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SIMULATION OF THE CTF DRIVE BEAM LINE AND COMPARISON WITH THE EXPERIMENT

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CERN, Geneva, Switzerland

Abstract

The tracking of particles in accelerating structures is presented for cases where the effects of the wake-fields are high. This is particularly the case when the structures are used with high current and relatively low energy as in the drive beam of the Compact Linear Collider Test Facility (CTF 2) with its 3 GHz accelerator and its 30 GHz decelerator. High initial energy spread and transverse wake-fields may impair the beam stability and generate particle loss. The CTF modelling is made with the code PARMELA for the 3 GHz part of the beam line, which includes 3 GHz accelerating sections and a magnetic bunch compressor. For the part containing the 30 GHz power-extracting structures, simulations are done with WAKE, a new algorithm dealing with the effects of the wake-field modes 0 and 1, as well as of the group velocity. Beam transmission through the overall beam line is studied, and results are compared with measurements made on the CTF beam.

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1 INTRODUCTION

CTF 2 [1] is designed for testing the CLIC two-beam acceleration. The drive beam line is sketched in Fig.1. A total of 48 short electron bunches with a typical charge of 10 nC and an rms length of 1mm are produced and accelerated to 7 MeV in a 3 GHz RF gun with a laser-driven photo-cathode. The division of the charge in a bunch train and the rapid acceleration, limit the effects of space charge and emittance growth. The normalised rms emittance is ~70 mm mrad and the total energy dispersion is ~1% (15% for 48 bunches). Two travelling wave High Charge Structures (HCS) raise the energy to about 45 MeV maximum (for a 10 nC bunch). The dispersion due to the progressive load of the HCS structures by the bunches is balanced by increasing the accelerating field [2]. Bunch length is then reduced to a minimum of 0.65 mm rms in a 3-bend compressor. Then the beam is focussed towards the CLIC Transfer Structures (CTS). As the bunch separation (0.1m) is a multiple of the 30 GHz period of the CTS [3], the beam transfers its energy gradually to the CTS, about 23% for 10 nC per bunch if 4 CTS are installed. The 30 GHz power is maximum after 5 bunches because of the 0.53 c group velocity in the 0.6 m long CTS. It is transported via wave-guides to load the 30 GHz accelerating structures of a parallel beam line, representing the main beam of CLIC, and accelerating a unique 1nC bunch.
The energy spread generated at the level of the CTS is very high because of the progressive load by the first 5 bunches. However it has been shown that this part of the dispersion in CTS is harmless, if the beam is dispersion-free at the entrance of the CTF [4]. However, the beam is chromatic there, and the transverse wake-fields associated with misalignments of beams and structures cause emittance blow-up.

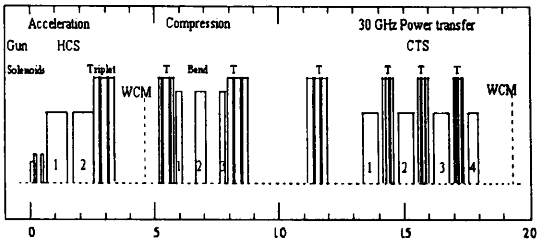

Figure 1: CTF 2: HCS and CTS structures and triplets.

2 BEAM SIMULATION CODES

2.1 *Codes used in the simulation*

No self-consistent code was able to simulate the dynamics of the 48-bunch drive beam in the 20 m CTF line. Therefore:

- MAFIA was used to simulate the dynamics in the RF gun and the solenoid focusing at the gun exit [5].
- PARMELA, was used to simulate the space charge effects, the acceleration in the HCS, the compression in the bending system, and, as shown in Fig.2, the focusing from the exit of the gun to the entrance of CTS [6] (with bunches 1, 24 and 48 input values derived from MAFIA outputs).

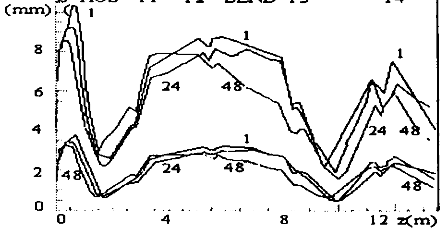

Figure 2: Envelope for 1 and 3 σ.

- WAKE was used for the effects of the wake-fields in the HCS and CTS and for focussing from the end of the compressor to the end of the line [7]. Input values were derived from PARMELA outputs, and all bunches of the train were tracked.

