LASER WIRE EMITTANCE MEASUREMENT LINE AT CLIC*

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Abstract

A precise measurement of the transverse beam size and beam emittances upstream of the final focus is essential for ensuring the full luminosity at future linear colliders. A scheme for the emittance measurements at the RTML line of the CLIC using laser-wire beam profile monitors is described. A lattice of the measurement line is discussed and results of simulations of statistical errors and of their impact on the accuracy of the emittance reconstruction are given. Laser wire systems suitable for CLIC and their main characteristics are discussed.

INTRODUCTION

To meet challenging performance specifications of the future CLIC collider it is planned to have a precise monitoring of the beam transverse space and a precise measurement of beam characteristics along the collider. For this an advanced non-invasive diagnostics based on laser wire (LW) beam profile monitors will be implemented in CLIC. The idea of the method was first proposed in [1], its further development for future linear colliders and a schematic setup for a LW beam profile monitors are discussed in Ref. [2]. Results of first successful measurements of electron beams of micron size at the ATF [3] and PETRA-III [4] facilities have been reported. A detailed analysis of a LW diagnostic section of the International Linear Collider (ILC) is given in Refs. [5, 6].

In the present paper we describe a proposal of a section for emittance measurements located at the end of CLIC Ring-to-Main-Linac (RTML) line, just before entrance to the main linac. Results of a preliminary study of characteristics of the laser system are discussed.

RTML EMITTANCE MEASUREMENT SECTION

The description and main characteristics of CLIC are given in Refs. [7, 8], the main important beam characteristics are summurized in Table 1.

It is proposed to measure the electron and positron beam profiles and sizes within a bunch train in a dedicated emittance measurement section (EMS) consisting of four equal FODO cells matched to the incoming beam. Its optics layout is shown in Fig. 1. The horizontal and vertical emittances are determined by measuring the beam profiles only in horizontal and vertical planes (2D measurement scheme). Details of the EMS optics and emittance reconstruction procedure are given in Ref. [9]. In case of the 2D scheme the entrance beam must be uncoupled so that the measurement section must be preceeded by a skew correction section (SCS) (see [6]). According to the ILC proposal the length of such section is about 120 m (see details for example in [10, 11]).

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Table 1: CLIC Beam Parameters

Beam energy E	9 GeV
Horizontal normalized emittance $\varepsilon_{N,x}$	600 nm · rad
Vertical normalized emittance $\varepsilon_{N,y}$	10 nm · rad
Horizontal beam size σ_x	24 μm
Vertical beam size σ_y	5 μm
Number of particles per bunch N_e	$4 \cdot 10^9$
Bunch length τ_b	0.15 ps
Bunch repetition frequency f_b	2 GHz
Number of bunches per train N_b	312
Train repetition frequency f_{tr}	50 Hz

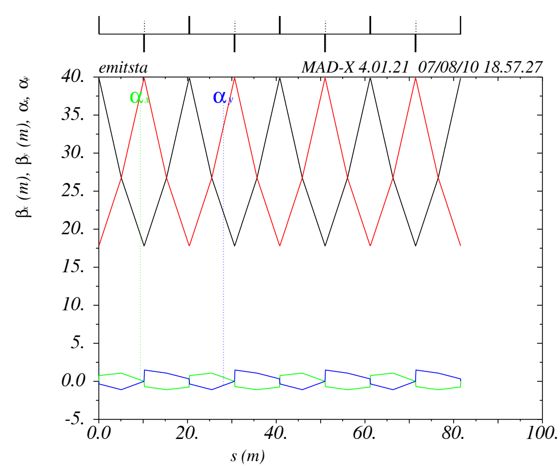

Figure 1: The optics layout of the 2D emittance measurement section.

Due to measurement errors the reconstruction procedure may give non-physical values of the emittances, namely negative ε_x^2 or ε_y^2. As it is shown in paper [6] for a measurement section with N FODO cells the number of such non-physical solutions is minimal if the phase advance per cell μ is equal to $\mu = 180°/N$. For this reason in our case the phase advance per cell in both planes is chosen to be $\mu = 45°$. Assuming the minimal beam size $\sigma_{min} \leq 5\mu m$, the quadrupole integrated strength $k_Q = 0.25$ m^{-2} and the quadrupole length $l_Q = 0.3$ m, the length of the FODO measurement section under consideration turns out to be $L_{EMS} \geq 81.6$ m (see details in [9]). The matched minimal and maximal values of the β-functions are $\beta_{min} = 17.8$ m, $\beta_{max} = 39.8$ m.

