Nuclear Instruments and Methods in Physics Research A 797 (2015) 234–246

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Time-resolved momentum and beam size diagnostics for bunch trains with very large momentum spread

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A R T I C L E I N F O

Article history:
Received 10 February 2015
Received in revised form
24 June 2015
Accepted 28 June 2015
Available online 10 July 2015

Keywords:
Beam size measurement
Energy measurement
Spectrometry
CLIC
Electron decelerator
Time-resolved diagnostics

A B S T R A C T

We propose a novel method to measure the time-resolved momentum distribution and size of beams with very large momentum spread. To demonstrate the principle we apply the method to the beam at the end of a Compact Linear Collider decelerator, where conventional diagnostic methods are hampered by the large energy spread of the drive beam after up to 90% of its kinetic energy is converted into microwave power. Our method is based on sweeping the beam in a circular pattern to determine the momentum distribution and recording the beam size on a screen using optical transition radiation. We present an algorithm to extract the time-resolved momentum distribution. Furthermore, the beam size along the bunch train can be extracted from the image left on a screen by sweeping the beam linearly. We introduce the analysis technique and show simulation results that allow us to estimate the applicability. In addition, we present a conceptual design of the technical realization.

1. Introduction

We discuss a method to determine the time-resolved momentum spread and beam size of bunch-trains with very large momentum spread by using time-varying transversely deflecting fields. This work was stimulated by the very large momentum spread occurring in the decelerator of the Compact Linear Collider [1].

Before delving into the analysis, we note that our methodology is related to the widely used method of using time-varying transverse fields to obtain information about the beam, first mentioned in Ref. [2] and experiments reported in [3]. In the early works the emphasis was on separating particles with different masses, later it was realized that fast-varying fields can be used to measure properties of bunches, too short to be analyzed using other methods, such as streak cameras. First results using circular deflectors for bunch length diagnostics appeared soon thereafter [4], and is still used to diagnose short bunches [5,6]. With the advent of free-electron lasers (FEL) and the need for ultra-short bunches with moderate momentum spread the radio-frequency deflectors experienced a renaissance, reported in the late 1990s [7]. Today, beam diagnostics using transversely deflecting structures is commonly used to measure the momentum spread and the transverse emittance of an ultra-short bunch as a function of the longitudinal position [8–11], the so-called slice momentum spread, and slice emittance, as important parameters for successful operation of FELs. The challenges of diagnosing beams with large momentum spread have been studied regarding emittance measurements [12,13] as well as for momentum diagnostics [14].

The present work is inspired by the development of using deflecting fields to measure time-dependent properties of the beam, but instead of focusing on the ultra-short time-scale needed for single-bunch diagnostics, we focus on the difficulties to diagnose the very large momentum spread that appears naturally as novel acceleration schemes are explored, e.g. in CLIC. The beams in CLIC after the interaction point have large momentum spread due to large losses from the emission of beamstrahlung in the collisions. This spread could be monitored as a complementary diagnostic, for the luminosity, to other methods discussed in [15]. A second subsystem of CLIC where extremely large momentum spread is encountered is the drive beam decelerator, where up to 90% of the incoming beam power is extracted from the drive beam [1,16]. The situation where the beams are constant or averaged in time was already investigated in [14,17], but in this report we extend the analysis to accelerators that are pulsed and momentum spread varies along the pulse train. This is an important quantity to measure, because it is a measure of the quality of the interaction, either the luminosity, or the power extraction in the CLIC decelerator. The latter is the system on which we base the discussion in the remainder of this report.

In CLIC the deceleration leaves the beam with the energy distribution depicted in Fig. 1, with a high energy transient at

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http://dx.doi.org/10.1016/j.nima.2015.06.063
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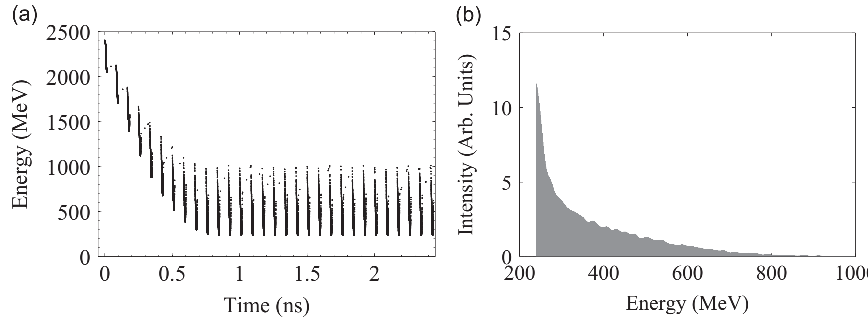

Fig. 1. The energy distribution in the decelerated CLIC drive beam, simulated with PLACET [18]. The high energy transient (a) extends all the way up to the initial energy of 2.4 GeV and is followed by a 240 ns long steady-state. The transient contains very few particles compared to the rest of the bunch train and the histogram to the right (b) shows the energy content of the steady-state only (a) Energy transient, (b) Histogram of the steadystate.

the head of the bunch train, shown in Fig. 1(a), reaching all the way to the initial energy. The majority of the bunches, in the steady state of the pulse, lose 90% of their energy. The resulting energy distribution, shown in Fig. 1(b) has a peak around the minimum energy with a long tail extending to higher energies. The stability of the drive beam under deceleration was identified as a crucial issue among others for the feasibility of CLIC [19]. This motivated the construction of the CLIC Test Facility (CTF3) [20] to experimentally address the issue, in particular how the momentum distribution in the beam can be monitored for an optimum setup of the decelerator.