2.2 *The WAKE code*

The charge in each bunch is gaussian-distributed in 10 slices, and each slice contains 5 bins with equal charge such that different initial energies may be assigned according to the bunch, to the slice and to each of the 5 bins within each slice. The macro-particles of the sub-slices of all bunches are tracked sequentially at a succession of z intervals along the beam line. The longitudinal and transverse wake-fields from the particles in front are added at these positions, and their actions on the particle are calculated. Only the fundamental frequencies are taken into account, the amplitudes associated with the other frequencies being very small. The envelope of each particle is obtained by adding the betatron amplitude to the trajectory calculated with the kicks due to the wake-field.

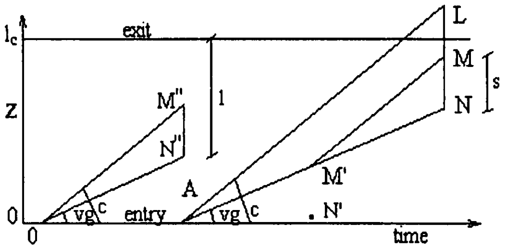

Figure 3: Role of the group velocity

Particle N crosses the cavity together with particle M, at the same speed c, but at a distance s behind. The distance to the entrance of the cavity is represented versus time in Fig.3, in which c and group velocity v_g are quoted instead of the tangents of the angles. M interacts with the cavity and the power of this interaction propagates towards the exit of the cavity at speed $v_g<c$. Therefore the field at N from particle M is that emitted when M was at M' (and N at N'). The total path length of N in the field is needed for evaluating the potential. It is not the total length l_c of the cavity, but: $l = l_c - s\, v_g /(c- v_g)$, as can be seen on the left of Fig.3. The transverse field depends on s but also on the transverse position r of M'. In the CTS, this transverse field is damped [3].

When a new particle N at the same position z is considered, the vectors of the fields and of the potentials are not recalculated but just modified by the rotation of the phase. It is also necessary to add the action of the new leading particle and to remove that of the particles whose fields have left the cavity (they are beyond L on Fig.3).

3 BEAM IN HCS STRUCTURES

The 2 HCS accelerate the beam to about 45 MeV. Their RF frequencies are shifted by ∓ 7.41 MHz from that of the RF gun (2.99855 GHz). The addition of their voltages during the passage of the successive bunches (0.1 m spacing) balances the reduction due to the beam loading (Fig.4). The phase for the RF crest is chosen for an intra-bunch correlation used in further bunch compression.

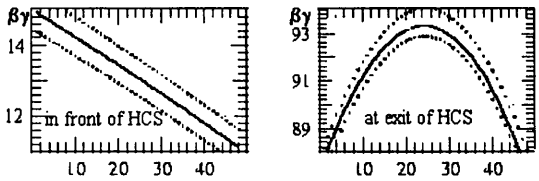

Figure 4: $\beta\gamma$ in the HCS, as a function of bunch number

As the ratio of the transverse frequency to the longitudinal is ~ 4.12/3 [8], the phase between bunches is ~ 120° for the transverse wake and the actions of bunches 1 and 2 on bunch 3 cancel each other, preventing the transverse wake-field building-up. However, the longitudinal wake-field does build-up, the group velocity being very low. The 48-bunch x-projected envelope, shown up to the compressor (Fig. 5), is not much larger than without wake-field (dotted line). Wake-fields and space charge [6] have similar effects.

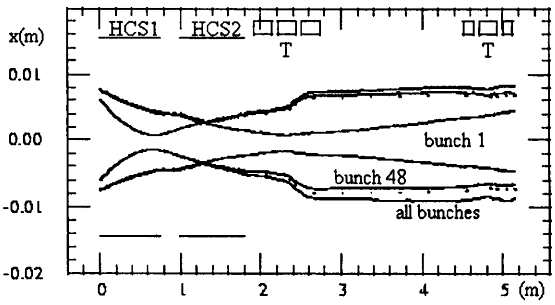

Figure 5: Envelope with transverse wake-field for bunches 1 and 48, all bunches, and with no wake-field (structures transverse displacement is 0.5 mm)

The envelopes of slice 1 of bunches 1 and 48 show how the energy spread at the HCS1 entrance prevents a perfect focussing by quadrupoles, as it shifts the waists of the bunches. This is independent of the wake-fields. The transverse wake fields in HCS do not really limit the transmission.

