DESIGN, TESTING AND OPERATION OF THE MODULATOR FOR THE CTF3 TAIL CLIPPER KICKER

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Abstract

The goal of the present CLIC Test Facility (CTF3) is to demonstrate the technical feasibility of specific key issues in the CLIC scheme. The extracted drive beam from the combiner ring (CR), of 35 A magnitude and 140 ns duration, is sent to the new CLic EXperimental area (CLEX). A Tail Clipper (TC) is required, in the CR to CLEX transfer line, to allow the duration of the extracted beam pulse to be adjusted. Fours sets of striplines are used for the tail clipper, each consisting of a pair of deflector plates driven to equal potential but opposite polarity. The tail clipper kick must have a fast field rise-time, of not more than 5 ns, in order to minimize uncontrolled beam loss. High voltage MOSFETs have been chosen to meet the demanding specifications for the semiconductor switches for the modulator of the tail clipper. This paper discusses the design of the modulator; measurement data obtained during testing and operation of the tail clipper is presented and analyzed.

INTRODUCTION

The aim of CTF3 is to investigate the feasibility of a high-luminosity, multi-TeV, linear e^+ e^- collider. The latest CLIC Test Facility (CTF3) is currently being built and commissioned at CERN, the European Laboratory for Particle Physics, by an international collaboration.

The CTF3 [1] includes a 70 m long linac followed by a 42 m delay loop, an 84 m combiner ring (CR) and a CLic EXperimental area (CLEX). The e^- beam pulse extracted from the CR is 35 A and 140 ns: a kicker, termed “Tail Clipper” (TC), is required in the transfer line to CLEX to adjust the length of the beam pulse. The TC must have a fast field rise-time, of 5 ns or less, to minimize uncontrolled beam loss. The maximum required duration of the tail clipper field is 140 ns: the flatness of the kick pulse is not important as deflected beam is to be discarded in a graphite collimator [2]. The TC has four sets of striplines: each of the deflector plates of a stripline is driven by an equal but opposite polarity pulse. Table 1 shows the TC kicker system parameters.

Table 1: Tail clipper kicker system parameters

Beam energy	200	MeV
Total deflection angle (vertically up)	1.2	mrad
Stripline plate separation	40	mm
Field rise-time (0.25% to 99.75%)	≤5	ns
Pulse duration	up to 140	ns
Initial repetition rate	5	Hz
Nominal repetition rate	50	Hz
Timing jitter	≤1	ns
Required pulse voltage between striplines · stripline overall length	4.8	kV·m

DESIGN

General

For striplines without dielectric or magnetic material, the angle of deflection due to the electric and magnetic fields are equal when the beam is travelling at the velocity of light (*c*): deflection due to the magnetic field is independent of the impedance of the striplines. In order to make use of commercially available components, such as coaxial cables and feed-throughs, an impedance of 50 Ω has been selected: each system is composed of two 50 Ω Pulse Forming Lines (PFLs), two fast switches, 50 Ω stripline plates and two matched terminating resistors (Fig. 1). In order to achieve the required 140 ns pulse duration, with some margin, each PFL is a 17 m length of HTC-50-7-2 coaxial cable (delay = 5 ns/m). The transmission line at the input and output of the striplines is also HTC-50-7-2 coaxial cable. The PFLs, fast switches, control electronics and terminating resistor are situated outside the high radiation environment.

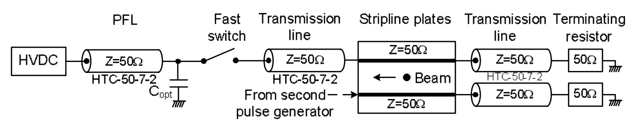

Figure 1: Schematic circuit of a CTF3 TC system.

Striplines

In order that the electric and magnetic fields seen by the beam do not annul each other the striplines must be “charged” from the CLEX (beam exit) end. The two plates of a stripline are charged to opposite polarity; there is a virtual ground mid-way between the two plates. A 1.2 mrad deflection, for 200 MeV electrons, requires ±2.4 kV·m with respect to the virtual ground. To establish the requisite deflection fields the applied pulse wave front must fully propagate along the stripline. To reduce the wave front propagation time, the overall length of the stripline assembly is mechanically sub-divided into 4 sections of equal length of 380 mm, with each section energized a time delay 1.27 ns (0.38 m/*c*) after the previous section, starting with the section at the beam entrance. Each of the four sets of striplines has a length of 0.295 m (feedthrough to feedthrough); this results in an overall stripline length of 1.18 m.

The coaxial feedthrough, interconnecting each transmission line and stripline, is an high-frequency, 50 Ω, hermetically sealed, coaxial connector, type 1084-01-W, from CeramTec [3]. In order to achieve a smooth transition, from the coaxial feedthrough to the stripline, the striplines are tapered to preserve their 50 Ω characteristic impedance and minimize reflections [4].

