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Fast phase switching within the bunch train of the PHIN photo-injector at CERN using fiber-optic modulators on the drive laser

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ABSTRACT

The future Compact Linear Collider (CLIC) e^-/e^+ collider is based on the two-beam acceleration concept, whereby interleaving electron bunches of the drive beam through a delay loop and combiner rings as well as high peak RF power at 12 GHz are created locally to accelerate a second beam, the main beam. One of the main objectives of the currently operational CLIC Test Facility (CTF3) is to demonstrate beam combination from 1.5 GHz to 12 GHz, which requires satellite-free fast phase-switching of the drive beam with sub-ns speed. The PHIN photo-injector, with the photo-injector laser, provides flexibility in the time structure of the electron bunches produced, by direct manipulation of the laser pulses. A novel fiber modulator-based phase-switching technique allows clean and fast phase-switch at 1.5 GHz. This paper describes the switching system based on fiber-optic modulators, and the measurements carried out on both the laser and the electron beam to verify the scheme.

1. Introduction

The future Compact Linear Collider (CLIC) e^-/e^+ collider is based on the two-beam acceleration concept [1], where 24 sub-pulses of the 0.5 GHz drive beam are interleaved through a delay loop and combiner ring to create high RF power, at 12 GHz locally, by deceleration of the drive beam. This is used to power the accelerating structures for a second beam, the main beam. The PHIN photo-injector was developed within the framework of the European CARE program to provide an alternative to the drive beam thermionic gun in CTF3 (CLIC Test Facility 3) at CERN [2]. Based on a specially designed Nd:YLF laser system [3], PHIN delivers 10 ps-long bunches with 2.3 nC charge at 1.5 GHz repetition rate with a total of 1908 bunches per train [4]. One of the main objectives of the CTF3 facility is to demonstrate beam combination from 1.5 GHz to 12 GHz, which requires satellite-free fast phase-switching of the drive beam with sub-ns speed. A detailed description of the beam combination can be found in Welsch et al. [5]. A total of 8 sub-trains (4 odd and 4 even) have to be produced, where each subsequent 140.7 ns-long sub-train, containing 212 10 ps bunches, is shifted 180° in phase. The thermionic source currently in use achieves this by sub-harmonic bunching and phase-switching over 5.7 ns [6]. However, this process results in unwanted satellite charges in the empty RF buckets, which will lead to efficiency loss and excessive radiation downstream in the system. The photo-injector, with the laser-driven gun, provides flexibility in the time structure of the electron bunches being produced by direct manipulation of the laser pulses. The phase has to be 0.5° accurate with respect to the 1.5 GHz RF frequency, equating to less than 1 ps jitter in time. Tight requirements on bunch charge stability for CLIC (< 0.1% RMS) also call for high accuracy in the amplitude of subsequent sub-trains from the coding and the laser. A scheme based on fiber-optic Mach–Zehnder modulators provides a clean, satellite-free switching between two consecutive pulses of the 1.5 GHz oscillator. This paper describes the fiber-based switching system with the procedure for accurate time and amplitude alignment, and its integration into the photo-injector laser setup. Measurements are given, carried out on both the laser and the electron beam, which verify the scheme.

2. Phase-coded photo-injector laser

2.1. The laser

An Nd:YLF mode-locked laser oscillator at 1047 nm, synchronized with an accuracy of less than 500 fs to 1.5 GHz of the

Abbreviations: Compact Linear Collider, CLIC; CLIC Test Facility 3, CTF3; CTF3 Photo-injector, PHIN

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machine's RF delivers a train of 5.5 ps mode-locked pulses with an average power of 320 mW. This is followed by two high power diode pumped amplifiers running in burst mode, reaching steady-state saturation to aid stability [7]. Up to 120 μs long flat pulse train is delivered, with up to 6 μJ/pulse and 8.5 ps pulse width. Fast Pockels cells, with ~5 ns rise time, cut the required number of pulses. For efficient photo-emission with Cs_2Te photo-cathodes, the pulses are then converted to the 4th harmonic at 262 nm and transported to the photo-gun. The 2.5-cell, 3 GHz RF gun with emittance compensation delivers the 2.3 nC/bunch charge with 1908 bunches in the train [4].

2.2. Design considerations for phase-coding

The specification of the phase-coded train is listed in Table 1. In the past, a system based on fast-switching Pockels cells at the end of the laser chain had been considered. However, for good transmission at high laser power levels, a ~7 kV of ~7.1 MHz pulsed drive voltage is necessary, which, together with the fast rise and fall times of < 500 ps, is too challenging for the solid-state voltage switches available at present.

