Transverse Wake Fields in the CLIC Transfer Structure

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Abstract

The transfer structure for generation of microwave power from the bunched drive beam presently consists of a smooth beam tube and a periodically loaded wave guide running in parallel and coupled to it by a slot. The bunches are in synchronous interaction with a forward $2\pi/3$-mode. Both the coupling from the beam to the output wave guide and the wave propagation down the tube have been measured on a scaled model at 8.6 GHz with the wire method, giving the longitudinal beam impedance and wake field. Transverse wake fields can be calculated from the longitudinal ones measured with the wire close to a shorting plate introduced in the centre of the structure. Quantitative estimates are then deduced for the real-scale transfer structure at 30 GHz and compared with results obtained from the three-dimensional MAFIA package, both being in good agreement. While the longitudinal wake fields from leading bunches are in phase with the following bunches, the transverse wake fields have a 90° phase offset. The wake field functions resulting from these studies have been inserted into the tracking program DTRACK and the transverse beam blow-up obtained seems to indicate that the effects of such wake fields remain tolerable.

I. INTRODUCTION

CERN Linear Collider (CLIC) studies are based on a two-linac scheme. The main linac accelerates the beam towards the experimental collision point, while the drive linac carries the strong beam to generate the required power. The drive beam is made of trains of intense bunchlets and its dynamics includes specific features [1]: the energy differences between bunchlets a.e unusually large due to increasing decelerating field, the energy spread within individual bunchlets is strong since the bunch length σ_z is assumed to be 10% of the 30 GHz wavelength, and the wake fields may endanger beam stability.

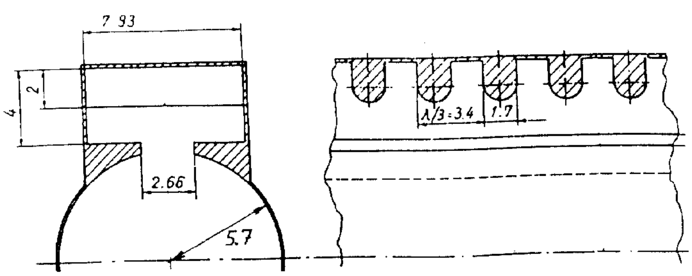

Fig. 1 Upper half of the vertically symmetric CTS showing the round beam chamber and the upper periodically loaded wave guide with $\lambda/3$ cells. The wave guides are charged with EM energy through constructive interference at the passage of bunch trains.

The impact of these features in the presence of misaligments, trajectory corrrections and magnetic focusing has been studied by tracking with the code DTRACK [1]. Since tracking requires a wake field description as realistic as possible, these fields were actually measured and calculated for a recent model (Fig 1) of the CLIC transfer structure (CTS). Simulations include ever since synchronous transverse fields and focus on the option of CLIC with a c.m. energy of 500 GeV and an RF frequency of 30 GHz [2].

II. CTS MODEL MEASUREMENT AND MAFIA SIMULATION

The Wenzel-Panofsky relation $j\omega\Delta p_x = -\partial(\Delta E)/\partial x$ [3] (x transverse co-ordinate, Δp_x transverse momentum kick, ΔE energy change at x caused by modes associated with the transverse kick only) together with the usual definitions

$$\Delta E = -Z_{||} e i(\omega) \quad \text{and} \quad \Delta p_x = -j Z_{\perp} e d i(\omega)/c$$

(d transverse beam offset, $i(\omega) = q(\mathrm{Exp}(-\omega\sigma)^2/2)$ spectral beam current for a gaussian bunch with charge q, σ RMS length) and with a linearity assumption $\Delta E(x,\omega) = \Delta E(d,\omega)x/d$ yields the simple relation

$$Z_{\perp}(\omega) = cZ_{||}(\omega,d)/\omega d^2$$

between the longitudinal impedance at d and the transverse one. In practice a measurement of the transmission S_{21} along a traversing wire of characteristic impedance Z_0, offset by d from a shorting mid-plane (suppressing all parasitic E_{0N}/H_{0N} modes), allows the evaluation first of

