DESIGN, MANUFACTURING AND TESTING OF 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 of the CLIC scheme. The extracted drive beam from the combiner ring (CR), a pulse of 35 A magnitude and 140 ns duration, is sent to the new CLic EXperimental area (CLEX). A Tail Clipper (TC) kicker is required, in the CR to CLEX transfer line, to allow the duration of the beam pulse to be adjusted: the unwanted bunches are kicked into a collimator. The TC must have a fast field rise-time, of not more than 5 ns, in order to minimize uncontrolled beam loss. Striplines are used for the TC: to establish the required fields, the applied pulse wave front must fully propagate along the striplines. To reduce the wave front propagation time, the overall length of the stripline assembly is sub-divided into 4 sections. The TC has been designed with the aid of detailed numerical modelling: the stripline cross-section and coaxial-to-stripline transitions were carefully optimized using a 3D code. The results of simulations and the measured behaviour of the striplines are presented; in addition measured current pulses are shown.

TAIL CLIPPER DESCRIPTION

The CLIC Test Facility-3 (CTF3) aims to demonstrate the concept behind the high frequency (HF) RF generation with a drive beam of electrons [1]. The Transfer Line-2 (TL-2) transports the electron beam at a nominal energy of 150 MeV (peak energy 200 MeV) from the Combiner Ring (CR) to the CLEX area (CLic EXperimental area). A Tail Clipper (TC) is installed in the TL-2 for controlling the duration of beam pulse delivered to CLEX. The TC can deflect a specified duration of the beam pulse into a collimator: the TC uses stripline technology.

Table 1: Tail Clipper Specifications

Parameter	Value	Units
Beam Energy	200	MeV
Deflection Angle (in vertical plane)	1.2	mrad
Stripline plate separation	≥40	mm
Field homogeneity radius (±20%)	30	mm
Characteristic impedance	50±1	Ω
Required pulse length (max.)	140	ns
Maximum field rise-time (0.25 to 99.75%)	5	ns
Maximum timing jitter	1	ns
Repetition rate (nominal-maximum)	5-50	Hz
Total available straight section length	1625	mm

The TC specifications are presented in Table 1: the TC must have a fast field rise-time of 5 ns or less, to minimize uncontrolled beam loss. 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 [2]. Theoretically a short single section of stripline could be used but an extremely high voltage pulse would be required [3].

DESIGN AND CALCULATIONS

Stripline Cross-Section

Three cross-sections have been considered for the striplines: planar, elliptical and circular electrodes (Fig. 1). In each case an aperture of 40 mm and an electrode width of 2 mm was considered. The circular electrodes cross-section (*c*) has finally been selected to minimize the beam-pipe diameter (decreasing the beam impedance) and to ease the fabrication process while meeting the specification for the deflection homogeneity.
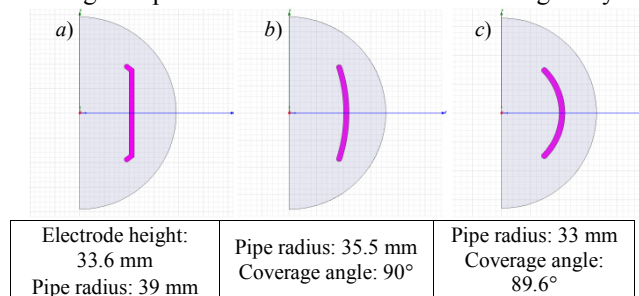

a)	b)	c)
Electrode height: 33.6 mm Pipe radius: 39 mm	Pipe radius: 35.5 mm Coverage angle: 90°	Pipe radius: 33 mm Coverage angle: 89.6°

Figure 1: Analysed cross-sections (note: different scales).

Analytical Calculations

The available space for the stripline assembly is 1625 mm, minus the length required for the flanges, feedthroughs and transitions (~400 mm), leaving ~1.2 m for the striplines: hence the 1.2 mrad deflection angle can be obtained using an integrated transverse voltage ($V_\perp$) of 240 kV. This results in $V_\perp$=60 kV per TC section (set of striplines). The required electrode to ground voltage (V_k) can be estimated from analytical equations to be ~2 kV.

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 [2]. Since the beam extracted with the TC is to be discarded it is permissible to "over-kick" the beam: ±2.65 kV 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% [2]. Pspice simulations show that, to

achieve a field rise-time of ≤ 5 ns, with 3 of 4 sets of striplines, requires a current pulse rise-time of ≤ 3.5 ns.

Coaxial to Stripline Transition

An excellent HF electrical transmission is required to obtain the 3.5 ns current rise time. Therefore, an optimized coaxial-to-stripline transition, using tapered electrodes with constant impedance (50 Ω) to improve the HF matching (Fig. 2), has been designed.
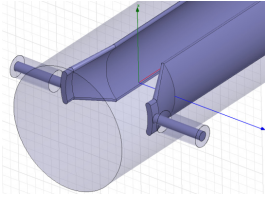

Figure 2: Tapered coaxial-to-stripline transition.

