EXPERIMENTAL VERIFICATION OF THE CLIC DECELERATOR WITH THE TEST BEAM LINE IN THE CLIC TEST FACILITY 3

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Abstract

The Test Beam Line in the CLIC Test Facility 3 is the first prototype of the CLIC drive beam decelerator. The main purpose of the experiment is to demonstrate efficient 12 GHz rf power production and stable transport of an electron drive beam during deceleration. The Test Beam Line consists of a FODO structure with high precision BPMs and quadrupoles mounted on mechanical movers for precise beam alignment. Nine out of the planned 16 Power Extraction and Transfer Structures have currently been installed and commissioned. We correlate rf power production measurements with the drive beam deceleration measurements, and compare the two measurements to the theoretical predictions. We also discuss the impact of the drive beam bunch length and bunch combination on the measurements.

INTRODUCTION

In the proposed future e^+e^- collider CLIC, 90 % of the energy of a high intensity *drive beam* will be converted into 12 GHz rf power for acceleration of the main beam [1]. The CLIC Test Facility 3 (CTF3) was set up to verify key technology concepts of the CLIC scheme, and the decelerator Test Beam Line (TBL) is the first prototype of the CLIC drive beam decelerator, with up to 55 % energy extraction in the final configuration [2].

A part of the kinetic energy of the beam is converted to rf power in constant impedance Power Extraction and Transfer Structures (PETS), which are passive microwave devices with a fundamental mode of 12 GHz. The main purposes of the TBL are to

- show stable power production in the PETS,
- demonstrate stable beam transport after significant deceleration, and
- test decelerator beam-based alignment schemes.

EXPERIMENTAL SETUP

The Test Beam Line consists of 16 units, each with one Power Extraction and Transfer Structures (PETS), one quadrupole on a mechanical mover and one BPM. A FODO structure is used because of the large energy acceptance, and the quadrupole gradients are scaled along the line to provide a constant phase advance for the most decelerated particles (normally 90° per FODO cell). The TBL lattice is shown in Figure 1, and at the time of writing, 9 out of 16 PETS are installed. Both the current and the nominal beam parameters are given in Table 1 for comparison.

Because CLIC uses a 3.6 times more intense beam than the nominal CTF3 beam, the TBL PETS are a factor 3.7 longer, and will produce slightly more power than the baseline 135 MW required for CLIC. The longer PETS lead to a longer fill-time of the structure, and therefore a longer high-energy transient in the pulse. The 12 GHz power is coupled out on both sides at the end of the structures. At one side the power is measured with either IQ demodulators or Schottky diodes. The accuracy of the power measurements is estimated to be on the order of 10 %, because of an attenuation chain of 90 dB which must be calibrated piecewise [3].

A segmented dump spectrometer is installed at the end of the line [4], and provides time-resolved (ns) energy measurements with an accuracy of about 5 %. The start of the line is equipped with a spectrometer with a single slit. In addition, OTR screens are placed in both of these locations. A streak camera – imaging an OTR screen located at the beginning of the line – allows for bunch length and bunch spacing measurements.

TBL uses high precision inductive BPMs designed and constructed by IFIC Valencia and UPC Barcelona [5], with a resolution of 5 μm. The quadrupoles are mounted on moving tables made by CIEMAT [6], which allow positioning in the micrometer range. A beam-based alignment campaign has been performed in the TBL [7], and has improved the orbit and eased the transmission.

DECELERATION RESULTS

The TBL has been operated with different beam currents using various combination schemes of the CTF3 drive beam. For the deceleration studies, the main interest lies in using a high intensity beam since the deceleration is linear in current. We therefore report results from a fully combined beam (using both the CTF3 delay loop and combiner ring). Some parameters upstream of the TBL were not fully optimized at the time of taking data, particularly the overall bunch combination and the phase coding. Because of this there were electrons outside of the main pulse, which can also be seen in the PETS power production and deceleration.

The incoming beam energy was 117 MeV instead of the nominal 150 MeV designed for CTF3, because of two

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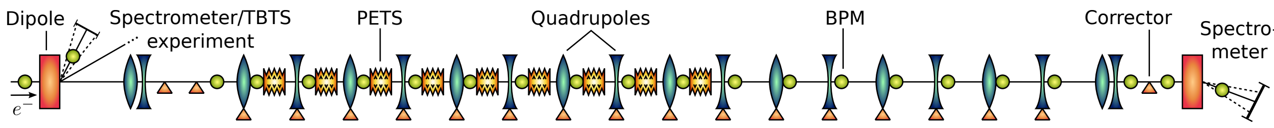

Figure 1: The TBL lattice with 9 out of 16 PETS installed, where the CTF3 drive beam comes from the left.

