DECELERATION MEASUREMENTS OF AN ELECTRON BEAM IN THE CLIC TEST FACILITY 3

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Abstract

The Test Beam Line at the CLIC Test Facility 3 at CERN is a proof-of-principle of the future CLIC decelerators, which will extract a large amount of beam energy for acceleration of the main CLIC beams. The current beamline consists of a FODO lattice with 13 Power Extraction and Transfer Structures (PETS). We discuss beam deceleration measurements of up to 37 %, taking into account effects from the bunch length and the bunch phase. The 12 GHz phase is reproduced based on measurements in a PETS with an uncombined beam. The spectrometer measurements are also compared to predictions based on the beam current and on the produced rf power in the PETS, as well as particle tracking simulations with the Placet code.

INTRODUCTION

In the Compact Linear Collider (CLIC) design, in order to reach efficient acceleration of the main beam the acceleration energy is extracted from a low-energy, high-current drive beam [1]. The energy will be extracted in 24 decelerator sectors which are 1 km long, and which consist of FODO lattices with Power Extraction and Transfer Structures (PETS). 90 % of the beam energy will be extracted and converted to 12 GHz power, and it is vital to understand the dynamics of the strongly decelerated drive beam.

At CERN, the CLIC Test Facility 3 (CTF3) was built to verify key concepts of the CLIC two-beam scheme [2]. The facility is essentially a small drive beam complex, where the electron beam is interleaved by up to a factor 8, in order to produce the low-energy, high-current beam needed by the experiments. One of the main experiments in the facility is the Test Beam Line (TBL), which is the first prototype decelerator. Here, the ~120 MeV electron drive beam is decelerated through a line of PETS, and the produced rf power is measured and dissipated in loads.

Most of the previously reported results have been produced with a beam current of up to 14 A [3]. In this paper, however, we discuss data taken with the full bunch combination scheme of the CTF3, that allowed a beam current of 21 A delivered to the TBL. This dataset includes 88 consecutive bunch trains.

EXPERIMENTAL SETUP

Being a prototype decelerator, the TBL consists of a FODO lattice with PETS in between the quadrupoles. The lattice of the beamline is shown in Figure 1. Currently 13 PETS are installed in the beamline, and at nominal conditions each of these can produce 135 MW of 12 GHz power. The power amplitude is measured with Schottky diodes. In addition, one PETS is also measured with IQ demodulators, which provide information about the rf phase. As will be seen later, phase information is important in order to fully understand the power production and beam deceleration. The produced power is attenuated by a total of around 90 dB before entering the measurement electronics, and the attenuation chain must be calibrated piecewise. This leads to a large systematic error on the absolute power measurement, which is estimated to a maximum of 0.8 dB (20 %).

The quadrupoles in the FODO lattice are mounted on precision movers made by CIEMAT [4], that allow efficient steering and the use of beam-based alignment routines. The bunch trajectory is measured by inductive pickup wall-current monitor BPMs, and these are also used for beam current diagnostics. The BPMs were designed and constructed by IFIC and UPC [5], and have a resolution of 5 µm. A novel segmented dump spectrometer at the end of the beamline provides time-resolved, single-shot energy measurements with a precision of 1 % [6]. The spectrometer at the beginning of the beamline is of a simpler type and contains a single slit. Optical Transition Radiation (OTR) screens are used for measuring the transverse beam distribution.

HIGH RF POWER PRODUCTION

The rf power produced in a PETS scales as [7]

$$P \propto I^2 F^2 \{\lambda(z)\}, \tag{1}$$

where I is the beam current and $F\{\lambda(z)\}$ is the charge distribution form factor. When the charge distributions of the individual bunches are equal and Gaussian, and relatively short compared to the bunch separation [3], we can write $F\{\lambda(z)\} = F_b(\sigma_z)\,\Phi(\{\phi_n\})$. Here $F_b(\sigma_z)$ is the single-bunch form factor, dependent on the bunch length σ_z, and $\Phi(\{\phi_n\})$ is the multi-bunch form factor,

$$\Phi(\{\phi_n\}) = \frac{1}{N_b}\sum_{n=1}^{N_b} e^{i\phi_n}, \tag{2}$$

where N_b is the number of bunches that contribute to the field build-up in a PETS (37 in the case of the TBL), and ϕ_n is the phase of each bunch.

