EXPERIMENTAL PROGRAM FOR THE CLIC TEST FACILITY 3 TEST BEAM LINE*

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Abstract

The CLIC Test Facility 3 Test Beam Line is the first prototype for the CLIC drive beam decelerator. Stable transport of the drive beam under deceleration is a mandatory component in the CLIC two-beam scheme. In the Test Beam Line more than 50% of the total energy will be extracted from a 150 MeV, 28 A electron drive beam, by the use of 16 power extraction and transfer structures. A number of experiments are foreseen to investigate the drive beam characteristics under deceleration in the Test Beam Line, including beam stability, beam blow up and the efficiency of the power extraction. General benchmarking of decelerator simulation and theory studies will also be performed. Specially designed instrumentation including precision BPMs, loss monitors and a time-resolved spectrometer dump will be used for the experiments. This paper describes the experimental program foreseen for the Test Beam Line, including the relevance of the results for the CLIC decelerator studies.

INTRODUCTION

The Test Beam Line (TBL) will be the first demonstration of the decelerator for the Compact Linear Collider (CLIC) [1]. In the CLIC decelerator 84% of the energy will be extracted from a 101 A electron drive beam, while in the TBL about 54% of the energy will be extracted from a 28 A electron beam. The drive beam in both the CLIC decelerator and TBL will be decelerated by the 12 GHz fundamental mode in a number of constant impedance power extraction structures (PETS) [2]. The high group velocity of this mode will induce a high-energy transient head of the beam, of length of the order of 1 ns. The deceleration of the steady state part will also vary significantly due to the 12 GHz mode frequency combined with the 1 mm rms bunch length. Because the sole purpose of the CLIC drive beam is to provide stable, uniform and efficient rf power for the main beam, particles of all energies must be transported equally well towards the end of the lattice. A FODO lattice is chosen for focusing, due to the large energy acceptance. The gradient of the quadrupoles will be adjusted to provide constant phase-advance per cell for the most decelerated particles.

The TBL consists of 16 cells each containing a 0.8 m long PETS, one quadrupole on mover and one inductive beam position monitor (BPM). It is installed in the CLIC Test Facility 3 Experimental Area (CLEX) [3], which provides the drive beam. Instrumentation and matching sections, to be described later, are installed before and after the TBL. The layout of the TBL is shown in Figure 1, including the location of key instrumentation. The length of the TBL PETS are 3.7 times longer than the CLIC PETS, allowing the TBL PETS to reach a power production slightly above the CLIC baseline of 135 MW, despite the 3.6 times lower drive beam current. For the nominal CLEX beam current of 28 A, this results in a total peak deceleration of about 84 MeV. Figure 2 illustrates the PETS induced energy spread in the first 4 ns of the TBL beam. See Table 1 for a comparison between TBL and CLIC decelerator parameters.

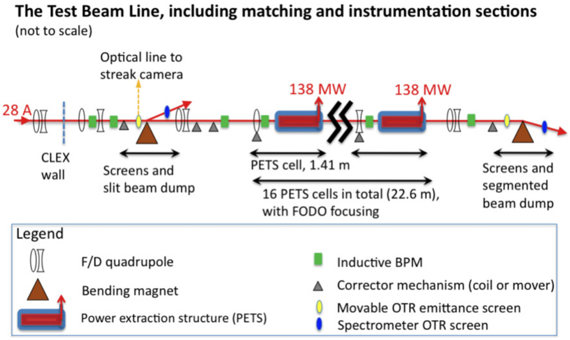

Figure 1: Functional sketch of the Test Beam Line. The line consists of 8 FODO cells, with 16 PETS in total. Matching and instrumentation sections providing emittance and energy measurement, are installed at the start and the end of line.

The main purposes of the TBL are 1) to show stable power production in 16 PETS, and to correlate the rf power output with energy loss and theoretical predictions, 2) to demonstrate stable beam transport while converting more than 50% of the electron energy to 12 GHz rf power and 3) to act as a test-bench for decelerator beam-based alignment schemes. In addition the TBL will provide valuable benchmarking of simulation codes and decelerator hardware. In this paper we describe in more detail the different purposes of the TBL and the expected performance, followed by a discussion of the instrumentation installed in order to acquire the necessary beam observables.