Similar to results obtained in Refs. [6, 10, 11] we found that with the increase of the error of the beam size measurement the number of unphysical cases also increases. The plot in Fig. 2 shows the fraction of non-physical cases of the vertical plane matrix as a function of the beam measurement error. Comparing this plot with a similar one in [6] one can see that the 2D measurement scheme is less sensitive to beam size measurement errors than the 4D one.

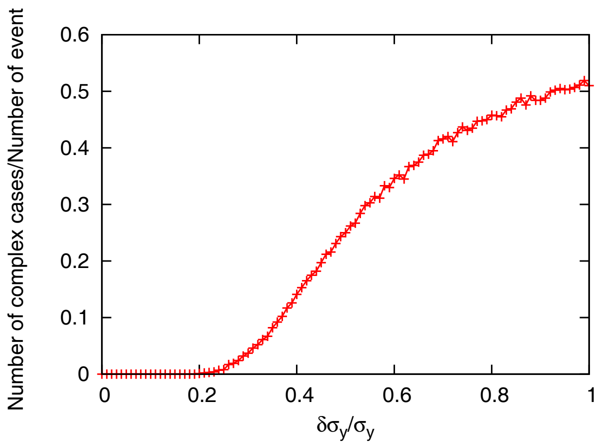

Figure 2: Fraction of simulations giving a non-physical beam matrix as a function of the beam measurement error.

We simulated the relative error in the determination of the emittances due to the measurement error $\delta\sigma_e/\sigma_e$. The result for the vertical plane is shown in Fig. 3, for the horizontal plane the plot is similar. Here for simplicity the measurement errors at all LW scanners were supposed to be the same. Notice that for $\delta\sigma/\sigma < 0.4$ the emittance error displays an approximately linear behavior.

LW SYSTEM

The LW method is based on the inverse Compton scattering on laser photons on electrons or positrons of the collider beam. The photons exit the beam pipe and are captured by a detector (calorimeter or Cherenkov detector), the particle beam being separated from them by a down stream dipole magnet. By counting the number of detected Compton photons as a function of the laser beam position the spatial distribution of the electron bunch can be reconstructed. The scanning laser beam can be sent to the collision point either vertically or horizontally, thus enabling to obtain a horizontal or vertical profile measurement. The setups of the existing LW systems are given [12] (PETRA) and [13] (ATF) (see also [2]). The LW method is non-invasive and existing examples have demostrated high resolution and fast scanning speed.

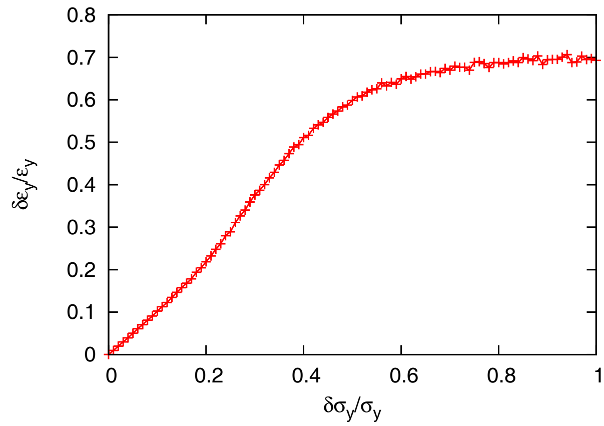

Figure 3: Relative error of the vertical emittance measurement as a function of the relative beam size measurement error.

Following the design of LW beam profile monitors at PETRA and ATF and taking into account a LW proposal for the ILC we have considered two proposals for CLIC, namely a system based on a mode locked seed laser and a system using an injection Q-switched laser. The chosen laser wavelength is $\lambda = 532$nm. It can be obtained from a frequency doubled fundamental wavelength of a Nd:YAG laser. This is a resonable compromise which provides sufficiently small focused laser spot size, large Rayleigh range and large number of scattered photons.