4 BEAM IN CTS STRUCTURES

4.1 *Longitudinal momenta and focusing*

CTS structures are only passive, with mode 0 and mode 1 frequencies nearly equal, and impedances R'/Q equal to 546 $\Omega\ m^{-1}$ and 3748 $\Omega\ m^{-1}$ respectively (circuit definition). The 'active' length is ~0.6 m, the iris radius

7.5mm, and the group velocity for both modes is v_g ~0.53c, therefore only 5 bunches contribute to the wake-fields. The transverse wake-field is highly damped (Q~100) [4]. The design of CTS 4 is different: 0.3m long and not damped. The momentum along the CTS line is shown in Fig. 6, for 13.5 nC per bunch, with a final dispersion of 66%.

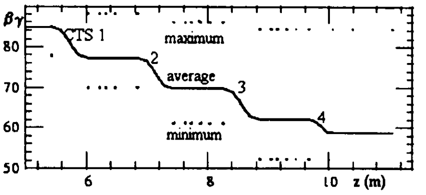

Figure 6: Momentum along the transfer structures line. The focusing is made for transverse wake ''off'' by setting the triplets in between the structures for the minimum energy, then by matching the triplets in front with the Twiss parameters of the mesh (Fig. 7). The periodicity of the envelope is better achieved for the y-projection than for the x-projection. This difference is amplified when the transverse wakes are "on".

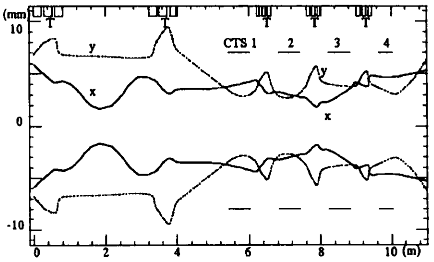

Figure 7: Focusing at end of CTF (no transverse wake)

4.2 *Effects of transverse wake-fields*

All structures are displaced by +0.5mm. The difference between the envelopes of the successive slices of a bunch increases gradually with the energy loss and with the transverse forces, due to preceding charges displaced transversely. The x-projection envelopes are shown in Fig.8, in the case of 10 nC per bunch, for each of the 5 energy bins in each slice of a bunch. The bunch number selected is greater than 5 in order to represent the steady regime of the wakes.

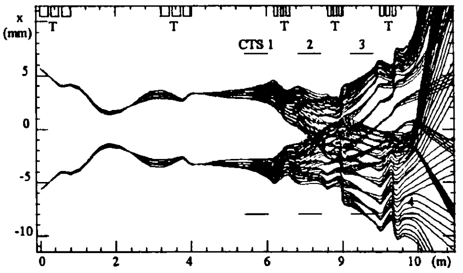

Figure 8: One bunch wake envelopes with transverse wake "on", for 10 nC

The 5 macro-particles of slice 1 are stopped on the iris of CTS3 (x<0), and all slices 9 and 10 on CTS4 (x>0). These losses, occurring at the tails of the longitudinal gaussian charge distribution, are small. Therefore, while a large blow-up occurs in front of the wall current monitor, most of the bunch reaches it.

The envelopes for the trains of 48 bunches may be compared (Fig.9) for 8, 10 and 13.5 nC per bunch, which are the charges used in the experimental investigation. For a train with 8 nC per bunch, nearly all the charge goes through all the structures, except for the first and last slices. More slices are intercepted when the bunch charge is 10nC. With 13.5 nC per bunch, a very large part of the beam is intercepted on CTS 3 and 4 .

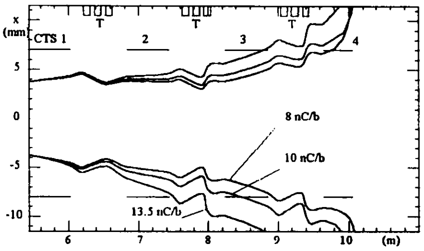

Figure 9: X-projection envelopes for all bunches, depending on charge.

5 CONCLUSION

Beam simulation in CTF 2 agrees with the experimental measurements. Clearly, a less chromatic beam at the entrance of the HCS and more acceleration would have been beneficial for the focusing and the transmission, but the beam quality at the entrance of CTS allows for 0.5 mm misalignment when the charge per bunch is ~10 nC. This is very similar to the experimental result: full transmission, obtained for 8 nC per bunch, is maintained up to about 10 nC, and then decreases.

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