FAST ION INSTABILITY IN THE CLIC TRANSFER LINE AND MAIN LINAC*

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Abstract

The Fast Ion Instability is believed to be a serious danger for bunch trains propagating in the CLIC electron transfer line and main linac, since it may strongly affect the bunches in the tail of the train if the vacuum pressure is not below a certain threshold. We have developed the FASTION code, which can track electrons through a FODO cell line and takes into account their interactions with the produced (and possibly trapped) ions. We describe how this tool can be used for setting tolerances on the vacuum pressure and for giving specifications for the design of a feedback system.

INTRODUCTION

The residual gases (H_2, H_2O, CO, N_2, etc.) present in the vacuum chamber of an accelerator are generally responsible for the formation of ion/electron clouds (through beam induced ionization), which can have destabilizing effects on the beam. The electrons created by residual gas ionization are very likely to be only the initial seed for the formation of electron clouds in hadron/positron machines, because their accumulation is actually dominated by the secondary emission process and not by trapping. The light electrons would in fact be lost between two subsequent bunch passages with the usual bunch spacings, and they would not accumulate if they did not multiply due to the fact that they can produce more electrons when impinging against the inner pipe wall with relatively high energies. On the contrary, the ions created from residual gas ionization in an electron machine may be either lost between two bunches or not enough accelerated during one bunch passage as to reach the pipe wall before the next bunch comes. In the latter case the machine is operating in trapping regime, and the number of ions around the beam increases linearly with the number of bunches passing through a certain accelerator section. Even in absence of an amplifying effect, this mechanism can result in a two-stream instability [1]. In circular machines, the ion instability can be of conventional type, when the number of ions rapidly increases over all the accelerator because there is simply no long enough gap between two bunches such as to clear the ions from the chamber and reset the accumulation process. Every electron ring must be conceived as not to operate in this regime. However, even when the beam structure is such that there exist more trains of bunches circulating in the machine, separated by long enough gaps as to clear the ion cloud in between trains, a strong instability could still develop over a train length, which is called fast ion instability. In the fast ion instability, individual ions last only for a single passage of the electron beam and are not trapped for multiple turns. This type of instability can equally occur in a linear machine, because it does not depend on the periodicity of the structure but only on the propagation of a train of bunches able to trap ions down a sufficiently long machine. Obviously, this is a head-tail effect, which affects only the bunches in the last part of a train, whereas the bunches in the head are totally unaffected.

CLIC is an electron-positron linear collider designed to have main linacs of about 20 km, and equally long beam transfer lines to transport both electrons and positrons from their sources to the interaction point [2]. Trains of 311 very short bunches spaced by less than 1 ns will have to propagate through these structures to reach the interaction point with the required features to achieve the nominal luminosity. Therefore, there are the basic conditions for a potential fast ion instability both in the long transfer line and in the main linac (for electrons), if trapping occurs and if the residual gas pressure is high enough as to produce enough ions to excite an unstable motion. The goal of this paper is to assess the pressure thresholds both in the transfer line and in the main linac, above which the fast ion instability sets in. For this purpose we have developed the FASTION code, which is described in the Section II and subsequently applied to CLIC in Section III. Conclusions as well as a view on the future work are given in Section IV.

THE FASTION CODE

The FASTION code has been developed at CERN to describe in detail ion generation and interaction with an electron bunch train along a linear machine. In the model, both ions and electrons are treated as macroparticles. The basic principle of the code is illustrated in Fig. 1. The electron bunches are made to interact with the ions, as they are generated bunch by bunch, twice per FODO cell (at the points of maximum and minimum beta functions). They are transported down the line using linear transfer matrices between the selected interaction points. In the latest version of the code, the lattice can be passed to the code through an external Twiss file (compatible with either the PLACET [3] or the MAD-X structure) and the interaction points are then defined by the locations specified in this file. Acceleration can be included by means of the variation of the relativistic gamma along the line. In ideal conditions, this results in a beam size change (usually shrinking) compatible with the designed beta function variation along the line and conservation of the normalized transverse emittances. Ions of dif-

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ferent species (desired number specified in the input file) are generated proportionally to their partial pressures and ionization cross sections. They are subsequently tracked along the train passage according to their masses.

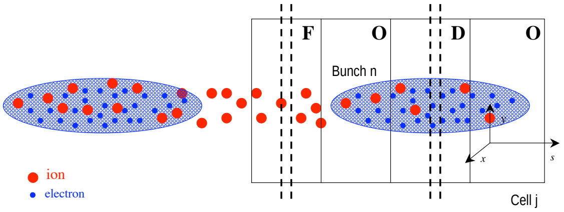

Figure 1: Principle of the FASTION code.