Table 1: Current (I) and nominal (II) parameters for the TBL for a fully combined beam. (*) corresponds to the PETS fundamental mode.

Parameter	Symbol	(I)	(II)
Number of PETS	N_{PETS}	9	16
Length of PETS [m]	L	0.80	0.80
Initial average current [A]	I	21	28
PETS power [MW]	P	70	138
Initial energy [MeV]	E_0	117	150
Mean energy extracted [%]	η	~26	55
PETS synch. freq. [GHz]*	f_{rf}	12.0	12.0
PETS imped. [linac-Ω/m]*	(R'/Q)	2222	2222
PETS group velocity [c]*	v_g	0.46	0.46
PETS ohmic loss factor *	η_Ω	0.985	0.985
Pulse length [ns]	t_{pulse}	140	140
Transient length [ns]	t_{fill}	3.1	3.1
Repetition rate [Hz]	f_{rep}	0.83	≤ 5
Bunch rms length [mm]	σ_z	1-2	1.0
Init. norm. emittance [μm]	$\varepsilon_{N_{x,y}}$	~500	150

missing klystrons in the CTF3 linac. The beam current was around 19 A (down from the nominal 28 A), mostly because of losses in the upstream transfer line.

The mean beam energy loss $\langle V \rangle$ can be deduced by three different methods based on three different measurements:

- Prediction from the measured PETS rf power P, using

$$\langle V \rangle = \frac{L}{2} F(\lambda, \phi) \sqrt{\frac{(R'/Q)\, \omega_{\text{rf}} P}{v_g}} \tag{1}$$

  with structure parameters from Table 1. $F(\lambda, \phi)$ is the charge distribution form factor, dependent on the bunch length and bunch spacing.

- Prediction from the measured beam current, using eq. (1) with

$$P = \frac{1}{4} (R'/Q) \frac{\omega_{\text{rf}}}{v_g} L^2 I^2 F^2(\lambda, \phi)\, \eta_\Omega^2. \tag{2}$$

- Direct measurement in the spectrometers.

The results of all three methods were correlated and are shown together in Figure 2, which shows the beam energy along the pulse. The circles, crosses and squares show mean values for the three measurement types over 48 consecutive pulses, corresponding to 58 seconds of operation. The colored bands around the means show one standard deviation for each measurement. This result corresponds to around 26 % deceleration and energy extraction, the highest achieved in the TBL so far.

The form factor $F(\lambda, \phi)$, which depends on both the bunch length and bunch phase (influenced by the bunch combination), affects both the deceleration and the power production. Here λ is the single-bunch charge distribution and ϕ is the bunch phase deviation from the synchronous phase. Since there was no direct form factor measurement available, it was used as a fudge factor in the analysis. The curves fitted well for a form factor of $F(\lambda, \phi) = 0.95$, close to the design value of 0.97 (corresponding to 1 mm Gaussian bunches with perfect phases, i.e., $\phi = 0$). In addition to this, the prediction from the rf power was scaled up by 10 %, and this deviation can be justified by the systematic error due to the very large signal attenuation before the electronics. The prediction from beam current deviates from the measurement and the prediction from rf power in the first part of the pulse, indicating a change in the form factor along the pulse. This probably originates from the CTF3 bunch combination.

In Figure 2, the rf derived signal is not shown outside of the main pulse. This is because the power production is quadratic in the current, and the measured satellites were much smaller than the main pulse, so that the signal there was not significantly above the noise floor.

A decelerated beam gets a larger envelope because of adiabatic undamping, making beam transport challenging when using many PETS. Most of the BPMs in the FODO structure were not calibrated with high beam currents and were saturated. They were therefore not usable for getting an estimate of the transmission. By trusting the very last BPM however, the transmission was close to 100 %, so operation with 9 PETS does not seem to have an impact on the transmission. Only the first BPM in the FODO lattice was used for the analysis in Figure 2 because of the saturation of the other BPMs. Since the curve still fitted the spectrometer measurement with a high form factor, this is also an indication of a good transmission.

FORM FACTOR ESTIMATES

The form factor is not known exactly in the power production and deceleration measurements, but can be estimated from streak camera measurements of the bunch lenghts and bunch spacings. One such measurement was performed with a 12 A beam. This gave bunch lengths of 1.9–2.8 mm, excluding one bunch which showed significant deviations from the others, one possible explanation being a measurement error. This corresponds to single-bunch form factors in the interval $F_\lambda(\lambda) \in [0.78, 0.89]$.

