INTRA-BEAM SCATTERING IN THE CLIC DAMPING RINGS

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Abstract

The CLIC 3 TeV nominal design requires very low emittance of the electron and positron beams to be reached in the damping rings. Due to low energy and to relatively high bunch charge and ultra-low emittance, Intra-Beam Scattering (IBS) effect is very strong and an accurate calculation is needed to check if the required emittance is effectively reached. For this reason a new software is being developed at CERN for IBS and Radiation Effects calculation, which simulates the evolution of the beam particle distribution in the damping rings, taking into account radiation damping, IBS and quantum excitation. In this paper we present the results of our simulations performed with SIRE on a lattice of the CLIC damping rings.

INTRODUCTION

According to the CLIC 3 TeV baseline configuration [1] very low emittances of the e^- and e^+ beams have to be reached in the Damping Rings (DR). With the choice of parameters and lattice operated in the DR design [2], the theoretical equilibrium emittance achieved is the result of the balance between radiation damping (RD), quantum excitation (QE) and IBS. For this reason a detailed optimization of the DR design has been performed [3]. Concerning the study of IBS, the two theories largely used to calculate its effect are the Piwinski [4] and Bjorken-Mtingwa [5] ones. Among the subsequent formalisms based on these theories along the years, K. Bane [6] developed a so called *Modified Piwinski* formulation for which he proved the asymptotical equivalence to the Bjorken-Mtingwa's one for high energy beams. In all these formalisms IBS effect on the beam emittance is calculated assuming a Gaussian distribution of the particles. While it is well known that Gaussian distribution is the stationary solution of the Fokker-Planck equation for the particle distribution in the phase space including RD and QE (see *e.g.* [7]), there is no warranty that in a strong IBS regime the distribution would remain Gaussian. In order to check whether the CLIC DR can achieve the target emittance it is then important to be able to calculate the combined effect of IBS, RD and QE in the DR regardless of the distribution of the particles. To this end a code capable of such calculations has been developed named Software for IBS and Radiation Effects (SIRE).

STRUCTURE OF SIRE

SIRE has been developed starting from a Monte Carlo code called MOCAC, developed by P. Zenkevich *et al.* [8-10], with the purpose of calculating the IBS effect for arbitrary particle distributions. The three physical processes taken into consideration in SIRE are IBS, RD and QE, the last two being not yet implemented in MOCAC.

IBS Calculation

The algorithm used to calculate IBS is similar to that implemented in MOCAC. Both SIRE and MOCAC are tracking codes where the beam is represented by a large number of macro-particles occupying points in the 6-dimensional phase space. They need as input data the Twiss functions calculated at different locations of the lattice (for example at the end of each element of the DR). With the Twiss parameters it is possible to give a formulation of the trajectories of the macro-particles in the phase space in terms of 3 invariants (the two Courant-Snyder ones and the longitudinal invariant) and 3 phases (two betatron and one synchrotron) instead of using the 6 coordinates (position and momentum). The 3 invariants are conserved between points around the lattice and can only change by effect of IBS, RD or QE, while the phases are chosen randomly at each given point of the lattice. The code SIRE uses time steps ΔT larger than the revolution time but smaller than the damping/growth times. An initial (Gaussian) distribution of the macro-particles is generated, and then SIRE proceeds until the end of the simulation as follow:

- At every point of the lattice the 3 phases of each macro-particle are randomly chosen and position and momentum of the macro-particles are calculated.
- The beam is geometrically divided into a number of cells and the macro-particles are assigned to each cell according to their geometrical position.
- In each cell intra-beam collisions between pairs of macro-particles are calculated. The number of collisions each macro-particle experiences can be decided in relation to the computational time available. The scattering angles in each collision are determined by formula (15) in [10].
- New invariants corresponding to each macro-particle are calculated, the beam distribution is then updated, and the code proceeds with the next lattice point.