The demand for high bandwidth switches for telecommunication has promoted the advance of fast fiber-optic modulators with reliable long-term stable operation [8]. Polarization switches based on gallium arsenide (GaAs), used in the same way as Pockels cells, are now available in the market with 40 GHz bandwidth, but are limited to the telecommunications wavelength of 1.5 μm [9]. Lithium niobate ($LiNbO_3$) fiber-optic modulators have been developed at 1 μm wavelength for amplitude modulation, and offer a high extinction ratio of 40 dB [10]. The waveguide-based Mach–Zehnder interferometer consists of a Y split, where the polarized optical input signal is split into two equal components. One arm contains the electro-optic crystal ($LiNbO_3$), where a phase-shift can be introduced by applying a voltage across the crystal. The two arms are then recombined, and, depending on the relative phase, interfere either constructively or deconstructively, giving an output signal that is $\sin^2$-dependent on the applied voltage [11]. The high bandwidth of 10 GHz, available at the laser's 1047 nm wavelength, ensures the fast rise time necessary for the application. To achieve a high extinction ratio, stable active control of the operating point (bias voltage) is necessary. However, $LiNbO_3$ suffers from photorefractive damage, and power levels at 1 μm are limited to 100 mW average power. Depending on the manufacturing process, each modulator will have a different damage threshold, which is estimated to be ~4 W peak power in pulsed operation. At low power, $LiNbO_3$ modulators are expected to have a 20-year lifetime under laboratory conditions, and the small physical size of the modulator ensures that there is no additional jitter to the timing of the laser.

Table 1
Coding system specifications.

Switching required for	> 400 μs
Burst repetition rate	1–50 Hz
Length of sub-pulse	~140.5 ns (212 pulses)
Switching frequency	~7.1 MHz
Delay between generated sub-pulses	333 ps
Pulse timing stability	< 0.2 ps
Amplitude stability	< 0.1% rms

Therefore, a $LiNbO_3$ fiber optic modulator was chosen as the switching element for the phase-coding setup. To comply with maximum input power constraints, it was installed after the laser oscillator, where the pulse energy is the lowest.

2.3. Phase-coding setup

The setup to provide the phase-coded train of pulses is shown in Fig. 1. The light leaving the 1.5 GHz mode-locked oscillator is coupled into a single-mode polarization maintaining fiber splitter. One arm contains a variable delay line (Ozoptics, ODL-300), consisting of an input and an output collimator, and free-space manually adjustable delay, which provides the total delay of 333 ps to the second arm (180° phase shift at 1.5 GHz). The second arm contains a variable attenuator (Ozoptics BB-700) to match the total attenuation in the delay arm. The modulators (Photline Techn. NIR-MX-LN-03) use the same drive signal, with separate voltage amplifiers, to adjust the working point and are driven 0%–100% transmission mode in one case and 100%–0% in the other. The output of the modulators is then added using a non-polarizing beam splitter in reverse. This results in a signal in which every second sub-train is delayed by 180° (333 ps in time) as shown in Fig. 2. The transmission of the setup was 1.5%, and is defined mainly by losses on injection to the fiber, splitters and connectors used for its assembling. The signal is then amplified to 200 mW using a fiber amplifier (Fianium FPA-320 mW) to bring the power level back to the oscillator's level, and is then coupled back into the rest of the laser chain (Fig. 3).

2.4. Amplitude and timing accuracy

To achieve high extinction ratio a bias voltage has to be applied to the modulators to set their working point, which is provided by a bias controller (MBC-DG-BT Photline). The active controller also has a feedback system to compensate for the drift of the bias point. The required RF modulating signal was produced by a custom made electronic designed at CERN creating a square

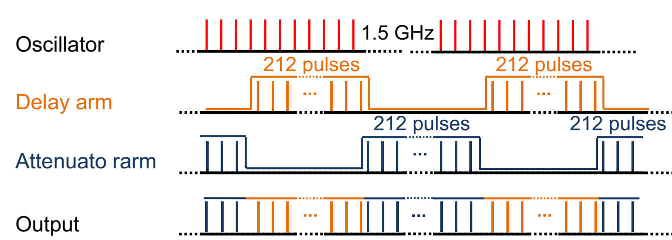

Fig. 2. Timing structure after phase-coding.

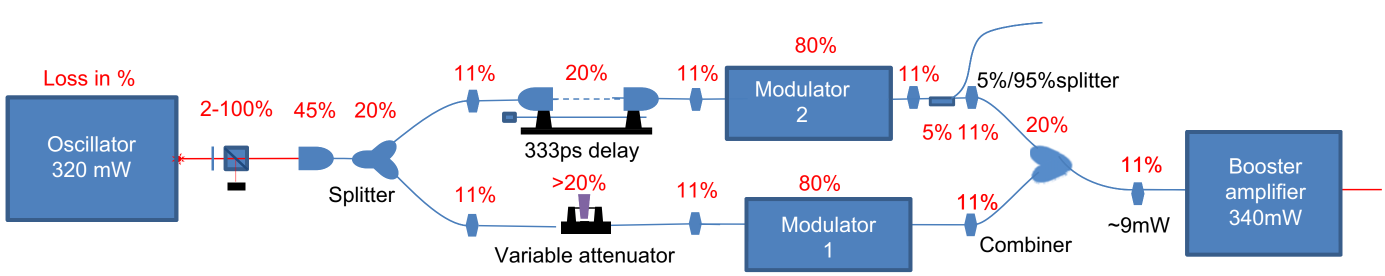

Fig. 1. Phase-coding setup with power losses marked.