ION EFFECTS IN THE DAMPING RINGS OF ILC AND CLIC

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Abstract

We discuss ion trapping, rise time of fast beam-ion instability, and ion-induced incoherent tune shift for various incarnations of the ILC damping rings and for the CLIC damping ring, taking into account the different regions of each ring. Analytical calculations for ion trapping are compared with results from a new simulation code.

INTRODUCTION

Ion effects and ion-driven instabilities have affected operation at many electron storage rings. A particular example is the SLC damping ring, which, though storing only two bunches, was under exceptionally poor vacuum conditions, e.g., about 100 ntorr pressure, limited by violent trapped-ion instabilities that occurred during the shrinkage of the beam emittance due to radiation damping [1]. The SLC instabilities appeared to reach maximum strength when particular ion species, i.e., hydrogen or carbon monoxide, were close to becoming untrapped. This resulted in a blow up of the beam emittance, re-stabilizing the ion motion and undoing the previous damping, with, as a consequence, recurring relaxation oscillations. The ion instabilities at the SLC thereby increased the effective damping time and necessitated a doubling of the store duration, and a halving of the collider repetition rate for a period of weeks.

At conventional storage rings, operating in steady-state conditions, ion instabilities are often cured by filling the ring only partially, leaving a large ion-clearing gap of 1 or 2 μs in length. However, as the beam intensity is increased and the emittances are reduced, the effects of ions created during the passage of a single bunch train become important. Among these the fast-beam ion instability [2] and the incoherent tune spread induced by the ions appear the most important. The fast beam-ion instability has by now been observed in several storage rings (for a summary see [3]). In 2004, a vertical coupled-bunch instability at the KEK/ATF damping ring observed after about 10 bunches in a train of 20 with 6×10^9 electrons per bunch at 5 ntorr pressure, and possibly correlated with the vacuum pressure, has also been attributed to ions [4].

ILC AND CLIC PARAMETERS

Parameters for various proposed ILC electron damping rings [5] and for the CLIC damping ring [6] are listed in Table 1. A 6-km long ring is the present ILC baseline, but other choices are still possible. As is evident from the table, the parameters for ILC and CLIC differ substantially. The bunch charge in CLIC is about 10 times lower, and the number of bunches per train almost 30 times less. On the other hand the bunch spacing in CLIC is also 10 times smaller. As a net result, the average current of a CLIC bunch train is about the same as for the 6-km ILC ring, but the CLIC train length of 18 m is several orders of magnitude shorter than the 6 km of the ILC train, thereby reducing the ion density at the end of a train by at least the same factor of 30. In addition, the four trains circulating in the CLIC damping ring occupy only 20% of the ring circumference (10% with two trains). The large gaps ensure a highly effective ion clearing between trains for CLIC.

ANALYTICAL ESTIMATES

In order to assess the importance of ion effects, we employ analytical formulae. Singly-charged ions are trapped within a bunch train if their mass, in units of proton masses, exceeds a critical value [7]

$$A_{\rm crit} = \frac{N_b L_{\rm sep} r_p}{2\sigma_y(\sigma_x+\sigma_y)} \ , \tag{1}$$

where N_b denotes the bunch population, r_p the classical proton radius, $L_{\rm sep}$ the bunch spacing, and $\sigma_{x,y}$ the horizontal or vertical rms beam size. The ion-induced incoherent tune shift at the end of the train is

$$\Delta Q_{\rm ion} \approx \frac{N_b n_b r_e C}{\pi\sqrt{(\gamma\epsilon_x)(\gamma\epsilon_y)}} \left(\frac{\sigma_{\rm ion} p}{k_B T}\right) , \tag{2}$$

where n_b designates the number of bunches per train, C the ring circumference, r_e the classical electron radius, $\epsilon_{x,y}$ the rms geometric emittances, $\sigma_{\rm ion}$ the ionization cross section, p the vacuum pressure, k_B Boltzmann's constant, and T the temperature in Kelvin. In (2), the ion distribution after filamentation has been approximated by a Gaussian with transverse rms sizes equal to the rms beam sizes divided by $\sqrt{2}$. However, the real ion distribution is not Gaussian, but rather resembles a "Christmas tree", described by a K_0 Bessel function [8]. The maximum tune shift at the center of the bunch will therefore be larger than our estimate. Under the same approximation, the central ion density at the end of the bunch train is $\rho_{\rm ion} \approx (N_b n_b \sigma_{\rm ion} p)/(\pi\sigma_x\sigma_y k_B T)$.