The beam is expected to be a few mm in diameter, but may also be several mm off centre. Therefore, in reality, there may be some beam at 10 mm radius. At a radius of 10 mm the predicted deflection is up to 4.3% less than the on-axis deflection. Simulations show that, with a stripline length of 1.18 m, ±1900 V (±38 A) pulses result in a deflection of 1.2 mrad on axis. However, to compensate for the field being 4.3% low at 10 mm radius, it is necessary to increase the stripline voltage to ±1982 V to give 1.2 mrad at 10 mm radius (1.25 mrad on-axis). In order to allow for redundancy, and thus increase reliability, the TC is designed such that it will provide the required deflection of 1.2 mrad with any three of the four sets of striplines energized: this requires a pulse voltage of ±2.65 kV for a set of striplines. Since the beam extracted with the TC is to be discarded it is permissible to "over-kick" the beam: ±2.65 kV per set of the four striplines provides a total deflection of 1.67 mrad on-axis and results in a reduction of the rise-time to 1.25 mrad on-axis by ~25%. The ±2.65 kV stripline voltage corresponds to a pulse current of ±53 A. In the event of a failure of one of the kickers, the other 3 sets of striplines will provide the nominal deflection of 1.2 mrad but with an increased rise time. The maximum permissible deflection from the TC kicker corresponds to a ~20 mm vertical offset ~3.5 m downstream of the striplines (2.57 mrad).

Switch

To satisfy the specification for time jitter of ≤1 ns a semiconductor switch is used. Several types of semiconductors have been considered for the TC [5] and the Behlke HTS-80-20-UF MOSFET switch has been chosen for this application. The HTS-80-20-UF is an ultra-fast MOSFET switch rated at 8 kV DC and 200 A pulse current (for a current duration of < 50 ns). Datasheet values are as follows [6]:

- trigger signal voltage: 2 V to 10 V;
- typical turn-on time jitter: 100 ps;
- static on-resistance: 2.7 Ω @ 20 A & 6.8 Ω @ 200 A.

Assuming a static on-state resistance of 3.5 Ω, at 53 A, for the MOSFET switch, a PFN voltage of ±5.50 kV is required to obtain ±53 A of current. This voltage is approximately 70% of the switch voltage rating and is thus considered to be a reasonable value for reliable long-term operation of the switch.

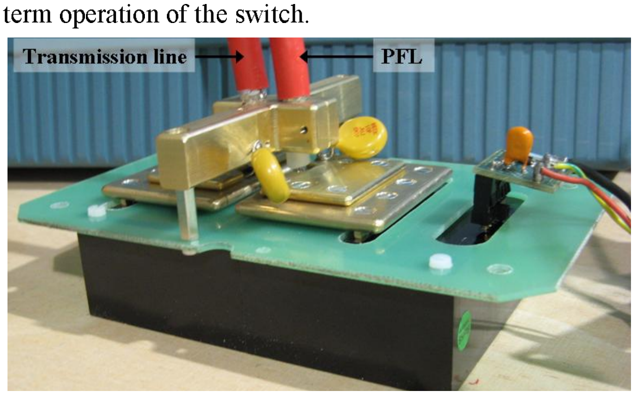

Figure 2: HTS-80-20-UF MOSFET switch, mounted on a circuit board, connected to a PFN and transmission line.

Figure 2 shows a Behlke HTS-80-20-UF MOSFET switch, mounted on a circuit board, connected to a PFL and transmission line. The mechanical configuration provides a low inductance layout. The inductance of the Behlke switch, together with connections to the PFL and transmission line, is ~50 nH. Low inductance capacitors are mounted between switch drain and ground (C_{opt} in Fig. 1). The optimum capacitance is ~50 pF: adding more capacitance does not further reduce the measured 10% to 90% rise-time of the load current, but does increase the maximum and minimum amplitude of oscillations superimposed upon the load current [7].

Measurements of turn-on delay of the HTS-80-20-UF switches versus the voltage of the (5 V) auxiliary power supply show a sensitivity of −7.5±1 ps/mV: thus a high stability DC power supply with low AC ripple is required.

Measurements have been carried out, on several HTS-80-20-UF switches, to determine the effect of the magnitude of the trigger voltage pulse on both load current rise-time and time-jitter of load current delay, with respect to the trigger signal [7]. Fig. 2a of [7] demonstrates that, to minimize the leading edge time (10% to 90%) of the load current pulses (summed with the 3σ time-jitter with respect to trigger signal), the trigger signal magnitude should be 7.5 V or greater. In addition the delay of the Behlke switch turning-on, after receiving the trigger signal, is dependent upon the magnitude of the trigger signal. In order to minimize time jitter in the TC field rise-time, it is important that this delay is repeatable for all 8 Behlke switches employed. Fig. 3a of [7] shows the sensitivity of this delay for two different HTS-80-20-UF switches and both PFN polarities. The sensitivities converge for a trigger signal magnitude of 5.5 V or more and are reasonably flat for 8 V or more. The above measurements indicate the need to use a trigger signal with a fast rise-time (e.g. 3 ns or less) with a magnitude of 7.5 V or above.

