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INTERPLAY BETWEEN SPACE CHARGE, INTRA-BEAM SCATTERING, AND SYNCHROTRON RADIATION EFFECTS

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Abstract

The objective of this research is to study the interplay of synchrotron radiation, intra-beam scattering and space charge in the vicinity of excited resonances. In this respect, two modules were developed to simulate intra-beam scattering and synchrotron radiation effects and plugged into pyORBIT to be used together with its space charge module. Different regimes of synchrotron motion were used to study the response of the beam to a lattice resonance when space charge, intra-beam scattering and synchrotron radiation are present.

INTRODUCTION

In ultra-low emittance rings, such as the Compact Linear Collider Damping Rings (CLIC DRs), magnet nonlinearities including strong sextupoles, errors from variable bends and wigglers can limit the quality and lifetime of the beam and thus the performance of the machine. Due to the high brightness of the beam in such machines, incoherent effects such as Intra-Beam Scattering (IBS) and Space Charge (SC) can further degrade the performance of the machine.

These effects have been intensively studied in several accelerators. IBS plays a crucial role in the evolution of the beam emittances in ion machines and in proton storage rings where the beam is stored for many hours. It can also limit the performance of damping rings and light sources [1–5]. Space charge effects have been studied in many low-energy machines, and also for damping rings [6–15]. The space charge induced tune spread can lead to particle losses and emittance increase in the presence of resonances.

The interplay of these effects has not been studied in much detail. Accelerator rings like the CLIC DRs that need to deliver beam emittances under strict requirements, can suffer from beam degradation in the presence of these effects. The goal of this work is to investigate the interplay of SC and IBS in the vicinity of an excited, vertical resonance and then, examine if Synchrotron Radiation (SR) damping can help preserve the vertical emittance by compensating these two effects and their potential interplay, in the context of the CLIC DRs.

THE CLIC DAMPING RINGS

The CLIC main DRs are part of the CLIC injector complex. Their purpose is to receive a beam with large transverse emittance, as coming from the upstream machine, and damp it down by 2 orders of magnitude within the repetition rate of 50 Hz. For this study, the CLIC DRs conceptual design [16] is used with the main parameters summarized in Table 1.

Table 1: CLIC DRs Parameters

Ring Parameters	
Circumference [m]	427.5
Energy [GeV]	2.86
Energy losses [MeV/turn]	3.98
Relativistic gamma, γ_r	5597
Harmonic number, h	2852
RF voltage [MV]	4.5
Momentum compaction factor	0.00013
Q_x, Q_y	48.357, 10.387
δQ_x, δQ_y	-0.005, -0.17

The natural equilibrium emittance at the output of the main DRs is defined by the effects of SR and Quantum Excitation (QE). The steady state emittance on the other hand is dominated by the IBS effect. The injection and extraction parameters such as the number of particles per bunch (N_p), the geometrical emittances $\varepsilon^{\text{geom}}$, the longitudinal rms bunch length (σ_s) and momentum spread (σ_δ) are summarized in Table 2 for the configuration that is used in the studies presented in this paper.

Table 2: Beam Parameters for the CLIC DRs

	Injection	**Output Values without/with IBS**	**Target**
N_p	4.4×10^9	4.4×10^9	4.1×10^9
$\varepsilon_x^{\text{geom}}$[pm]	9.63e3	55.7 / 103	89.3
$\varepsilon_y^{\text{geom}}$[pm]	268	0.59 / 0.68	0.89
σ_s[mm]	3.2	1.46 / 1.56	1.81[a]
$\sigma_\delta[10^{-3}]$	1.04	1.09 / 1.16	1.16

[a] Evaluated from the momentum spread, considering the requirement of ε_s = 6 keV·m

STUDIES OF THE RELEVANT INCOHERENT EFFECTS

Simulations were performed to study incoherent effects such as SC, IBS and SR. The parameters of the steady state emittances including the IBS effect from Table 2 were used as input beam parameters.

Space Charge Studies

The SC kick used for the simulations presented in this paper is based on the ”frozen” potential, commonly used for

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long-term simulations, using the pyORBIT code [17]. The SC kicks for a chosen (fixed) particle distribution are computed analytically using the expression derived by Bassetti and Erskine [18], taking into account the local longitudinal density and the transverse beam sizes.

To verify that the SC induced incoherent tune shift indeed becomes the most critical for the beam parameters close to the equilibrium emittances, tune footprints were calculated for on-momentum particles up to 3 σ for different stages of the CLIC DR cycle as shown in Fig. 1. The tunes of the test-particles were determined using the NAFF algorithm [19] and the tune diffusion is indicated by the color code. The red and blue lines correspond to systematic and non-systematic resonances accordingly, while the full and dashed lines correspond to normal and skew resonances. Starting with large transverse emittances, particles experience large amplitude detuning from the non-linearities introduced by the sextupoles. As the emittances are damped down, the detuning from magnet non-linearities is decreased but the SC induced tune spread becomes dominant, reaching a maximum vertical tune shift of the order of $\delta Q_y = -0.15$.