Lastly, the exponential vertical instability rise time of the fast beam-ion instability is estimated as [9]

$$\tau_{\rm FBII} \approx \frac{\gamma\sigma_y\sigma_x}{N_b n_b c r_e \beta_y \sigma_{\rm ion}} \left(\frac{k_B T}{p}\right) \sqrt{\frac{8}{\pi}} \left(\frac{\sigma_{\rm f_i}}{f_i}\right) \ , \tag{3}$$

where the spread of the vertical ion oscillation frequency f_i as a function of longitudinal position, $\sigma_{\rm f_i}$, has been taken

Table 1: Parameters of the CLIC damping ring and various incarnations of ILC damping rings, distinguishing arcs, wigglers, and straight sections ('str.'). For the TESLA damping ring, we assume that emittance-coupling bumps are present in the long straight sections.

ring	ILC OTW			ILC OCS			ILC TESLA			CLIC	
	arc	wiggler	str.	arc	wiggler	str.	arc	wiggler	str.	arc	wiggler
circumference [km]	3.2			6.1			17			0.365	
length [km]	1.74	0.24	1.24	3	0.12	3	2.0	0.54	14.5	173	192
energy [GeV]	5			5			5			2.42	
no of bunches / train	2559			2820			2820			110	
bunch population	2.2×10^{10}			2×10^{10}			2×10^{10}			0.256×10^{10}	
bunch separation [m]	1.259			1.844			5.994			0.16	
horiz. emit. $\gamma\epsilon_x$ [μm]	4			5.5			5	5	2.5	0.55	
vert. emit. $\gamma\epsilon_y$ [μm]	0.02			0.02			0.014	0.014	2.5	0.0033	
av. β_x [m]	12	4.51	85.9	26	15.7	29.3	11.9	10.2	139	0.85	3.7
av. β_y [m]	24.8	4.94	90.9	32.5	9.2	39	24.8	13.5	142	2.22	3.9
av. σ_x [mm]	0.374	0.043	0.187	0.618	0.094	0.128	0.357	0.072	0.19	0.016	0.021
av. σ_y [mm]	0.007	0.003	0.014	0.008	0.004	0.009	0.06	0.004	0.19	0.0012	0.0016

into account, as well as the variation of the vertical ion oscillation frequency with horizontal position and the nonlinear component of the beam-ion force.

For all four rings, we assume a total pressure of 1 nTorr (1.3×10^{-7} Pa), as specified in Ref. [10]. This pressure is roughly consistent with the best values achieved at the KEK/ATF and with typical pressures at the KEKB HER. Both growth rate and tune shift linearly scale with the pressure. We also assume that 20% of this vacuum pressure is due to carbon monoxide (CO), the rest being dominated by hydrogen. The pressure is taken to be the same in the arcs, wigglers and straight sections of the damping rings, respectively. Some previous studies have considered a vacuum pressure in the straight sections much better than that in the arcs [11]. However, at several operating storage rings, such as DAFNE, the pressure is observed to be high in the straights and lowest in the well-conditioned arcs [12]. Assuming a uniform pressure is a compromise.

The resulting estimates are compiled in Table 2, invoking an ionization cross section for CO molecules of 2 Mbarn, and a 30% relative ion-frequency spread $\sigma_{\mathrm{f_i}}/f_i$. Also, when estimating the instability rise time and ion-induced tune shift, we have, for simplicity, assumed trapping of CO ions along the train for all regions of the rings. This assumption is slightly pessimistic, as in the short wiggler sections of the ILC 'OCS' and 'OTW' rings, as well as in the TESLA-ring arcs, for the fully damped equilibrium beam carbon-monoxide ions may not be trapped within the train. However, according to our analytical estimate, in all cases the carbon-monoxide ions will be trapped over most of the ring circumference, and the error we make by assuming trapping everywhere is less than 10%. On the other hand, the analytical estimates are also optimistic as they ignore any possible contributions from hydrogen ions. Especially in the long straight section of the ILC TESLA ring hydrogen ions are likely to be trapped.

At 0.2 ntorr CO pressure, the incoherent tune shift at the end of a train are found to be enormous for the three ILC rings, of order 0.4–0.8, to be compared with a more acceptable value of about 0.003 for CLIC. The exponential instability rise time is 10–50 μs for the ILC rings, corresponding to about one turn, whereas the 200 μs rise time estimated for CLIC, at the same gas pressure, translates into 200 turns. Therefore, a turn-to-turn multi-bunch feedback system seems to be indispensible for the ILC. This may prove a challenging device, since noise introduced by such feedback also is a concern. For CLIC a slow feedback with 100-turn response time would suffice.

How reliable are the above numbers? First, it is reassuring that an analytical estimate of the instability rise time for the present KEKB equal to 1400 μs [13], obtained from (3), is consistent with measurements [14]. Second, we have only considered the ions produced during the passage of a single train. To avoid ion accumulation between trains, the inter-train gap must be larger than $L_{\mathrm{g,cl}} \approx 10 \times c/(\pi f_i)$, with c the velocity of light. Values for the minimum clearing gap between trains, $L_{\mathrm{g,cl}}$, are also listed in Table 2. For the CLIC damping ring, clearing gaps of a few meters are sufficient, while for the ILC the gaps must cover several tens of meters in order to avoid ion accumulation between trains or turns, and a resulting further increase in tune shift.

SIMULATIONS

Complementary to the above analytical estimates, we have explored the ion trapping condition, the survival between trains, and the evolution of the central ion density in simulations using a newly developed computer code [15].

