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Beam Dynamics Studies and Emittance Optimization in the CTF3 Linac at CERN

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Small transverse beam emittances and well-known lattice functions are crucial for the 30 GHz power production in the Power Extraction and Transfer Structure (PETS) and for the commissioning of the Delay Loop of the CLIC Test Facility 3 (CTF3). Following beam dynamics simulation results, two additional solenoids were installed in the CTF3 injector in order to improve the emittance. During the runs in 2005 and 2006, an intensive measurement campaign to determine Twiss parameters and beam sizes was launched. The results obtained by means of quadrupole scans for different modes of operation suggest emittances well below the nominal $\in_{n,rms}$ = 100 πμm and a good agreement with PARMELA simulations.

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BEAM DYNAMICS STUDIES AND EMITTANCE OPTIMIZATION IN THE CTF3 LINAC AT CERN

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Abstract

Small transverse beam emittances and well-known lattice functions are crucial for the 30 GHz power production in the Power Extraction and Transfer Structure (PETS) and for the commissioning of the Delay Loop of the CLIC Test Facility 3 (CTF3). Following beam dynamics simulation results, two additional solenoids were installed in the CTF3 injector in order to improve the emittance. During the runs in 2005 and 2006, an intensive measurement campaign to determine Twiss parameters and beam sizes was launched. The results obtained by means of quadrupole scans for different modes of operation suggest emittances well below the nominal $\epsilon_{n,rms}$ = 100 $\pi\mu$m and a good agreement with PARMELA simulations.

INTRODUCTION

The CTF3 injector consists of a thermionic gun, three 1.5 GHz sub-harmonic bunchers (SHB), one pre-buncher, a tapered phase velocity travelling wave buncher and two 1.2 m long accelerating structures. The transverse beam size is controlled with solenoids surrounding these injector elements [1]. In this paper, we first report on beam dynamics simulations aimed at improving the performance of the CTF3 injector. Following results obtained with PARMELA [2], two additional coils were installed close to the gun to improve the transverse beam emittance. Fig. 1 shows the layout of the CTF3 injector with the new solenoids. Then, we discuss the results of emittance measurements performed in 2005 and 2006 along the CTF3 Linac, the layout of which is shown in Fig. 2.

PARMELA SIMULATIONS

Extensive simulations were performed with PARMELA, starting at the exit of the electron gun with an initial emittance of 7 $\pi\mu$m and a kinetic energy of 140 keV for the reference particle. The particles were randomly distributed in the four-dimensional transverse phase space. They were then tracked through the CTF3 injector and the following magnetic chicane until the measurement plane in girder 5.

Simulations were done for different beam currents (3.5 A, 5 A), and with on- or off-crest (20°) acceleration in the cavities of the CTF3 injector. According to these simulations, the newly installed coils decrease the emittance by about a factor 2. The obtained bunch emittances were found within the range of 15 - 25 $\pi\mu$m. Switching on the sub-harmonic bunching system did not significantly influence the results.

BEAM STUDIES AT THE CTF3 LINAC

During the CTF3 runs in 2005 and 2006, a large number of measurements were performed in order to determine the transverse beam emittance and the Twiss parameters at several locations along the CTF3 Linac, in particular after the magnetic chicane (girder 5), close to the PETS region (girder 10) and towards the end of the Linac.

The beam parameters were determined by means of quadrupole scans, where the current value of one quadrupole located in front of the measurement plane (OTR screen [3]) was automatically changed. The acquired beam profiles were analyzed to derive the beam parameters at the entrance of the quadrupole. Fig. 3 shows the result of a typical quadrupole scan. The measured Twiss parameters are then used to perform a proper re-matching of the CTF3 Linac.

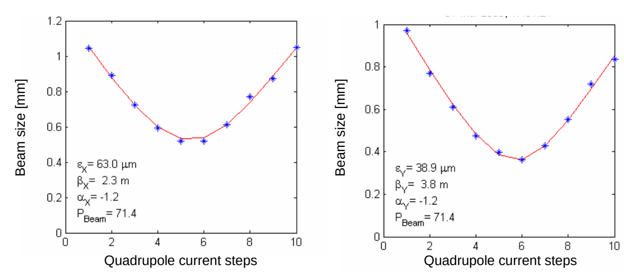

Figure 3: Result of a typical quadrupole scan.

Emittance measurements in 2005

In 2005, intensive studies were performed at the first two locations in the CTF3 Linac with the main purpose to set-up a high current beam (5 A), as required for high power production in the PETS [4].