In the case of the mode locked laser the laser pulse illuminates only one particle bunch so that the laser pulse length τ_l is supposed to be approximately the bunch length τ_b. For the Q-switched case laser shots are relatively large, we have considered $\tau_l = 5$ns similar to the PETRA LW system [12]. The $f_\#$-number, defined as the ratio of the focal length of the focusing lens to its diameter, is assumed to be equal to $f_\# = 6$, while the laser quality factor M^2 is chosen to be equal to $M^2 = 1$ $M^2 = 1.5$ for the mode locked and Q-switched lasers, respectively. Using formulas in [6, 14] one can check that in both cases the Rayleigh range is at least 3-4 times larger then the horizontal beam size σ_x so that the approximation of infinite Rayleigh range is valid and the laser spot radius at the collision point can be considered as constant across the beam.

To get an estimate of laser detected photons formulas from Sect. III.A.1 of Ref. [6] have been used. We assume that the average power P_l^{av} of the laser does not exceed $P_l^{av} = 1$W. Assuming the detector efficiency $\eta_{det} = 0.05$ and using the fact that for the laser wavelength $\lambda = 532$nm and beam energy $E = 9$GeV the factor $f(\omega)$, relating the Compton and Thomson cross sections, is $f(\omega) = 0.87$ we obtain that for the vertical profile measurement the number of the Compton photons produced is equal to $N_\gamma = 3200$ per laser pulse in the case of mode locked LW system and $N_\gamma = 250$ per laser pulse for the Q-switched laser. These numbers are obtained for the zero value of the offset Δ

between the centroids of the electron bunch and laser beam.

The LW parameters are summarized in Table 2.

Table 2: Summary of LW System Parameters

Parameter	Mode locked	Q-switched
Laser wavelength	532 nm	532 nm
$f_{\#}$	6	6
Mode quality factor M^2	1	1.5
Rayleigh range z_R	90 μm	820 μm
Laser spot size σ_l	3 μm	5 μm
Instantaneous laser power P_l	440 MW	4 MW
Laser pulse duration τ_l	0.15 ps	5 ns
Pulse repetition frequency f_l	2 GHz	50 Hz
Compton photons per laser pulse N_γ (for $\Delta = 0$)	3200	250

After exiting the EMS the particle beam is deviated by a dipole magnet in order not to hit the photon detector. We assume that the distance between the EMS and the detector is $l = 10$m and take into account that the beam deviation about $d = 25$cm is enough for a standard detector. Then the magnetic field integral of the bending dipole placed at the exit of the last FODO cell for the 9GeV electron beam turns out to be quite moderate $\int Bds = 0.75$ T $\cdot$ m.

The particle beam travelling through the SCS and EMS produces beam-gas bremsstrahlung photons. To get an estimate of this background we follow Ref. [15]. To accomodate the SCS and EMS the distance from the bunch compressor to the main linac should be about $D = 200$ m. Using an estimate for the cross-section for bremsstrahlung of N_2 or CO gas $\sigma_B \approx 7$ barns and assuming the pressure in the vacuum chamber $P = 10$ nTorr and temperature $T = 273$K we calculate the number of background photons per bunch as $N_{\gamma,B} = DPN_e\sigma_B/k_BT$, where k_B is the Boltzmann constant. This gives $N_{\gamma,B} \approx 0.18$ background photons per laser pulse in case of mode locked system and $N_{\gamma,B} \approx 1.8$ in case of the Q-mode laser. Comparing this estimate with the number of Compton photons per laser pulse (Table 2) one can see that for both schemes the signal can be well distinguished by the detector. Synchrotron radiation background issues will also be studied, as in [15].

Using an approximate formula from [6] we get an estimate of the error on the electron beam sizes σ_e extracted from the beam profile scan $\delta\sigma_{e,y}/\sigma_{e,y} < 0.06$, $\delta\sigma_{e,x}/\sigma_{e,x} < 0.003$ (here the assumed accuracy in determination of M^2 is $\delta_{M^2} = 0.1$.

CONCLUSIONS

A 2D emittance measurement section proposed for the RTML line of the CLIC collider consists of four FODO sections of the total length 81.6 m and is equipped with four LW beam profile monitors placed just after the horizontally defocusing quadrupoles. At the entrance to this section the horizontal and vertical beam oscillations must be decoupled, therefore it must be preceded by a skew correction section. From the estimate of the relative beam size error and the plot in Fig. 3 one can see that the emiitance can be reconstructed with an error better than 10 %.

We have also outlined proposals of LW beam profile measurement systems, with a mode locked laer and with Q-switched laser, and analyzed their main requirements.

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