The simulations were performed for an arc section of the CLIC damping ring considering a partial pressure of 0.1 ntorr and 2 Mbarn ionization cross section.

Figure 1 shows sample trajectories in the $x - z$ plane for CO (left) and H ions (right). The hydrogen ions are overfocused between bunches of the train, and most of them are quickly lost to the wall, while the CO ions perform stable oscillations, which is consistent with (1). In Fig. 2 (left),

Table 2: Estimates for the incoherent tune shift and exponential fast beam-ion instability rise time for the three damping rings of Table 1. A partical CO pressure of 0.2 ntorr is assumed.

ring	ILC OTW			ILC OCS			ILC TESLA			CLIC	
	arc	wiggler	str.	arc	wiggler	str.	arc	wiggler	str.	arc	wiggler
critical mass	8	151	8	6	69	24	44	285	1	15	9
vert. ion freq. [MHz]	33.4	144	33.3	19.2	66.5	39.2	16.4	41.5	2.8	360	275
min. gap $L_{\mathrm{g,cl}}$ [m]	29	7	29	50	14	24	58	23	340	2.7	3.5
ion dens. ρ_{ion} [cm^{-3}]	0.86	16.9	0.90	0.46	5.7	2.0	1.1	7.3	0.06	0.58	0.34
exponential rise time	22	6	6	32	9	6	18	5	102	189	185
at train end [μs]	[average rise time 10]			[average rise time 11]			[average rise time 47]			[av. rise t. 187]	
incoherent tune shift	0.011	0.0055	0.028	0.013	0.002	0.064	0.0154	0.0145	0.019	0.001	0.001
at train end ΔQ_y	[total $\Delta Q = 0.44$]			[total $\Delta Q = 0.79$]			[total $\Delta Q = 0.49$]			[total 0.0026]	

we display the central CO-ion density evolution. The final density value at the end of the train is about 2.5 times higher than predicted by our analytical formula, which we attribute to the non-Gaussian shape of the real ion distribution. Some of the hydrogen ions re-stabilize at large amplitudes, under the influence of the nonlinear beam field, and they are not lost to the chamber wall during the train passage, as indicated in Fig. 2 (right).

The simulation confirms that in CLIC only a small fraction of CO ions survive from train to train for inter-train gaps larger than 3 m, consistent with our estimate. For the actual average inter-train gap of at least 73 m in CLIC, i.e., more than 20 times the minimum gap needed for ion clearing, the residual ion population from the previous train is negligible.

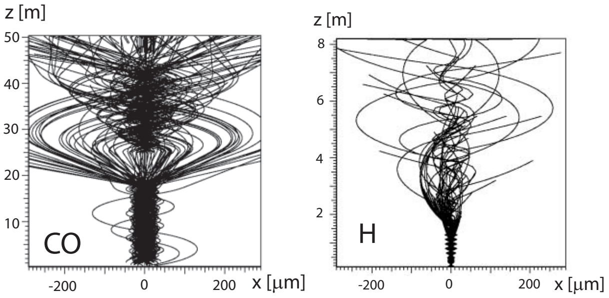

Figure 1: Simulated vertical trajectories for CO ions during the passage of 17.6-m long CLIC bunch trains separated by 7.5 m (left) and for H ions and half of the first train (right).

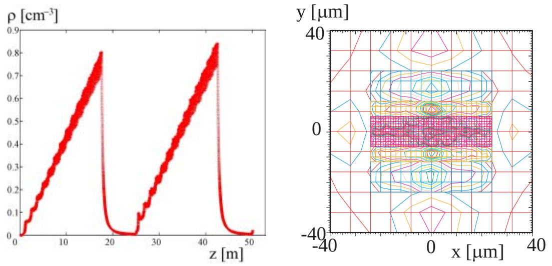

Figure 2: Simulated evolution of central ion density along a CLIC bunch train (left); transverse H ion distribution during single-train passage (right).

CONCLUSIONS

Single-pass ion effects are a potentially serious issue for the ILC damping rings. For realistic pressure values of a fraction of a ntorr, the ion-induced tune shift approaches integer values, and the exponential fast beam-ion instability rise time is about 1 turn. For CLIC, ion effects appear more benign, with a tune shift of a few 10^{-3} and a rise time of a few hundred turns. A possible solution for ILC is to split the beam into about 100 trains separated by large gaps of 20–100 m in length each. Simulations corroborate the analytical estimates of ion density and trapping. They also suggest that a fraction of the ions which are overfocused during a bunch-train passage may not be lost to the chamber wall but instead form an “ion cloud” around the beam. The latter could still contribute to ion-driven instabilities.

ACKNOWLEDGEMENTS

We thank S. Guiducci, M. Korostelev, T. Raubenheimer, L. Wang, and A. Wolski for helpful discussions. This work is supported by the Commission of the European Communities under the 6th Framework Programme “Structuring the European Research Area”, contract RIDS-011899.

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