The main default outputs of the FASTION code include:

- Snap shots of the bunch by bunch centroids and emittances in the two transverse planes at all the interaction points chosen in the line. An unstable motion will be revealed by an exponential correlated growth of the centroid motion in the bunches located at the tail of the train. Emittance growth can accompany this type of coherent instability.
- Sample trajectories of ions from their generation to the end of the train passage to be able to check whether they are trapped. In the case of changing energy along the line, these sample trajectories are saved up to 10 times along the full line in order to check on the trapping condition at several locations (as the beam size may change a lot due to acceleration).
- Ion distributions in x and y after each bunch passage at the beginning of the line (also up to 10 points along the line in case of acceleration).

APPLICATION TO CLIC

The Long Transfer Line

The parameters of the CLIC long transfer line are summarized in Table 1.

Table 1: Parameters used in our study: the transfer line

Energy	p_0 (GeV)	9
Norm. transv. emitt.	$\epsilon_{x,y}$ (nm)	680, 10
Bunch length	σ_z (ps)	0.15
Bunch spacing	ΔT_b (ns)	0.667
Bunch population	N	4×10^9
Number of FODOs	N_{FODO}	500
Number of bunches	N_b	300
FODO length	L_{FODO} (m)	40
Phase advance	ϕ_{FODO} (^{o})	70
Gas pressure	$P_{H_2O,CO}$ (nTorr)	1, 1
Ioniz. cross sect.	$\sigma_{H_2O,CO}$ (MBarn)	2, 2

Analytical evaluations of the ion effect are reported in the companion paper [4]. Ions are trapped in the long transfer line, as Figs. 2 depict. We see horizontal and vertical trajectories of two sample ions of different species, which are essentially sinusoidal oscillations with frequencies depending on the mass of the ions and on the plane we are observing (the beam has almost two orders of magnitude different emittances in the two planes).

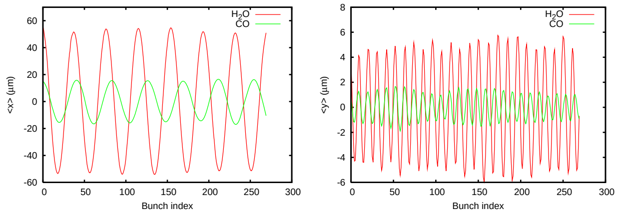

Figure 2: Horizontal and vertical trajectories of two sample ions (generated at the first bunch passage) as the 300 bunches of the electron beam go through the chanber.

Trapping is a condition which may easily translate into beam instability if the residual gas pressure in the vacuum chamber is too high. In fact, the simulation shows that partial pressures of 1 nTorr for both H_2O and CO (or N_2, since they have the same mass number) are sufficient to drive the electron beam unstable in the vertical plane. The instability manifests itself with both coherently growing vertical centroid motion and emittance growth in the second part of the bunch train. Figures 3 display several snapshots along the line of both vertical centroid and emittance bunch by bunch. The centroid motion exhbits clear frequencies on which it is excited (depending on the ion oscillation frequencies), whereas the emittance growth amounts to about 50% for bunches in the second half of the train and has some peaks of 100% increase for a few bunches in the very tail of the train.

The main result of this study is that in the long transfer line a vacuum better than 1 nTorr is required against fast ion instability. This poses a serious constraint on the design of the vacuum system.

The Main Linac

The parameters of the CLIC main linac are summarized here below in Table 2.

Table 2: Parameters used in our study: the main linac

Energy	p_0 (GeV)	9 to 1500
Norm. transv. emitt.	$\epsilon_{x,y}$ (nm)	680, 10
Bunch length	σ_z (ps)	0.15
Bunch spacing	ΔT_b (ns)	0.667
Bunch population	N	4×10^9
Number of bunches	N_b	311
Gas pressure	$P_{H_2O,CO}$ (nTorr)	10, 10
Ioniz. cross sect.	$\sigma_{H_2O,CO}$ (MBarn)	2, 2
Length	L (km)	20.5

The lattice with the increasing beta functions is described through a PLACET output file. which is used as an auxiliary FASTION input file (from which also the energy information can be taken). In this case the situation is more complex than in the transfer line, because trapping,