POWER PRODUCTION AND ENERGY LOSS

It is important to understand and measure with good precision the drive beam deceleration in the TBL. The energy loss of the beam can be 1) predicted by the incoming beam characteristics, 2) deduced from the rf power produced or 3) measured directly. The three different calculations will

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Table 1: TBL versus CLIC parameters

Parameter	**Symbol**	**TBL**	**CLIC**
Number of PETS [-]	$N_{\rm PETS}$	16	1492
Length of PETS [m]	$L_{\rm PETS}$	0.80	0.21
Initial average current [A]	I_0	28	101
Power per PETS [MW]	P	∼138	135
Initial energy [MeV]	E_0	150	2400
Mean energy extracted [%]	$\eta_{\rm extr}$	∼54	84
PETS sync. freq. [GHz]	$f_{\rm rf}$	12	12
Number of FODO cells [-]	$N_{\rm FODO}$	8	524
Length of FODO cells [m]	$L_{\rm FODO}$	2.82	2.01
Pulse length [ns]	$t_{\rm pulse}$	140	240
Transient length [ns]	$t_{\rm fill}$	3	1
Bunch rms length [mm]	σ_z	1.0	1.0
Init. norm. emittance [μm]	$\epsilon_{\rm N\,x,y}$	150	150
Beam pipe radius [mm]	a_0	11.5	11.5

be correlated, and we aim to achieve correlation of the calculations to an accuracy of the order of 10%. The predicted power generation in a PETS depends on the beam intensity I and the form-factor F(λ) as $P \propto I^2F^2(\lambda)$. In the case of a detuning between bunch and resonant frequency, Δf, power production is further reduced by a factor $P \propto \frac{1-\cos(2\pi t_{\rm fill}\Delta f)}{1-\cos(2\pi \Delta f/f_{\rm rf})}/(t_{\rm fill} f_{\rm rf})^2$, to first order.

A long optical line will transport Optical Transition Radiation (OTR) from a screen at the beginning of the TBL to a streak camera for bunch length ($<$ 1 ps resolution) and bunch spacing measurements (2-3 ps resolution). An RF pickup, based on power measurements of higher order harmonics of 12 GHz will, once calibrated with the streak camera measurement, provide an online monitoring of the bunch form factor along the pulse train. The BPMs will measure the beam intensity with an accuracy of about 1%. Two spectrometers will be equipped with OTR screens for integrated average energy and energy spread measurements at the beginning and end of the TBL. A segmented beam dump, installed in the final spectrometer, will provide a time resolved (ns) energy spread measurement, with an accuracy estimated to about 5% [4]. The rf measurements accuracy will be limited by the fact that the 138 MW PETS output signal needs to be attenuated by about 90 dB, and we expect a measurement accuracy of 10%.

For a perfectly constructed PETS the power production is expected to be independent of the beam offset, to first order. Dedicated tests will be performed to correlate the 12 GHz power production with the beam offset, using the prototype PETS [5] where the signals from the directional couplers at each side of the PETS can be measured independently.

TRANSPORT OF DECELERATED BEAM

The beam envelope is estimated to grow mainly due to adiabatic undamping, wake fields and misalignment [1].

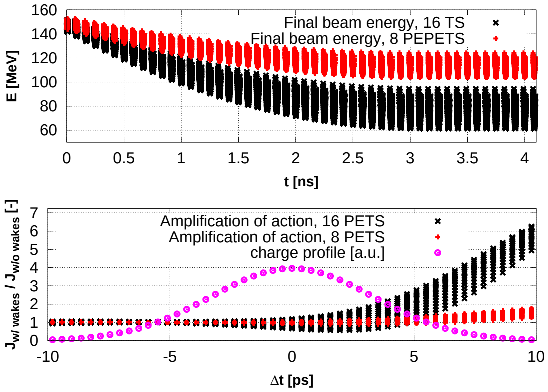

Figure 2: The upper plot shows the beam energy after deceleration (8 and 16 PETS, first 4 ns of pulse). For 16 PETS the leading particle is about 2.3 times more energetic than minimum energy particle. The lower plot shows the amplification of macro particle action due to the dipole wake for an offset beam, within a bunch in the steady-state part of the beam (8 and 16 PETS).

For a perfect incoming beam and perfect injection, the 3σ beam envelope in the TBL will reach 2/3 of the aperture. The TBL envelope is more than a factor of two larger than for CLIC, from this point of view yielding a more challenging transport in the TBL. An estimation of the amplification of a trailing point-like particle due to the dipole wake from a leading particle can be estimated as $\Upsilon \sim \int ds \frac{W'(s)\beta(s)q_b}{E(s)}$ [6], where W' is the wake amplitude, β the beta function, q_b the bunch charge and E the energy, all taken at location s. This yields $\Upsilon_{\rm CLIC}/\Upsilon_{\rm TBL} \approx 7$. Thus, we expect the effects of the multibunch dipole wakes to be much less significant for the TBL than for CLIC. Calculations of the single-bunch wakes show, however, that a small fraction of macro particles towards the end of the bunches increase their transverse action by several factors in the case of injection offset, see Figure 2 (similar values are obtained for CLIC). Assuming all 16 PETS are installed with SiC damping material for higher-order mode damping, beam dynamics simulations show that the dipole wakes should not significantly impede beam transport, for reasonable values of beam injection and misalignment [1]. It is however of interest to provoke an observation of wake effects in order to benchmark the simulations. The only potentially directly observable effect we predict from the dipole wake is an increase in emittance, measured on the final emittance screen, when the beam is injected with a significant offset. For the nominal TBL parameters we estimate 10-15% increase in the rms beam size, for an injection offset of one σ, which we expect to be challenging to disentangle from other effects. Most of the emittance growth occurs towards the end of the line, thus most of the PETS would have to be installed in order to observe an eventual emittance growth due to wakes. One way to achieve direct observations of the transverse wake effects could be to use resonant kickers to introduce beam jitter at a specific frequency before the TBL, and measure the amplification of the jitter at the end, as suggested in [7]. However, this equipment is not in the current baseline for the TBL.