In the test beam line (TBL) of CTF3, the drive beam decelerator is experimentally studied in small-scale [21]. The analysis of the beam profile diagnostics in TBL in Refs. [22,23] has shown that segmented beam dumps, though currently used for time-resolved spectrometry in TBL, are not suitable for the CLIC decelerators due to the high beam power. On the other hand, OTR screens have a good chance of sustaining the high intensity, assuming that it is sufficiently diluted. We therefore intend to base the time-resolved measurements of transverse and energy profile on OTR screens.

The general layout envisioned for the diagnostics is to have two scanning kicker magnets sitting close together in the beam line; one kicking in the vertical direction and the other in the horizontal direction, similar to the dilution kickers in the LHC dump line, which forms the figure "e" of the beam on a screen [24,25]. We assume that the kickers are excited in a cycle corresponding to the 240 ns drive beam duration and with a rise of the magnetic field that provides a kick from zero to a few milliradian in the same time range. Furthermore, we assume that the magnets are excited such that the horizontal kicker is driven by a cosine wave while the vertical is driven by a sine wave, thus creating a Lissajous figure of the beam on the screen. Forming the sweep into a circle allows us to analyze the momentum distribution along the beam pulse. A linear sweep in one direction at a time gives information about the transverse beam distribution along the pulse. The deflection cycle of a few hundred nanoseconds means that we focus on diagnosing variations along a bunch train rather than on single-bunch diagnostics, and, that the steady-state is favored over the transient.

We will begin with discussing spectrometry for large momentum spread beams and then turn to the particular measurement setup proposed. There, we will first predict what will be seen on the screen for a given beam distribution in time and momentum when the circular sweep is applied. Secondly, we will show examples of the measurement and of the analysis. Then, we discuss the time-resolved beam size measurement. Lastly, we present a conceptual design of the fast kicker magnet system together with a thermal–mechanical study of potential screen materials, with the particular case of the CLIC decelerator in mind.

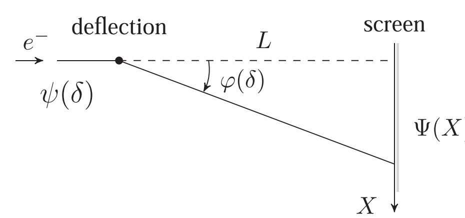

Fig. 2. Sketch of a horizontal deflection onto a screen, defining the variables used in the equations.

2. Spectrometry for beams with large momentum spread

In a spectrometer the beam is deflected by a dipole magnet with field B and length l. Since the deflection angle $\varphi = Bl/pc$ depends inversely on the momentum p of the beam particles, particles with different momenta after a distance L from the center of the dipole intercept a downstream screen at different positions $X = L\tan\varphi$. See Fig. 2 for an illustration of the geometry. Since we anticipate very large momentum spread we restrict ourselves to small deflection angles φ such that we can use the approximation $\tan\varphi \approx \varphi$. Parametrizing the momentum by $\delta = (p-p_0)/p_0$ where p_0 is the reference momentum of the beam and φ_0 the deflection angle for the reference beam, we can write

$$X = \frac{D_0}{1+\delta} \tag{1}$$

where we introduce the abbreviation $D_0 = L\varphi_0$. Incidentally, D_0 coincides with the dispersion generated by the dipole. If the momentum spread is small, i.e. when $\delta \ll 1$, we obtain the linear approximation $X \approx D_0(1-\delta)$. In our case, however, this assumption is not valid. Instead, we use Eq. (1) to determine the particle density on the screen by integrating over all initial momenta through

$$\Psi(X) = \int \psi(\delta)\, \delta_D\left(X - \frac{D_0}{1+\delta}\right) d\delta \tag{2}$$

where δ_D denotes the Dirac delta function. The interpretation of the previous equation is straightforward: We start with a momentum distribution $\psi(\delta)$ of the beam and the delta function collects all the δ that end up at a particular position X on the screen. For the integration over δ we use the relation

$$\delta_D(h(u)) = \sum_i \frac{\delta_D(u-u_i)}{|h'(u_i)|} \quad \Longrightarrow \int f(u)\delta_D(h(u))du = \sum_i \frac{f(u_i)}{|h'(u_i)|} \tag{3}$$

where u_i are the zeros of $h(u)$. In our case, $h(\delta) = X - D_0/(1+\delta)$ with one zero at $\delta = (D_0 - X)/X$ and with $h'(\delta_0) = X^2/D_0$. The