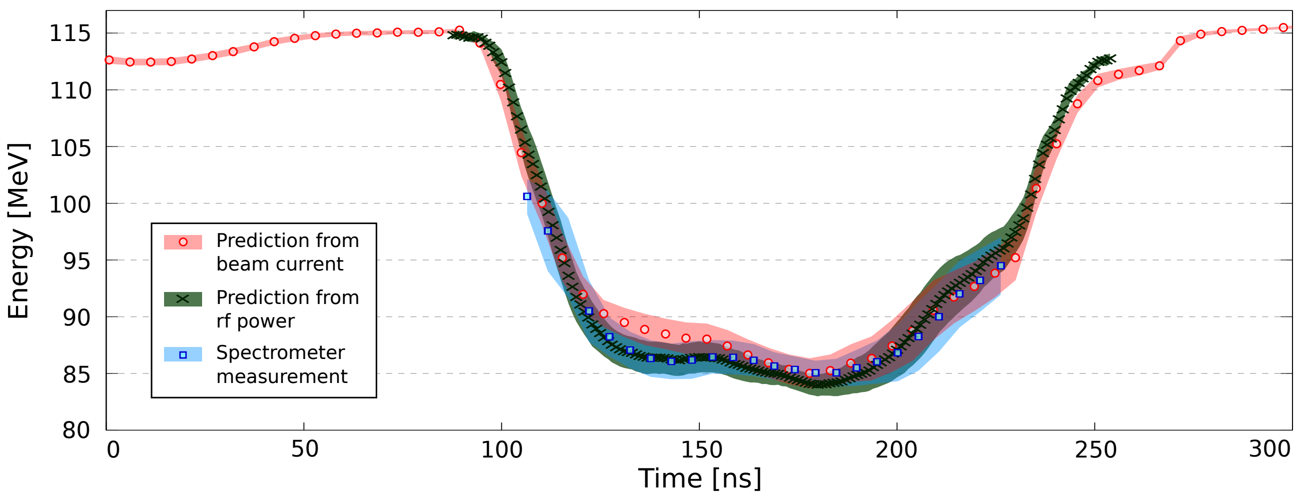

Figure 2: Beam energy along the pulse as measured in the spectrometer, and predicted from the beam current and the rf power. The symbols show the mean values over 48 pulses, while the bands show one standard deviation on each side.

In earlier work [2], the single-bunch form factor has been treated as the total contribution to the form factor. However, the bunch phase will also influence the power production and deceleration, and is especially important for a combined beam. For the same streak camera measurement, bunch spacings were used to calculate phase between bunches. A contribution to the form factor was then calculated using

$$F_\phi(\phi) = \frac{1}{N}\left|\sum_{n=1}^{N} e^{i\phi_n}\right| \tag{3}$$

where ϕ_n is the phase deviation from zero for bunch n and N is the number of bunches in the measurement. This gave contributions to the form factor in the interval $F_\phi(\phi) \in [0.83, 0.88]$ along the pulse. The total form factor can be approximated $F(\lambda, \phi) \approx F_\lambda(\lambda)F_\phi(\phi)$[1], and therefore lies between $F(\lambda, \phi) \in [0.65, 0.79]$. The statistics of the streak measurement was low however, and it would be preferred to measure a larger number of bunches in the future.

The total form factor was estimated in the TBL from beam current and rf measurements in the same week, also using a 12 A beam, and gave values of $F(\lambda, \phi) \in [0.85, 0.90]$. This is outside of the interval calculated from the streak measurements, and the cause is likely that the machine and the beam had changed between the different days. For the next run, streak measurements should be taken in close connection to TBL operation for comparison.

CONCLUSION

The TBL has been operated with a total of nine PETS and a beam current of 21 A. Under these conditions a beam deceleration of 26 % was measured in the spectrometers. The measured energy loss was correlated with predictions from beam current and PETS rf power. A form factor of 0.95 and an adjustment of 10 % of the rf power had to be assumed.

The form factor contributions from bunch length and bunch spacing measurements have been evaluated. They differ from estimates from the beam current and rf power performed on different days. For the future we aim to perform both types of measurement on the same day for comparison. It is also preferable to take more streak measurements, also using a higher number of consecutive bunches.

For the next run, TBL will have 13 PETS installed, providing even higher deceleration, before eventually all 16 PETS are installed next winter. Effort will be made to improve the incoming beam parameters for the TBL, in particular the beam current. This will allow going towards the nominal 55 % deceleration.

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[1] Assuming an equal and even charge distribution per bunch, the total form factor can be separated with an equality.

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