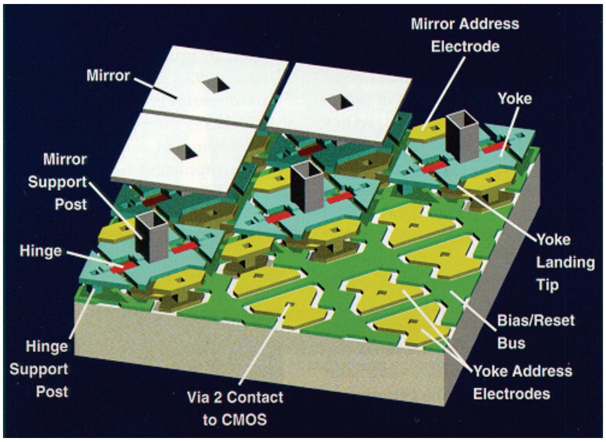

Figure 18: Schematic of a Micro Mirror Array.

In Figure 19, the performance of a standard acquisition system as it is used in the CLIC test facility (CTF3) is compared with CID camera system and measurements performed with a micro mirror array. Adaptive optics and CID technology allow reaching dynamic range higher than 10^5 to be compared with the 10^3 dynamic range of classical CCD cameras.

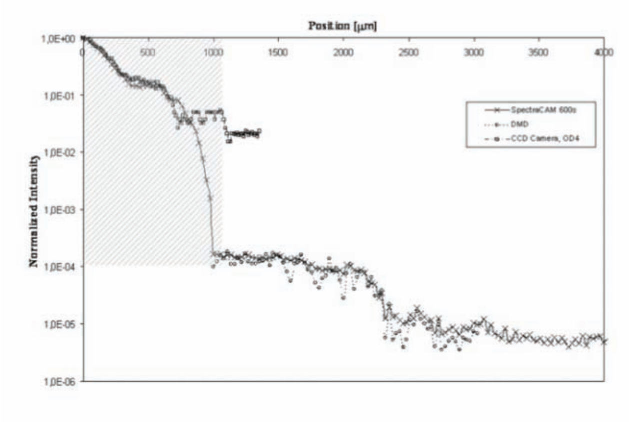

Figure 19: Laser beam profile measured with a CCD camera, a CID camera and a micro mirror array (DMD).

Femtosecond Phase Monitor and Feedback

One important aspect of the two beam acceleration scheme is to synchronize precisely the Main Beam with respect to the RF power produced by the Drive Beam. Timing errors lead to energy variations in the main linac and would have an impact on the collider performance. A jitter of 15fs would give a luminosity reduction of around 2% [32]. It is extremely doubtful that this required tolerance could be met without feedback, feedforward or both types of beam-based correction.

As shown in Figure 20, a possible scheme [33] for CLIC is to measure the arrival time of the Drive and the Main beam in the transfer line between the injector complex and the main linac.

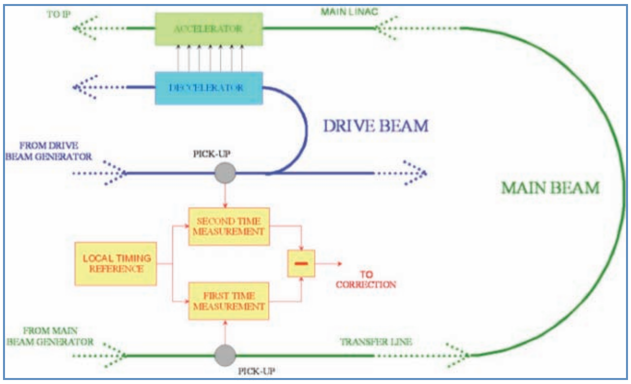

Figure 20: Phase measurement in CLIC.

A precision local clock would be required to keep time from the arrival of the reference until the end of the drive beam train, 92µs later. Precise time measurements of both beams are performed and compared, and depending on the observed difference, a correction on the drive beam would be applied. Corrections could be done using RF structures, either with deflecting cavities or by varying the energy before the final drive beam bunch compressor. The system relies on a precise timing measurement with a resolution better than 20fs.

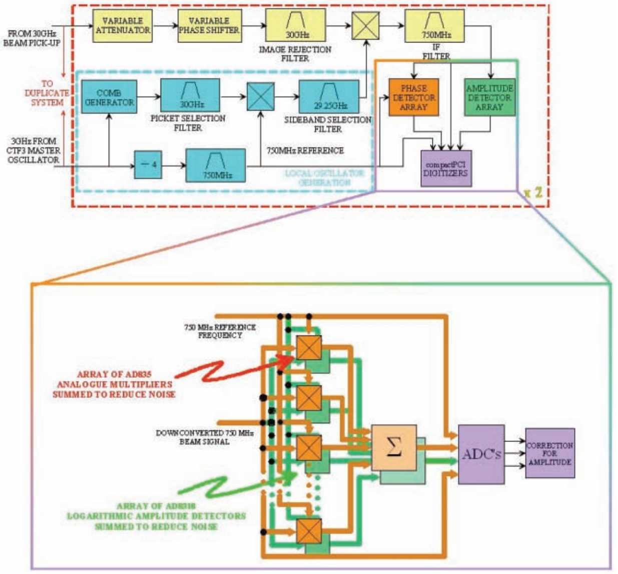

Figure 21: Layout of the femtosecond timing measurement in CTF3.

On CTF3, a heterodyne approach has been taken, measuring the phase of the 10th harmonic of the 3GHz bunch frequency as depicted in Figure 21. The 30GHz component of the beam was sampled in a pick-up and then mixed down to an IF of 750MHz. The phase and the amplitude of this signal are then measured with respectively an array of 8 analogue multipliers and 8 logarithmic amplitude detectors, with their outputs summed and averaged. The phase difference of two independent phase monitors is then computed so that the noise level of the measurement can be estimated. A resolution better than 10fs for a beam timing measurement over 9dB amplitude has been already demonstrated [34].

CONCLUSIONS AND PERSPECTIVES

Since 2003, a large number of beam diagnostics have been developed in the framework of the CLIC test facility 3. New challenges in terms of beam instrumentation development would have to be faced with the construction of the Test beam line [4] and the Two-beam test stand [5] in the CLEX area.

A major step for the CLIC study will be to provide a conceptual design report by 2010. In this context an exhaustive review of beam instrumentation has been initiated. It will critically review all the technical solutions envisaged so far. This work will be based on the expertise gained on CTF3 and also based on the numerous developments performed in the framework of the International Linear Collider project and of the 3rd or 4th generation light sources.

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