Two movable OTR emittance screens, indicated in Figure 1, will be installed in order to measure the emittance growth resulting from filamentation and wake fields. The screens will also be used to measure beam ellipse parameters for matching into the periodic lattice and into the final spectrometer. Cerenkov light based loss monitors for the TBL are currently being studied, and a prototype is expected to be tested in the TBL in 2010 [8].

DEMONSTRATION OF DECELERATOR ALIGNMENT

The 1 km CLIC decelerator sectors contain one quadrupole per meter in order to provide strong focusing for dipole wake mitigation [1]. Due to quadrupole misalignments, the beam envelope might increase by an order of magnitude, and because of the large energy spread, 1-to-1 steering into BPMs might not ensure sufficient orbit control for particles of all energies. As alternative, an orbit correction scheme based on dispersion-free steering, varying the average pulse intensity using the CLIC delay loop [9] and exploiting the PETS beam loading, is proposed. The scheme shows excellent performance by simulation [10]. However, due to its novelty it is crucial that the scheme be tested under realistic conditions. In the TBL the decelerator scheme will be tested, exploiting the CTF3 delay loop to vary the average pulse intensity. We aim to perform the dispersion-free steering within a single pulse of 140 ns.

Inductive BPMs [11] with a position resolution of 5 μm will enable measurement of the orbit with precision similar to what is required for the decelerator, and the analog and digital bandwidth ensure spatial resolution of < 10 ns. As orbit correctors, specially designed quadrupole movers [12] with a precision of 5 μm will be used.

SCHEDULE

By spring 2010 all dipole magnets, quadrupole magnets and quadrupole movers and one PETS have been installed. A power production of almost 20 MW has been achieved by a drive beam of around 10 A. Two to three additional PETS are scheduled for installation in 2010, a total of nine PETS by the spring of 2011, and all 16 PETS by the end of 2011. The end-of-line segmented spectrometer dump is under production and scheduled for installation in Autumn 2010 [4]. In 2010 the line will be further commissioned with up to four PETS installed, and correlations between beam offset and power production will be measured. Correlations between total rf power produced and total energy loss are planned using the segmented dump. In 2011 the commissioning will continue with 8-9 PETS (up to 30% rf power extraction), and by 2012 the line should be fully commissioned and demonstrate stable power production and beam transport with more than 50% rf power extraction. Once stable beam transport is achieved, alignment experiments may start. The dispersion-free steering should be performed with 16 PETS in order to provide a convincing demonstration for the decelerator, however the principle could be demonstrated with fewer PETS. Rf processing time of the PETS might be a concern, as there is currently no plan to pre-condition the PETS before installation. For the PETS tested in the ASTA test-bench at SLAC [13] in the order of 10^7 rf pulses were needed before reaching the nominal power production of 135 MW at low break down rate, while for the Two-beam Test Stand tests in CTF3 in the order of 10^5 beam pulses were needed in order to reach a power level of > 135 MW [13]. However, the full TBL program can be completed with a relatively high break down rate with respect to the CLIC target of 10^{-7}, thus a relatively smaller number of pulses may be needed for processing before experimentation can start.

ACKNOWLEDGEMENTS

The Test Beam Line experiment is built and operated by CERN within an international collaboration; beam physics studies are performed by the University of Oslo, the PETS prototype and the quadrupole movers are provided by CIEMAT, Madrid, BPMs by IFIC, Valencia and BPM electronics by UPC, Barcelona and LAPP, Annecy.

CONCLUSIONS

The Test Beam Line will provide the first demonstration of the CLIC decelerator. We aim to show stable beam transport while converting more than 50% of the electron drive beam energy into rf power, using CLIC baseline PETS structures operating at least at the CLIC nominal power production level of 135 MW. The effect of transverse wakes is expected to be significantly smaller in the TBL than in the decelerator. If the rf simulations for the baseline PETS structure are accurate, direct observations of the transverse wakes will be challenging to observe with the available instrumentation. Beam-based alignment schemes specially devised for the CLIC decelerator are planned to be demonstrated in the TBL once stable beam transport and power production have been shown.

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