$$Z_{||}(\omega,d) = 2Z_0\,(1-S_{21})/S_{21}$$

and then of $Z_{\perp}(\omega)$ from $Z_{||}(\omega,d)$ as described above. The transverse kick $\Delta p_x(t)$ is subsequently calculated via inverse Fourier transformation of $-jedi(\omega)Z_{\perp}(\omega)/c$ (see Fig. 2). The cumulative wake from many bunches is obtained by superposition. The wake is shown at time intervals of 5 RF cycles (167 ps) after the passage of the single bunch that created the wake. The wake exhibits zero crossings at the centres of subsequent bunches. This wake results from a non-centred bunch inducing unequal fields in the 2 opposite wave guides. It fades away as the energy in the wave guides propagates out of the CTS.

The CLIC transfer structure was simulated using the code MAFIA 3D on a SUN IPX workstation [4]. A twelve-cell section of the structure with some 120'000 mesh points was used in the time domain processor T3310 to find the wake fields induced by a bunch of charge 1 pC with a longitudinal dimension $\sigma_z = 1$ mm. The longitudinal wake field was found placing the bunch on the axis of the cylindrical beam chamber, while for the transverse wake the bunch was offset 1 mm vertically away from the axis.

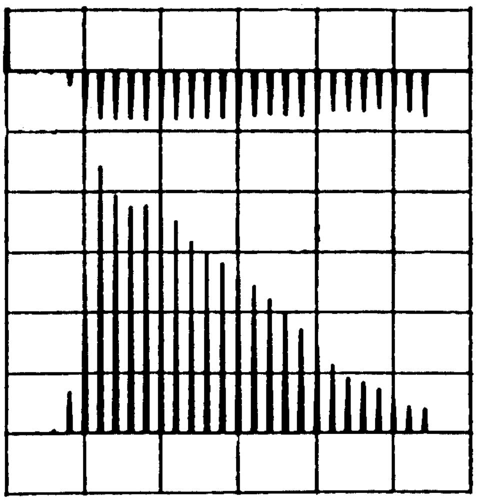

Fig.2 Phase (90°/div.) and amplitude (12.2 V/pCm/div) of the CTS wake obtained from inverse Fourier transformation of measured wire transmission data $S_{21}(\omega)$

The transverse wake field is the most dangerous for beam stability. Its calculated shape is shown in Fig. 3

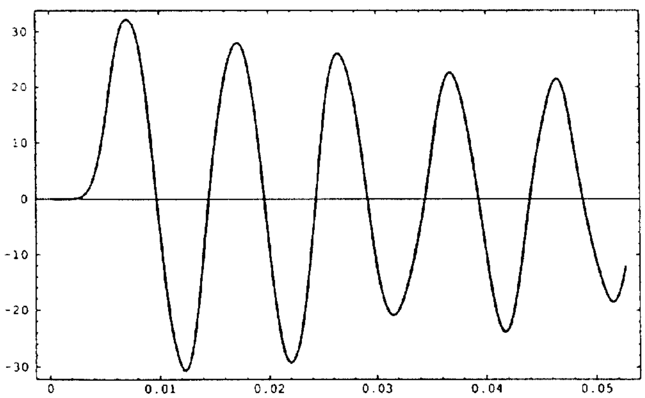

Fig. 3. Transverse wake field of one bunch with charge 1pC traversing one CTS structure. (Vertical scale: V/pCm, horizontal scale: m).

The peak value of the transverse wake field found in the simulation corresponds to a peak deflecting field of 32 V/pCm for one CTS structure with 144 cells. This value is slightly lower than the one found by model measurement.

