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Beam dynamic simulations of the CLIC crab cavity and implications on the BDS

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ABSTRACT

The Compact Linear Collider (CLIC) is a proposed electron positron linear collider design aiming to achieve a centre of mass energy of up to 3 TeV. The main accelerating structures in CLIC operate at an X-band frequency of 11.994 GHz with an accelerating gradient of 100 MV/m. The present design requires the beams to collide at a small crossing angle of 10 mrad per line giving a resultant overall crossing angle of 20 mrad. Transverse deflecting cavities, referred to as "Crab cavities", are installed in the beam delivery system (BDS) of linear collider designs in order to ensure the final luminosity at the interaction point (IP) is comparable to that in a head on collision.

We utilise the beam tracking code PLACET combined with the beam–beam code GUINEA-PIG to calculate the resulting luminosity at the IP. We follow a similar tuning procedure to that used for the design of the ILC crab cavities and anitcrab cavities. However an unexpected loss in luminosity of 10% was observed for the 20 mrad design was observed. It was discovered that the action of the crab cavities can affect the geometric aberrations resulting from the sextupoles used to correct chromatic effects in the beam delivery system. This has direct consequences regarding the design of the present CLIC BDS.

1. Introduction

The Large Hadron Collider (LHC) explores collisions in the TeV range and together with validating the standard model, aims at exploring new physics regimes. An electron positron collider (a lepton machine) is a complementary machine to a hadron design. However for energies above a 200 GeV centre of mass, building a circular lepton machine becomes impractical due to the inherent synchrotron radiation generated. Hence several linear collider designs have been proposed to overcome this synchrotron radiation limitation [1,2]. CLIC is a proposed electron positron linear collider design aiming to achieve centre of mass energies up to 3 TeV. The main accelerating structures in CLIC are normal conducting travelling wave structures that operate at an X-band frequency of 11.994 GHz with an accelerating gradient of 100 MV/m [2].

All the CLIC parameters used herein were taken from CLIC Beam Delivery System (BDS) lattice v_10_01_25 [3,4] values of importance in terms of the beam dynamics in the BDS are presented in Tables 1 and 2.

PLACET (Program for Linear Accelerating Correction Efficiency Tests) is a beam tracking code written, developed and expanded initially by E d'Amico et al. [5]. It is written in a combination of compiled C and TCL programming languages. PLACET is capable of complicated beam dynamic simulations in which collective effects such as wakefields (long range, short range, geometric and resistive), synchrotron radiation emission from various elements as well as beam misalignments, imperfections and amplitude errors can all be included in any given simulation. Each bunch can be treated separately as a series of macroparticles (slices) containing a user specified number of elementary particles.

All beam dynamic calculations herein were conducted using a specialised version of the code known as "PLACET-OCTAVE" [6]. This specific version of PLACET has several additional features. These include a user interface via the OCTAVE language suite and a special class of Lattice Elements called "CrabCavity". The new user interface allows users to directly implement both their own subroutines as well as pre-existing OCTAVE subroutines, programs and libraries. The new class of "CrabCavity" Lattice Elements permits transverse cavities such as crab cavities to be included in the beam dynamic lattice within the code.

GUINEA-PIG (Generator of Unwanted Interactions for Numerical Experiment Analysis – Program Interface to GEANT) was originally developed by Schulte [7,8]. GUINEA-PIG is a beam-beam interaction

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code and is used to determine the resulting luminosity at the IP. Once the beams have been tracked through the CLIC BDS using PLACET, they are passed onto GUINEA-PIG.

Crab cavities operate using transverse dipole modes where the primary mode of operation is the TM_{110} like hybrid mode of an iris loaded cavity. This mode has both transverse magnetic and electric fields which operate to kick the head and tail of the bunches in opposite directions within the same plane such that a rotation is imparted to each bunch. A rotation of the bunch is achieved when these cavities are tuned such that magnetic field along their centre is zero when the centre of a bunch is within the cavity.

The present CLIC crab cavity is designed to be of the same phase advance as that of the main CLIC accelerating linac cavities, which is $2\pi/3$ rad. The current CLIC crab cavity design is a travelling wave structure using between 10 and 20 cells; however for the purposes of this initial investigation the precise number of cells is irrelevant for the explicit reason that we implement the crab cavity as an idealised cavity within PLACET and as such no field maps are required. Instead the electromagnetic field of the idealised crab cavity is analytically calculated as a sinusoidal wave as a function of both cavity phase advance and applied cavity gradient. This allows the idealised crab cavity to be initially tuned as a function of applied cavity gradient without requiring the express knowledge of the number of cells.