Two different modes of operation were analyzed: The electron bunches were either accelerated on- or off-crest in the accelerating structures in the CTF3 injector. The off-crest mode is used for power production in the PETS, since the introduced correlated energy spread leads to shorter bunches in the magnetic chicane and hence to a higher 30 GHz power form factor. Table 1 gives an overview on the emittance values for a 5 A beam, as measured in girders 5 and 10. The beam energy is about 28 MeV in girder 5 and 90 MeV in girder 10.

The emittances measured for on-crest operation are well below the nominal rms emittance $\epsilon_{n,rms}$ = 100 $\pi\mu$m[1]. In

[1] specified for a 3.5 A beam current accelerated on-crest in all cavities.

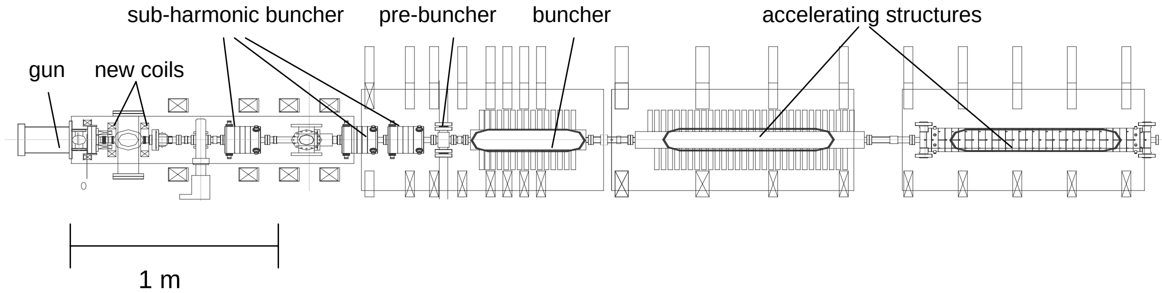

Figure 1: Layout of the CTF3 injector.

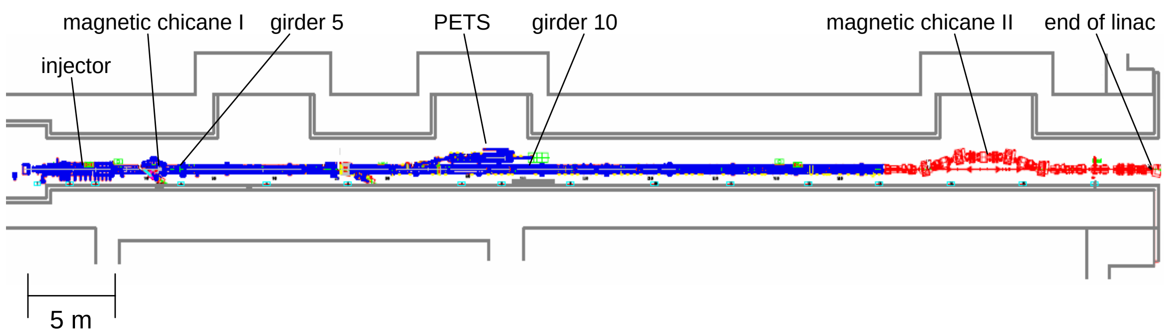

Figure 2: Layout of the CTF3 Linac.

Table 1: Average normalised rms emittances measured in girders 5 and 10 of the CTF3 Linac.

Girder	Mode of operation	ϵ_x [π μm]	ϵ_y [π μm]
5	on-crest	45	25
5	off-crest (20°)	75	30
10	on-crest	85	80
10	off-crest (20°)	130	140

addition, the vertical emittance measured on girder 5 agrees with the results of PARMELA simulations, however larger emittances were found in the horizontal plane. Still in the on-crest operation mode, larger emittances were obtained in both transverse directions on girder 10. This is presumably due to a lower magnification of the OTR light, limiting the optical resolution there. For the off-crest operation mode, higher emittance values were consistently measured. This can be explained by the larger energy spread of the bunch. Chromatic effects in the Linac are therefore enhanced.

Emittance measurements in 2006

The first run of 2006 focused on the commissioning of the Delay Loop with a 3.5 A beam. Hence, emittances and Twiss parameters were determined for this beam in order to allow re-matching the Linac optics upstream the Delay Loop. Measurements were done at all three locations in the Linac. The optical magnification of the measurement system in girder 10 was increased to the same level than in girder 5 and at the end of the Linac, to maximize the resolution and facilitate the comparison of the measurement results.

First comparative measurements were done on girders 5 and 10, and did not confirm the emittance growth observed in 2005. Instead, similar values were obtained, e.g. for the horizontal emittance: $\epsilon_{x,5}$ = 53 $\pi\mu$m and $\epsilon_{x,10}$= 52 $\pi\mu$m. With the increased optical magnification in girder 10, no emittance growth was observed anymore.