III. BEAM DYNAMICS

Unavoidable acceleration at low frequency and 30 GHz power transfer force the use of several trains with bunchlets separated by λ_{RF}. The difficulty of generating short and intense bunchlets pleads for a relatively large number of these with lower population. A proposal to use, beside the superconducting (SC) 352 MHz cavities, harmonic cavities 2 and 4 [5] makes it possible to lengthen the pre-acceleration ramp such as to accelerate up to 43 bunchlets instead of 11 as in the simplest arrangement (reducing the bunchlet charge from 160 to 40 nC). In order to partly counterbalance beforehand the beam energy deposition, the bunchlets may have different injection energies, increasing from the beginning to the end of a train following the pre-acceleration ramp. Using harmonics, this ramp can last 180° at 352 MHz but have the shape of a sinus function between 45° and 90° at 88 MHz for instance (Fig. 4, thick curve). Since the focusing drops with energy in the last part of the linac and the phase advance increases monotonously, the last bunchlet has to be injected at about 3.5 GeV to avoid betatron instability. This implies an energy of about 2.3 GeV for the first bunchlet.

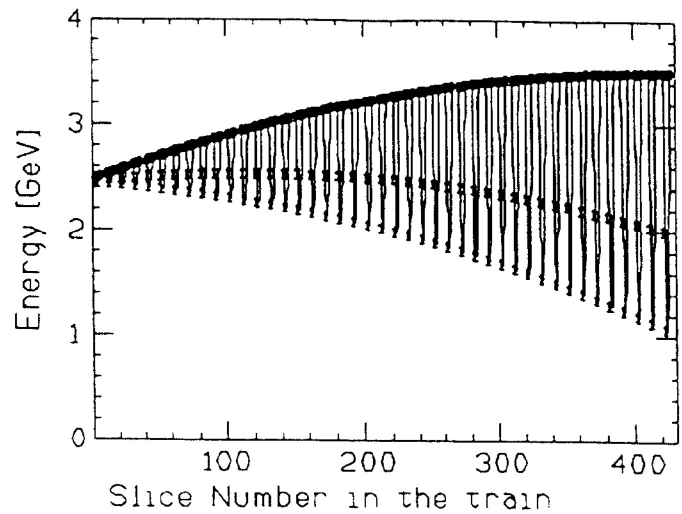

Fig. 4 Initial (thick curve) and final (thin curves) bunchlet energies in the drive beam.

Hence, in a 3.5 km drive linac, the energy of the train tail falls to ~1 GeV, which satisfies the two conditions [6]

$$\left\langle \gamma^2 \right\rangle \ge \frac{L_t}{2\sigma_z} \qquad \left\langle \gamma \right\rangle \ge \frac{\gamma \varepsilon_y L_t}{4\sigma_z} \left\langle \frac{1}{\beta} \right\rangle$$

that velocity spread due to finite energy and path length spread due to transverse emittance do not make bunches drift apart. If the linac length L_t = 3500 m and σ_z = 1 mm, the first condition (the most restrictive) gives an energy threshold of approximately 0.7 GeV. The second condition is less restrictive mainly because we assume an r.m.s. normalised emittance $\gamma\varepsilon_y$ of 5 10^{-4} rad m for 2.5 10^{11} particles per bunch. Such a value prevents intermediate re-acceleration in the 3.5 km long linac (500 GeV c.m. option).

The wake field model includes now two components: i) the fundamental modes that are synchronous with the beam at 30 GHz and come from model measurements and computations, ii) the asynchronous part that is calculated for a circular and smooth resistive pipe. With a charge of 40 nC the decelerating field per bunchlet is about 17 kV/m and the worst transverse wake field (measured peak value) is $\sim 2 \cdot 10^6$

V/m. The synchronous wakes increase linearly from bunchlet to bunchlet, but the longitudinal amplitude has peaks at every bunch centre while the transverse one is shifted by 90° and has zeros at bunch centres. Wake field effects have been investigated for misalignments of 50μm r.m.s. for quadrupoles and transverse structures and of 5μm r.m.s. for the position monitors. Trajectory is corrected on the basis of measurements integrated over the whole train and with a one-to-one algorithm. Focusing has to begin with a phase advance of 30° at 3.5 GeV (last bunch) in order to avoid a core instability near the linac exit at ~1 GeV. Betatron functions must however remain low so that the emittances stay confined within the linac acceptance. This is achieved by having quadrupoles every 2 m, i.e. a total of ~1750.