The chosen transition length (25 mm) is a compromise between good HF transmission (long) and high kick strength (short). The kick strength and the homogeneity of the deflection are slightly reduced by the transitions [4], but improved by the curved electrodes. This is taken into account when calculating the required voltage [2].

Frequency Domain Simulation

Frequency domain simulations are carried out using HFSS [5] to obtain the S-parameters and the transverse voltage. The reflection scattering parameter (S_{11}) is plotted in Fig. 3 up to 2 GHz for a 4-port lossy model. However, when the TC is fed in differential mode (S_{11} is calculated in a 2-port lossy model), the reflected power is lower than 0.3% (S_{11}=0.05) up to 400 MHz, which is considered to be the maximum significant frequency of the current pulse. Nodes of the transmission parameters, attributable to identical impedance mismatches in the transitions, happen at $\lambda/2$ (electrode length ≈ 0.3 m).
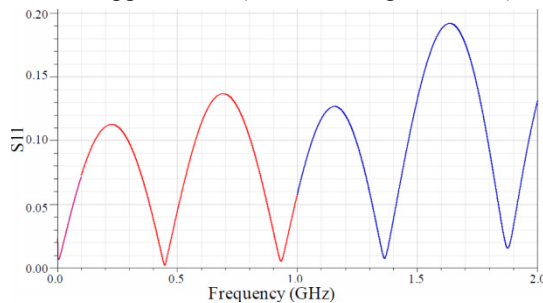

Figure 3: S_{11} (magnitude) simulation for the TC.

The required transverse voltage is ~62.85 kV, slightly higher than the analytically calculated value of 60 kV. The curved geometry of the electrodes increases the field on the axis but the tapered transitions are less effective than the electrodes: neither of these effects is taken into account by the analytical expressions.

HOM Analysis

The dangerous modes are those with the electric field in the longitudinal axis (TM modes) because they affect the power production in the CLEX area. The frequency range to search for TM modes in the equivalent pipes (40 and 67 mm diameter) is between 3.43 GHz and 5.74 GHz: there are many possible modes, but the predicted quality factor of the resonant modes never exceeds 3500. In addition, the possibility to excite dangerous HOMs is very small given that the beam only passes through the TC once: if a HOM is excited, it is damped by the resistive walls in only a few oscillations (low quality factor). Therefore, no HOM damping has been incorporated in the design.

Wakefield Calculations

A 2D axi-symmetrical model has been developed using ABCI [6] to estimate the Wakefield behaviour of the TC. The calculated wake loss factor is 2.34 V/pC for a 3 mm bunch. For CTF3 the bunch charge is 2.33 nC, hence the lost energy passing through the TC is 5.45 keV. The maximum energy spread accumulated by the bunch is 13.7 keV. Both the energy loss and spread represent a very small fraction of the beam energy.
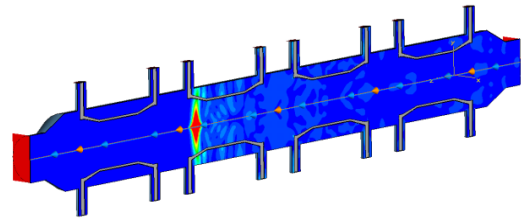

Figure 4: Simulation of a 3 mm bunch in a "short" TC.

To validate the wakefield axi-symmetrical simulations, a 3D simulation of the TC was developed using a short model in CST Particle Studio [7] (Fig. 4). The predicted wake loss factor is 2.22 V/pC; lower but very similar to the ABCI's calculated value, as expected.

MAIN MANUFACTURING CHALLENGES

The material used for the whole assembly, except the electrodes, is stainless steel, type AISI 304L (DIN 1.4306): the 304L facilitates relatively straightforward general assembly and welding of the feedthroughs. The curved electrodes are CNC machined and are therefore manufactured from aluminium (AL6082).

The feedthroughs are constant impedance (50 Ω) and commercially available up to 7 kV DC. They are welded to the TC beam-pipe using an adaptor case and connected to the electrodes using a sliding contact to allow for thermal differential expansion of the electrodes.
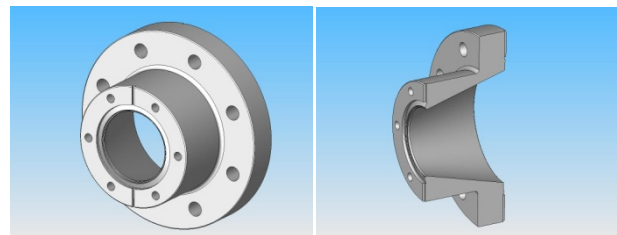

Figure 5: 3D model of the TC beam pipe transitions.