A Crab cavity has a time varying transverse electric and magnetic field such that a particle transversing the cavity will experience a transverse kick that will alter its trajectory based upon both its longitudinal position from the centre of the cavity (in terms of the bunch axis) and the applied peak transverse voltage V_0 [9]. This is described by Eq. (1) where $V_\perp$ is the transverse voltage experienced by the particles and is directly proportional to the longitudinal offset s [9]

$$V_\perp = V_0 \sin(\omega s/c) \tag{1}$$

Eq. (1) is used to tune the operating gradient of the crab cavity such that the rotation of the bunches is manipulated until maximum luminosity is obtained at the IP. The routine within PLACET where this is implemented is known as "crab.cc".

The CLIC crab cavity was incorporated at the end of the drift space D2OD, the rational behind this was the same as that used for the ILC Crab cavity calculations [9,10]; these being as it has a high R_{12}, the correct phase advance and has minimum distance between cavities in the opposing Beam Delivery Systems, which is required for phase control reasons. The CLIC BDS lattice taken from the point where the CLIC crab cavity was installed is presented in Table 3 in which, for reasons previously outlined, the crab cavity is considered as an idealised structure in which neither the number of cells nor geometry are required for the initial PLACET calculations. A scaled diagrammatic representation of this lattice is also displayed in Fig. 1.

In Section 2 the tuning methodology is outlined, allowing the operating cavity gradient to be determined including the basic operating tolerances allowable on both phase and roll errors to maintain 98% maximum luminosity. In Section 3 we report on an unexpected result encountered during the tuning procedure which results in a loss in luminosity of the order of 10% compared to that of a head on collision and identify the underlying factors behind this observation. The final section is concerned with the findings of this investigation and the immediate ramifications to the present CLIC BDS design.

Table 1
CLIC BDS parameters of importance used in PLACET based on information from Refs. [3,4].

Beam Delivery System plus IP	Symbol	Value
Crossing angle at IP	θ_c	20 mrad
Bunch length	σ_s	44
Initial RMS energy spread	$\sigma^*_{\Delta E/E}$	0.29
Horizontal IP beta function	β^*_x	6.9
Vertical IP beta function	β^*_y	0.068
Horizontal IP beam size before pinch	σ^*_x	45
Horizontal IP beam size before pinch	σ^*_y	1
Transverse horizontal emittance (norm)	$\gamma\varepsilon_x$	660
Transverse vertical emittance (norm)	$\gamma\varepsilon_y$	20

Table 2
Overall CLIC parameters of importance used in PLACET based on information from Refs. [3,4].

Overall parameters	Symbol	Value
Centre of mass energy	E_{cm}	3 TeV
Main linac frequency	f_{RF}	11.994 GHz
Number of particles per bunch	N_b	3.72×10^6
Number of bunches per pulse	k_b	312
Bunch separation	Δt_b	0.5 (6 periods)
Bunch train length	τ_{train}	156

Table 3
Parameters of the CLIC BDS lattice used in the PLACET calculations, taken from CLIC BDS lattice v_10_01_25 [4]. Here the lattice is taken from the adjusted drift space D2OD in which the Crab cavity has been installed. Note for initial PLACET calculations the crab cavity is considered as an idealised structure in which neither the precise number or cells nor geometry are required.

Name	Type	Length:m	Aperture:m	βx:m	βy:m	μx:m	μy:m	αx	αy
D2OD	Drift	11.12894	–	76543.04	82684.36	5.165597	7.48979	−579.599	−589.353
CRABCAV	CrabCavity	0.16	–	–	–	–	–	–	–
OCTDRIFT	Drift	2	–	78879	85058.58	5.165601	7.489794	−588.377	−597.754
SF1	Sextupole	0.496824	0.00483	79171.59	85355.81	5.165601	7.489794	−589.467	−598.798
LX0	Drift	0.248412	–	79758.39	85951.85	5.165602	7.489795	−591.648	−600.885
QF1	Quadrupole	3.256681	0.00469	53037.15	133610.5	5.16561	7.4898	7587.965	−16069.1
D1OD	Drift	0.48412	–	45944.62	149622.2	5.165611	7.489801	7062.403	−17004.7
OCTDRIFT	Drift	2	–	22037.41	225371.3	5.165621	7.489802	4891.201	−20869.9
Dec-00	Octupole	0.496824	0.00359	17445.24	246585.6	5.165625	7.489803	4351.848	−21830
LX0	Drift	0.248412	–	15350.13	257550.6	5.165628	7.489803	4082.171	−22310.1
SD0	Sextupole	0.496824	0.00376	13389	268754	5.16563	7.489803	3812.495	−22790.2
DD0	Decapole	0.248412	0.00382	9868.685	291876.5	5.165637	7.489803	3273.142	−23750.4
QD0	Quadrupole	2.732532	0.00383	4051.412	292274.6	5.165673	7.489804	1288.162	23480.35
D0	Drift	3.502609	–	0.006963	6.77E−05	5.423069	7.74473	−0.04796	−0.03097