Longitudinal wake fields induce strong energy variations as shown in Fig. 4. Bunchlet cores have energies between 2.3 and 1 GeV while heads and tails maintain their injection energies (from 2.3 to 3.5 GeV). If the Twiss functions remain constant for the first bunch whose energy does not change much, they may vary a lot for the last one. Its phase advances rise from 30° to close to 180° and its β-function, which decreases initially, increases when $\mu > 90°$ (Fig. 5) and the beam sizes blow-up. When β_{min} reaches zero, focusing instability occurs and this point has to be kept beyond the linac exit (Fig. 5).

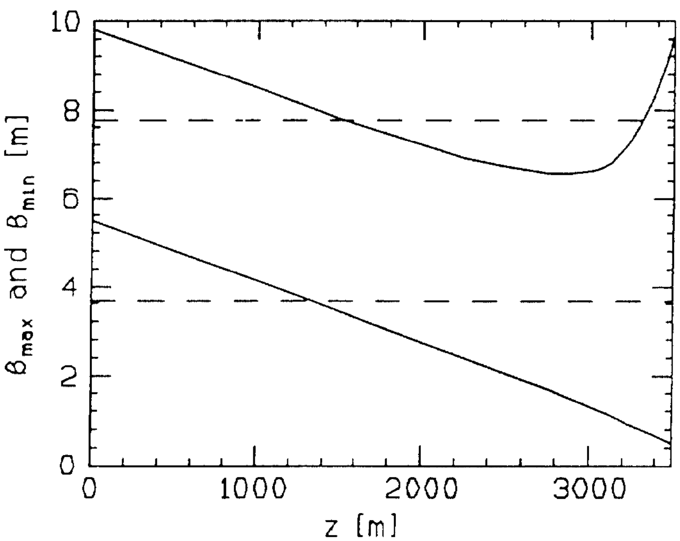

Fig. 5 Betatron functions for the first (dotted line) and the last (full line) bunchlet.

Furthermore, β-functions differ between the head, the core and the tail of the bunchlets because of strong energy variations. Hence, when the contribution to emittance blow-up of transverse wake fields is calculated, the emittances of these different parts of the bunches are tracked and normalised separately. They are eventually compared to the pipe acceptance to verify that the beam gets through the linac. Fig. 6 shows a plot of the vertical core emittances at the end of the linac, which are confined within the acceptance represented by a circle tangential to the frame.

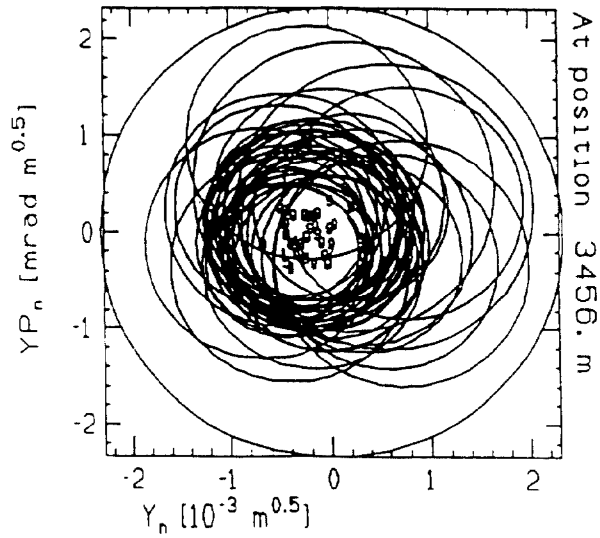

Fig. 6 Vertical bunchlet emittances at the linac exit.

IV CONCLUSIONS

Transverse wake fields of CTS have been actually measured on a model and calculated with MAFIA, both results being in good agreement. Beam tracking in these conditions indicates that all the bunchlets remain inside the linac aperture over the required 3.5 km, provided the injection energy is adjusted along the train. With the retained parameters the stability limitation comes not so much from the wake fields due to the transfer structure as from the drop of the focusing with energy.

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