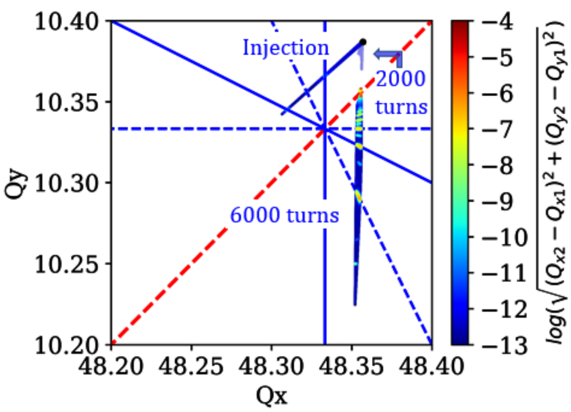

Figure 1: Evolution of the tune footprint during the CLIC DR cycle at injection, after 2000 turns and after 6000 turns.

The incoherent tune footprint touches several low order resonances. A resonance that could limit the performance of the machine in that respect is the $3Q_y = 31$. This resonance can be excited by skew sextupole errors in the machine. To excite this resonance in a controlled way in the simulation, two skew sextupoles were added as errors in the lattice which were adjusted such as to avoid exciting the $2Q_x + Q_y = 107$ resonance. The effective strength of the sextupoles was chosen as $k_{2sl} = 100\,\mathrm{m}^{-3}$. To achieve a quasi self-consistent evaluation of the SC kick during the simulation, the frozen potential was recomputed according to the evolution of the beam parameters every 100 turns.

For the following simulations, the horizontal tune was set to $Q_x = 48.39$ while the sensitivity to the $3Q_y = 31$ resonance was studied for a range of vertical tunes. Figure 2 (top) shows the result of tracking macroparticle distributions for 16000 turns, which corresponds to slightly more than the entire cycle duration of the CLIC DRs. Although the $3Q_y = 31$ resonance is strongly excited, there is only a relatively

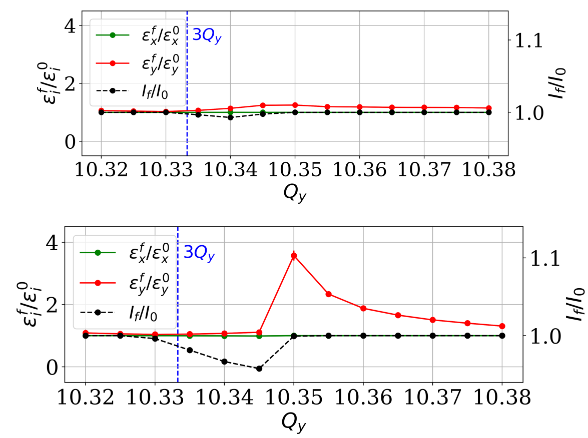

Figure 2: Relative emittances and intensity as a function of the vertical tune for the nominal T_s (top) and T_s=1 500 turns (bottom), considering only SC.

weak response of the beam in terms of losses and emittance growth in presence of SC. The reason for that is the fast synchrotron motion, as the synchrotron period in the CLIC DRs is only about $T_s = 150$ turns. The fast modulation of the space charge force results in the creation of resonance side-bands at even multiples of the synchrotron tune [20], which lead to a relatively weak diffusion of the particle motion. For comparison, the same simulation is repeated for a case where the synchroton period was increased to $T_s = 1\,500$ turns, as shown in Fig. 2 (bottom). In this case, the vertical emittance growth for working points above the resonance is clearly pronounced. This is the typical signature of trapping and scattering of particle trajectories on a resonance, as observed in hadron machines [6–10]. Note however that due to the small beam size the losses are quite small.

Space Charge Studies with IBS

The IBS effect was included in the simulation model by a simplified effective kick given by the following form [21]:

$$\Delta p_u = r\sigma_{p_u}\sqrt{2T^{-1}_{\mathrm{IBS},u}T_{\mathrm{rev}}\sigma_s\sqrt{\pi}\rho_s(z)}, \tag{1}$$

where r is a Gaussian random number with zero mean and unit standard deviation, T_{rev} the revolution period, σ_{p_u} the standard deviation of the momentum p_u in plane u, σ_s the bunch length, ρ_s the longitudinal line density and $T^{-1}_{\mathrm{IBS},u}$ the IBS growth rates that are evaluated using the Nagaitsev's method [22]. Every turn, each particle receives a change of its momenta depending on the beam parameters and the particle's longitudinal position. As will be shown later, the emittance evolution resulting from this effective kick was benchmarked with analytic calculations.

Simulations were performed to study the interplay of SC and IBS. The case of the working point which was most affected by the resonance, i.e. $Q_y = 10.35$ will be presented here. Figure 3 shows the vertical emittance evolution for the cases where only SC (green), only IBS (blue) and the interplay of both effects (red) is considered. For the nominal

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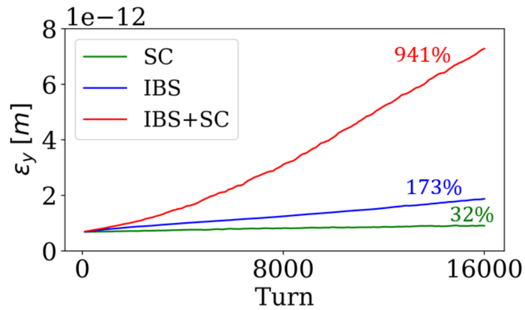

Figure 3: Vertical emittance evolution with SC, IBS and for both effects combined.

synchrotron motion there is approximately 30% increase due to SC and 170% due to IBS while the combination of both effects leads to an increase of almost 1000%. Thus the interplay of these two effects clearly results in enhanced particle diffusion.