The simulation continues until the end time is reached. A lattice compression technique has been implemented to speed up the calculations. Indeed, the increase of the invariants due to IBS being linear to the first order in the travelling time along an element, when two elements of the lattice are identical (or almost identical) IBS effect can be evaluated for only one such element doubling its time of crossing.

Radiation Damping and Excitation

Radiation Damping acts on the invariants of the macro-particles producing an exponential decrement of them

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depending on the elapsed time. To take account of it, a routine has been introduced which is called at each iteration after the calculation of the IBS effect. Since it corresponds to an advancing of ΔT of the simulated time it is only necessary to apply the replacement:

$$\varepsilon^{i}_{H,V,L} \rightarrow \varepsilon^{i}_{H,V,L} \exp\left[-\Delta T / \tau_{H,V,L}\right] \qquad (1)$$

where $\varepsilon^{i}_{H,V,L}$ are the transverse and longitudinal invariants of macro-particle i and $\tau_{H,V,L}$ are the horizontal, vertical and longitudinal damping times.

At the equilibrium between RD and QE the distributions of the 6 coordinates of the macro-particles in the phase space are Gaussians with standard deviations derivable from the lattice and parameters of the ring design. This means that the contribution of QE compensates exactly the reduction in Eq. 1 due to RD. In SIRE QE is then implemented by adding to the 6 coordinates of each macro-particle a random Gaussian contribution with variance derived by exact compensation of Eq. 1, calculated at the equilibrium. It is assumed that QE can be described with this scheme also when the beam is not at the equilibrium.

VALIDATION

A validation of the IBS routine has been performed on the CLIC DR lattice design. To this end the Twiss functions at the end of each element of the DR lattice have been calculated (see Fig. 1) and a simulation has been performed with the parameters specified in Table 1 (i.e. for the zero current equilibrium emittance), considering only the IBS effect.

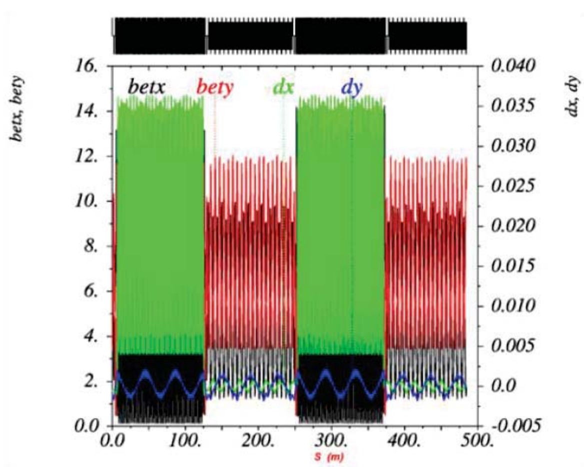

Figure 1: Twiss functions of the DR lattice.

With SIRE it is possible to track the emittance of the beam along the lattice to check in which elements IBS effect is stronger (see Fig. 2). From the results of the simulation it is possible to compute the IBS growth rates, defined as the inverse of the growth times $T_{H,V,L}$:

$$\frac{1}{T_{\mathrm{H,V,L}}} = \frac{d \ln \varepsilon_{H,V,L}}{dt} \qquad (2)$$

Table 1: Parameters for validation

Parameter	Unit	Value
Energy	GeV	2.86
Bunch Population	10^9	4.07
Circumference	m	493.16
Norm. Emittance H,V	nm	229.6 , 3.74
Momentum Spread	%	0.109
Bunch Length	mm	0.922
N. macro-particles	10^3	200
N. cells	10^3	200
ΔT	μs	1.645

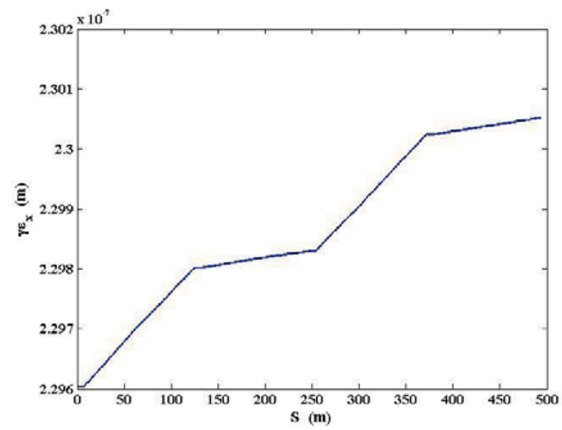

Figure 2: Evolution of the horizontal emittance in validation simulation.