Measurements were then carried out with the beam specified in Table 2. The three sub-harmonic bunchers were switched on. Table 3 presents the results.

Table 2: Main beam parameters.

Parameter	Value
Beam current	3.5 A
Pulse length	1.4 μs
Bunch repetition frequency	1.5 GHz
Energy in girder 5	21 MeV
Energy in girder 10	75 MeV
Energy at the end of the Linac	100 MeV

The results indicate that the measured emittances remain smaller than the nominal ones. We also found that the emittance is correlated to the pulse length. In general, the emittance decreased when the pulse length was increased. This

Table 3: Averaged normalised rms emittances measured in girder 10 and at the end of the Linac.

Location	ϵ_x [π μm]	ϵ_y [π μm]
Girder 10	75	51
End of Linac	82	86

effect is explained by the presence of an energy transient during the first 100 ns of the pulse, which is less dominant when longer pulses are considered. As a result, the measurements mentioned above, were done with subtraction of the transient. Two quadrupole scans were recorded: one with a long pulse (700 ns) and one with a short pulse (300 ns). The corresponding images were then subtracted in order to take only the steady part of the pulse into account for the determination of the emittances and the Twiss parameters.

Re-matching of the Linac

The knowledge of the Twiss parameters at one location allows a re-matching of the Linac using a MAD model of the machine. Fig. 4 shows the beta functions from the magnetic chicane to girder 10, taking into account the measured lattice parameters in girder 10 before the re-matching. The Linac was then re-matched based on the quadrupole scans, see Fig. 5. The beam energies after each accelerating section were calculated from the RF signals.

The Twiss parameters predicted from the MAD model were then compared to the results of new quadrupole scans. Table 4 shows the expected and measured Twiss parameters on girder 10.

Table 4: Comparison of the predicted and measured Twiss parameters on girder 10.

Twiss parameter	MAD model	Measurement
α_x	-1.2	-0.8 to -1.2
β_x	3.4 m	2.3 to 3.0 m
α_y	-1.2	-1.0 to -1.2
β_y	3.4 m	3.8 to 4.5 m

The agreement of the results emphasizes that the existing machine model is well established. It is an essential tool to set-up the Linac from girder 5 to the Delay Loop.

CONCLUSIONS

The installation of the two solenoids in the CTF3 injector decreased the transverse beam emittance by about a factor 2 and hence facilitated the beam set-up in the machine. The measurements in girder 5 yielded emittance values which are close to those derived from PARMELA simulations. Furthermore, the measured emittances are well below the nominal ones at all three locations along the CTF3 Linac and no significant emittance growth in the horizontal plane

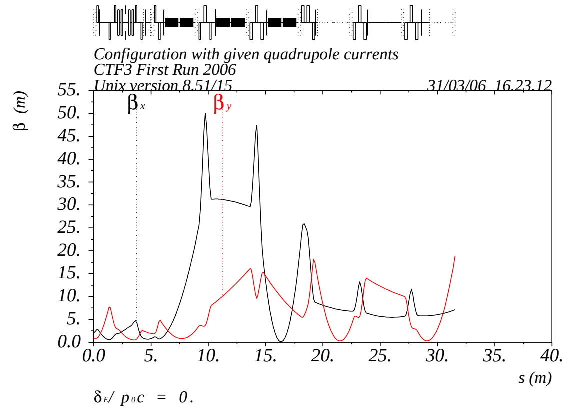

Figure 4: Lattice functions before the re-matching.

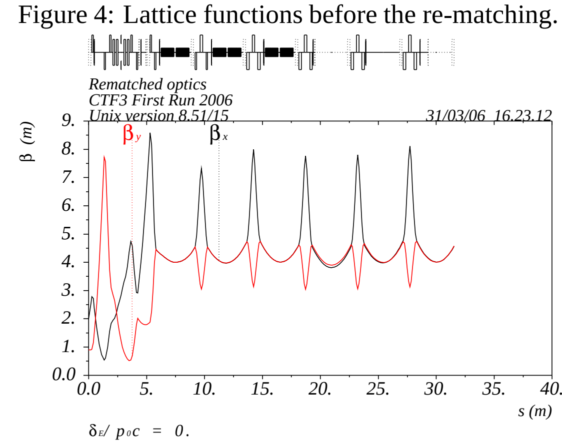

Figure 5: Lattice functions after the re-matching.

was found from girder 5 to the Delay Loop. Finally, the agreement between the Twiss parameters predicted with the MAD model and those experimentally measured in the machine is satisfactory. The MAD model has shown to be an indispensable tool for the set-up of the whole Linac.

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