Beam pipe transitions are manufactured by turning and are designed to give a smooth change in inside diameter between CF40 and CF63 flanges (Fig. 5): due to space restrictions the transitions are quite short.

The manufacturing and assembly of the TC was made by the Spanish Company Trinos Vacuum Projects [8].

MEASUREMENTS

A 2-port network analyzer was used for low power RF tests. The four sets of striplines all give a very similar frequency response and hence only the S11 and S12 measurements for one set of striplines are shown (Fig. 6). Differences between measurements and simulations at higher frequencies are explained due to the roughness of the surfaces which increases the losses of the transmission line. This is much more noticeable at higher frequencies.
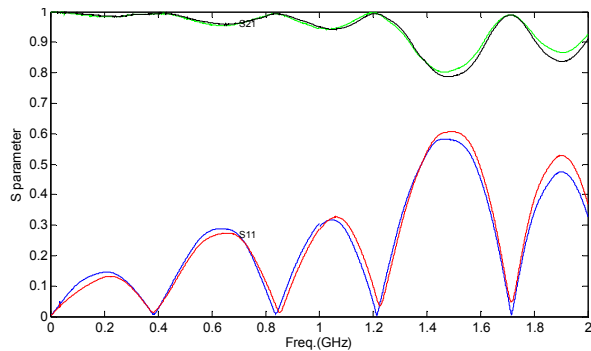

Figure 6: Measurements on one set of striplines.

The vacuum leak rate was very low (2.53.10^{-11} mbar.l/s) and the achieved vacuum level complied with the specifications after a mild bake-out.
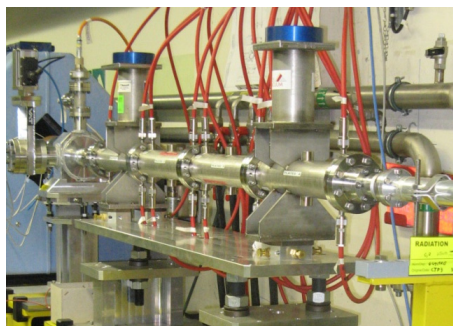

Figure 7: TC installed at CERN in CTF3 TL2 zone.

All 4 sets of striplines were tested at 3 kV DC to ground: no breakdown occurred. Fig. 8 shows a measured load current-pulse in the CTF3 TC installation. The pulse has a 2.5 ns rise-time, which indicates excellent matching of the striplines for the pulse frequency content. Recent measurements with Bergoz [9] Current Transformers (CTs), used to measure the load current, show that there is no significant change in relative timing of the CTs with respect to 12 months ago. However one of the eight Behlke [10] switches shows an increase in relative delay (measured between 50% levels of the leading-edge of the current pulse) by almost 400 ps with respect to the average delay: at the other extreme, another switch shows

a decrease in relative delay by almost 240 ps with respect to the average. However the time jitter, measured over almost 4000 pulses at 5 Hz, is still ~40 ps. Following the measurements, the relative timing of the switches was re-adjusted by trimming the length of coaxial cable to the trigger of several of the switches. Although the 400 ps change in relative timing is less than the permissible jitter of 1 ns (Table 1) it indicates the need to check and adjust the timing of the Behlke switches at annual intervals.
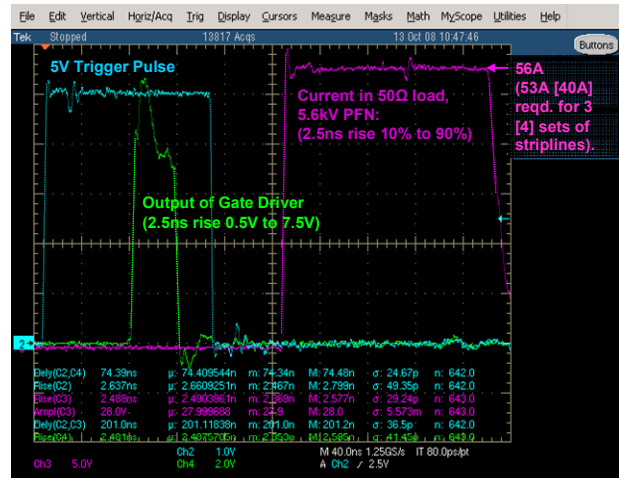

Figure 8: 5 V trigger for driver circuit [cyan trace], output of driver when connected to nine 50 Ω loads [green trace] and load current [purple trace] (PFN charged to +5.6 kV).

CONCLUSIONS

The fast TC has been carefully researched, designed and manufactured. Detailed tests and measurements have demonstrated good vacuum, RF, high voltage and pulse behaviour. The TC has been installed in CTF3 TL-2 and has operated successfully.

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