The validation is then made by comparing the IBS growth rates derived from SIRE simulation carried out over a single DR revolution with those calculated by conventional formalism. Table 2 compares the growth rates derived by SIRE (with and without lattice compression) with the ones calculated by Bjorken-Mtingwa and Modified Piwinski formalisms.

Table 2: Comparison SIRE – conventional formalisms

Formalism	$1/T_H$ (s^{-1})	$1/T_V$ (s^{-1})	$1/T_L$ (s^{-1})
Bjorken-Mtingwa	1579	739	969
SIRE	1186	665	800
SIRE (compressed)	1239	687	786
Modified Piwinski	1300	626	775

RESULTS

The main reason for which SIRE has been written is to find out whether the target emittance for the CLIC DR is reached or not at the end of the 20 ms cooling time. The simulation has been performed using the lattice in Fig. 1 with the parameters specified in Table 3.

Table 3: Parameters of the DR simulation

Parameter	Unit	Value
Circumference	m	493.16
Energy	GeV	2.86
Bunch Population	10^9	4.07
Damping times H,V,L	ms	1.62, 1.64, 0.82
Norm. Eq. Emit. (No IBS) H,V	nm	229.6, 3.74
Eq. mom. spread (No IBS)	%	0.109
Eq. bunch length (No IBS)	mm	0.922
Injection Emittance H,V	μm	74.3, 1.74
Injection Long. Emittance	eV m	130589
ΔT	μs	10

The number of macro-particles and number of cells are the same as in Table 1. Fig. 3 shows the evolution of the horizontal emittance during the cooling time.

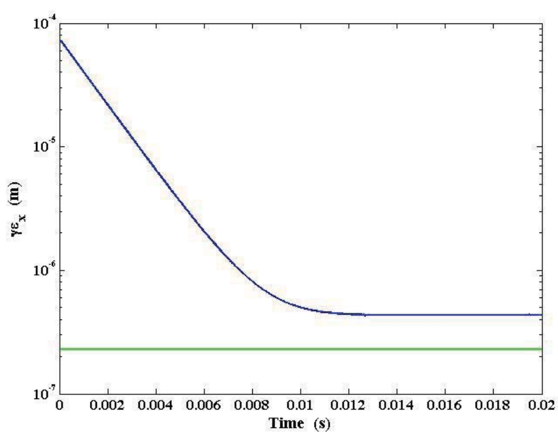

Figure 3: Evolution of the horizontal emittance during the cooling time in the CLIC DR (blue) and zero current equilibrium emittance (green).

The final equilibrium emittance in presence of IBS, RD and QE is shown in Table 4.

Table 4: Final equilibrium emittance in the CLIC DR.

Parameter	Unit	Value
Horizon. Norm. Eq. Emit.	nm	435.8
Vert. Norm. Eq. Emit.	nm	5.54
Eq. mom. spread	%	0.123
Eq. bunch length	mm	1.04

CONCLUSIONS

In this paper a new code to investigate the equilibrium between RD, QE and IBS, occurring in the CLIC DR has been presented. The code (named SIRE) has been developed starting from a previous code (MOCAC) developed to investigate IBS for arbitrary particle distributions. A crosscheck of SIRE with conventional IBS formalisms has been performed resulting in reasonable agreement. Simulations of the beam evolution in the DR have been performed giving confirmation of the theoretical equilibrium emittance reachable. The code proved to be useful in determining the parts of the ring where IBS is stronger, helping the design study. Investigation will continue in order to study the equilibrium beam distribution in presence of strong IBS and check possible deviations from Gaussian distribution.

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