Driver Circuit for MOSFET Switches

If independent drivers were used for each HTS-80-20-UF switch, individual time jitter of each driver would increase the effective rise-time of the TC field; and small changes in output voltage of one driver, with respect to another driver, would change the switches delays and increase the effective rise-time of field (see above). Hence a driver circuit has been developed that provides a trigger signal to 9 parallel 50 Ω outputs: one for each of the 8 HTS-80-20-UF switches plus one for monitoring [7].

The turn-on delay of ten different HTS-80-20-UF switches, triggered by the driver, has been measured: the maximum spread in delays is 930 ps. Two coaxial cables, connected in series, are used between the output of the driver circuit and each Behlke switch. One of these cables is used to correct for the turn-on delay of the switches, so that the turn-on of the switches is nominally synchronized. The second, longer, coaxial cable is used to set the relative turn-on time of a Behlke switch, depending on the position of the striplines relative to the beam entrance (see above).

Load

The 50 Ω load resistor utilized is an HVR, axial, type RT818A [8] with an average power rating of 2 W, an impulse rating (1.2 µs/50 µs) of 7.5 kV, and a tolerance of ±10%. The nominal voltage across the load resistor is 2.65 kV, and the nominal energy dissipation is 24 mJ/pulse. Resistance values are measured and selected to obtain a value close to 50 Ω. However the temperature coefficient of resistance results in a reduction of the resistance value with increasing frequency of operation: at 50 Hz the resistance value determined from the magnitude of load current is ~46 Ω. The temperature coefficient of resistance of the load resistors has been measured and is approximately −0.15%/°C.

The load is designed to have a low inductance. There are two fast Current Transformers (CTs), per load resistor: the CTs have a specified rise-time of 0.7 ns and an output of 0.5 V/A into 50 Ω. Detailed measurements with the CTs show that there is a spread in delays of the output from the CTs with respect to the load current: a spread of up to 700 ps, between 20 CTs, has been measured. The length of the output coaxial cable, connected to each CT, has been chosen such that the signal measured at the remote end of this coaxial cable has the correct relative timing for all CTs.

MEASURED LOAD CURRENT

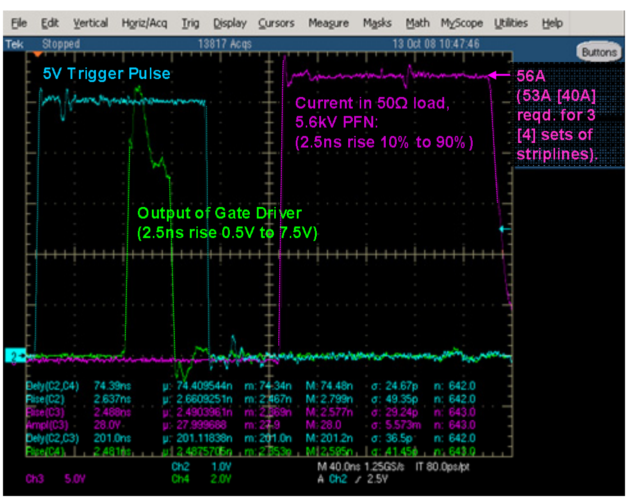

Figure 3: 5 V trigger for driver circuit [cyan trace], output of the driver when connected to nine 50 Ω loads [green trace] and the load current [purple trace] resulting from a PFN charged to +5.6 kV.

Figure 3 shows the 5 V trigger for the driver circuit, the output of the driver when connected to nine 50 Ω loads (eight HTS-80-20-UF switches and the 50 Ω input of the oscilloscope) and the load current resulting from a PFL charged to +5.6 kV. The load current rise-time, between 10% and 90% of the 56 A flattop, is 2.5ns (note: from above, assuming an on-state resistance of 3.5 Ω for the Behlke switch, 54 A of flattop current is expected for 5.6 kV PFL). The 56 A is chosen such that the minimum flattop current, including ripple, is 53 A. The measured load current has been saved to file for subsequent analysis using PSpice: the current is used as an input to an ideal 50 Ω transmission line of delay 0.983 ns (0.295 m); this represents a stripline section. The modelled transmission line is terminated in a 50 Ω load: the voltage difference between the input and output of the transmission line is integrated to predict the stripline field. Using this model the predicted rise time between 0.25% and 99.75% of 1.2 mrad is 3.2 ns assuming all four striplines kickers are functional and 4.0 ns if only 3 of the 4 striplines kickers are functional.

Measurements of time jitter, between the timing signal received at the modulator and the load current, show a (worst-case) 3-sigma time jitter of <300 ps.

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CONCLUSIONS

A deflection of 1.2 mrad, for the 200 MeV beam, can be achieved with ±2.0 kV pulses and an overall stripline plate length of 1.18 m. To achieve a kick rise-time of <5 ns, a segmented kicker system consisting of 4 sets of striplines, each of 0.295 m length (feedthrough to feedthrough), is used. A pulse voltage of ±2.65 kV per set of striplines provides a total on-axis deflection of 1.67 mrad with a rise-time of ~3.2 ns to 1.25 mrad on-axis. In the event of a failure of a single kicker, the TC will operate with three striplines to provide 1.25 mrad on-axis with a rise-time of 4 ns.

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