When the bunch phase is constant, as it should be in CLIC, $\Phi(\{\phi_n\})$ evaluates to one. In the CTF3, however, the bunch phase changes over the bunch train due to the injector setup. This leads to a multi-bunch form factor less than one, and consequently a reduced power production and energy extraction. The calculated value along the bunch train for the

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Figure 1: The current TBL lattice, with 13 PETS installed (not to scale). Quadrupoles are shown as blue lenses, dipoles as red rectangles, corrector magnets as orange triangles, BPMs as green circles, OTR screens as purple pentagons and PETS as brown corrugated structures.

Figure 2: The calculated multi-bunch form factor along the bunch train, based on the measured bunch phase and Equation (2).

dataset is shown in Figure 2. In this calculation, the phase was measured upstream of the bunch combination in the CTF3. This was needed because the bunch combination leads to large bunch-to-bunch phase jumps that are not possible to see in the phase measurement after combination due to the lower sampling frequency.

The measured rf power is shown with blue dots in Figure 3, averaged over the 13 PETS and over the dataset. Since the average beam current was 21.4 A instead of the nominal 28 A, the produced rf power of around 50 MW is also lower than nominal. The power can also be predicted based on the beam current measured in BPMs. Without taking into account the bunch phase, this prediction is shown as a red dashed line. Since the electronics for the BPMs have a lower bandwidth than those used for PETS, the PETS signals can be treated with a low-pass filter, and the result is shown with a green line in Figure 3. The remaining difference between the red and green curves can be attributed to the form factor, where the multi-bunch form factor plays the largest role in the CTF3. When including $\Phi(\{\phi_n\})$ from Figure 2 in the prediction of the power, the resulting black line is very close to the green one.

BEAM DECELERATION

The incoming energy to the TBL was measured to 119 MeV. The measured energy spectrum at the end of the line is shown in Figure 4, which shows the average energy spectrum over the dataset. The contour lines show 10 % increments of signal compared to its maximum value. The final energy distribution features a large energy spread, es-

Figure 3: The average measured PETS power along the beamline (blue), and treated with a low-pass filter (green). The predicted power based on the measured beam current, with (black) and without (red) including the multi-bunch form factor.

Figure 4: An average energy measurement from the end of the beamline. The mean energy along the bunch train is shown with crosses, and the maximum deceleration is shown with a star.

timated to 21 % FWHM. This is partly due to the beam dynamics in PETS, but also because of a large incoming energy spread. The mean energy along the bunch train is shown with crosses in the figure, and is around 85 MeV. The lowest energy is shown with a star. For finding the peak deceleration (the lowest energy), we define a threshold of 10 % of the maximum signal, which is found at an energy of 74.9 MeV. This corresponds to a maximum deceleration of 37 %, which is the highest achieved in the TBL so far.

The average final energy is also shown in Figure 5 in blue. The curve itself shows the mean over the dataset, while the

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Figure 5: Measured final beam energy along the bunch train (blue), and predicted energy based on the beam current (red) and the measured rf power in the PETS (green). Each of the curves shows the mean over the dataset, while the correspondingly colored band around shows the standard deviation. A prediction based on the beam current neglecting the multi-bunch form factor is shown as a black dashed line.

blue band around it shows the standard deviation. The deceleration can also be predicted based on the measured beam current along the beamline or on the power produced in the PETS. A prediction based on the beam current is shown in red, and here the multi-bunch form factor shown in Figure 2 is again included. The prediction based on the beam current is calculated first since the only free parameters are the beam current and the form factor, which can be calculated. A similar prediction based on the measured rf power is shown in green. As mentioned, there is a systematic uncertainty on the power measurements, and therefore an empirically derived scaling factor is needed for the prediction based on the rf power. Therefore, a reduction of 5 % of the rf power amplitudes was used in the analysis. For reference, we also show a prediction (based on the beam current) neglecting the multi-bunch form factor in black, which shows a significant deviation from the energy measurement.

CONCLUSION

We have discussed strong deceleration of an electron beam through a beamline with 13 PETS structures. A maximum deceleration of 37 % has been achieved, which is the highest in the CTF3 to date.

The measured difference in energy was correlated with predictions based on the beam current and the rf power produced in the PETS, and all showed a very good agreement. This was also the case for the correlation between beam current and PETS power, when bandwidth limitations were taken into account. In the predictions we have seen the importance of taking the bunch phase into account, which affects the multi-bunch form factor.

The main foreseen deceleration studies have now been addressed in the TBL. Currently a 14th PETS is being installed in the beamline, which will allow the exploration of the 40–45 % deceleration regime.

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