Space Charge Studies with IBS and SR

Having observed that indeed there is a strong interplay between SC and IBS, especially in the presence of an excited resonance, the next step is to see if the damping from SR can compensate this enhanced emittance growth. SR was implemented in the simulations as a simplified kick, similar to the implementation of the pyHEADTAIL code [23]. This kick acts every turn on particles' momenta considering the energy loss per turn, the damping times and the equilibrium values that are evaluated from the radiation integrals that also include the contribution from quantum excitation.

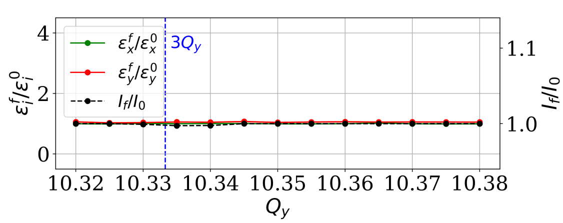

Figure 4: Relative emittances and intensity as a function of the vertical tune taking into account SC, IBS and SR.

Figure 4 shows the full tune scan with all three effects taken into account, for the nominal T_s. It can be seen that the strong SR mostly cancels the vertical blow-up. The residual blow-up remains always below 5% and particle losses below 1%. This result is very encouraging, as even in the presence of strong one-dimensional resonances SR damping seems to sufficiently counteract beam degradation from SC effects, as shown for the case of a vertical resonance.

Figure 5 shows the emittance evolution through the full cycle of the CLIC DR for the nominal working point. The tracking simulations with pyORBIT include SC, IBS and SR. The results are compared with the numerical evaluation of the analytical expressions for the growth and damping rates from IBS and SR. Since the two cases show very good agreement, it seems that in this case SC does not change the final steady state of the operational scenario despite the very small emittances and the large vertical tune spread. However, it should be emphasized that this simulation was done for the ideal CLIC DR lattice, i.e. without imperfections.

CONCLUSIONS AND FUTURE PLANS

A study of incoherent effects in the context of the CLIC DRs was performed. It was shown that the beam degradation due to resonance crossing induced by SC alone is relatively weak. This is due to the fast synchrotron motion, which results in resonance side-bands rather than periodic resonance crossing. Particle diffusion and thus emittance growth is however strongly enhanced when taking into account also IBS, which was modelled by a simplified kick applied once per turn. On the other hand, the strong damping from SR counteracts this diffusion and the final beam degradation with all three effects combined is on the order of a few percent for the case of the strong vertical sextupole resonance studied here. Furthermore, a first simulation of the operational scenario of the CLIC DR without imperfections did not reveal a strong impact of SC effects on the final equilibrium emittance. Future studies will address the impact of lattice imperfections including coupled resonances, which might degrade the machine performance due to emittance exchange.

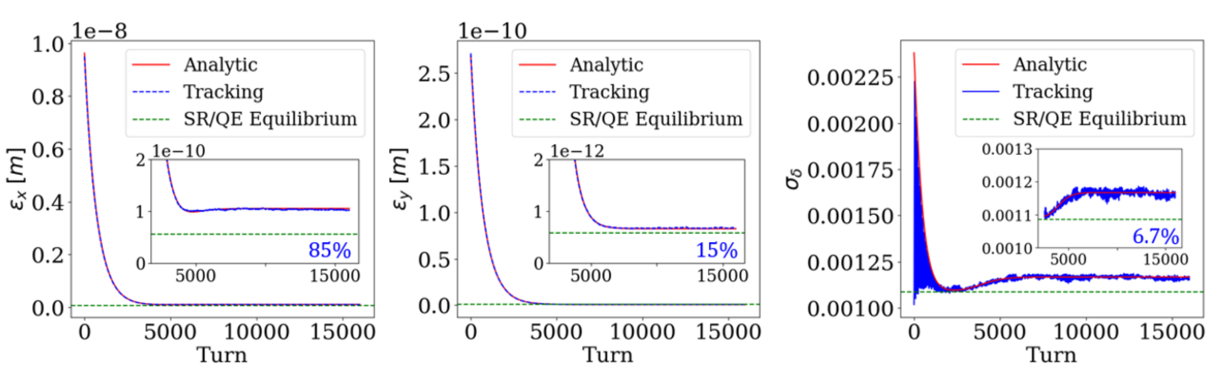

Figure 5: Evolution of the horizontal emittance (left), vertical emittance (center) and momentum spread (right) in the CLIC DR. SR and IBS are taken into account for the analytic calculations. For the tracking SC is also included. Zoomed plots embedded in the main plots with the relative difference to the SR/QE Equilibriums.

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