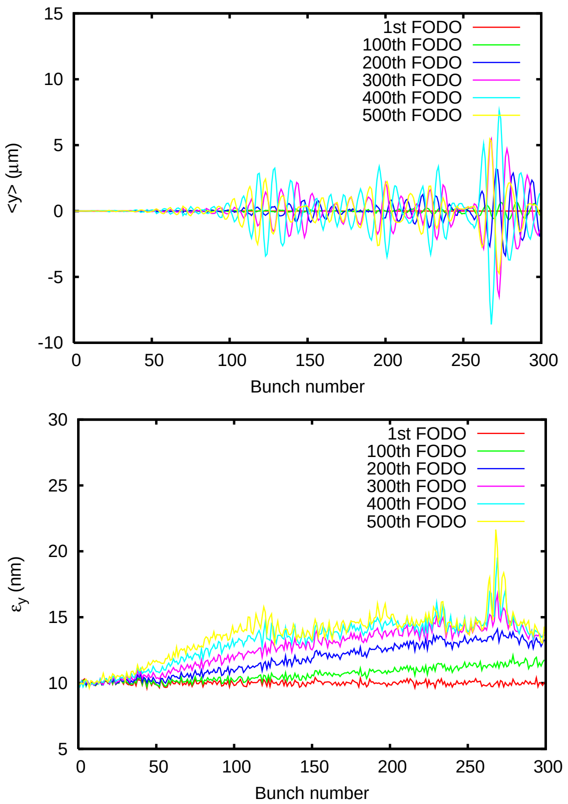

Figure 3: Vertical centroids and emittances of the 300 electron bunches at six locations along the transfer line.

which certainly occurs at the beginning of the main linac, can be lost along the way, as the beam size shrinks. This has a stabilizing effect, because it limits the ion accumulation around the beam, and adds up to the other stabilizing mechanism coming from the beam becoming stiffer.

The fact that trapping is lost along the line can be seen looking at the distribution of ions (for example, in the vertical direction) after the first and last bunch of the train at the end of the main linac (plotted in Figs. 4). While at the beginning of the linac the produced ions remain relatively close to the beam up to the passage of the last bunch, at the end of the line they tend to spread much farther off the beam center. Therefore, the effect of their interaction with the beam (which at the same time has become transversely smaller and more energetic) becomes very weak.

It should be not be surprising that the electron beam in the main linac is much more stable against fast ion mechanisms than in the transfer line, and the vacuum constraint in principle much more relaxed. First signs of fast ion instability appear for a residual gas pressure of about 50 nTorr and the instability becomes strong at 100 nTorr (see Fig. 5), hinting that even a vacuum of few 10^{-8} Torr could be tolerated. Attention has to be paid to the fact that, since one of the reasons why the beam gets more stable is the loss of trapping, reducing the bunch charge can have the effect of making the beam more unstable, since it would restore trapping where it would have been lost with a higher charge. For example, simulations were run at 50 nTorr and it was observed that the beam would become significantly unstable for numbers of electrons per bunch between 10^{8} and 10^{9}, but it would be quickly stabilized outside of this range.

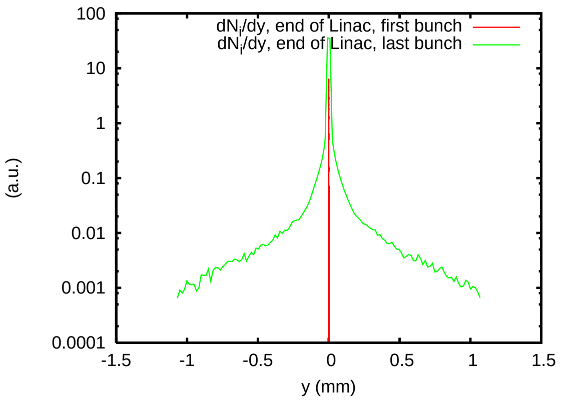

Figure 4: Ion distributions in y after the first and last bunch of a train, taken at the end of the linac.

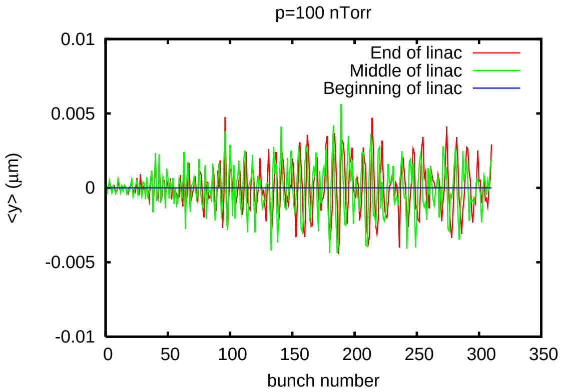

Figure 5: Snap shots of the bunch by bunch vertical centroid distributions along the main linac.

CONCLUSIONS

Fast ion instability simulations were run with a newly developed code (FASTION) both for the CLIC long transfer line and for the main linac. The main purpose was to pin down vacuum constraints for both lines. The outcome of the study is that in the tranfer line a vacuum in the order of 10^{-10} Torr is required to ensure beam stability, whereas the tolerance seems to be relaxed in the main linac due to the higher energy and to the loss of trapping ($p < 10^{-8}$) Torr). However, one has to bear in mind that in this simulation we have ignored both the effect of rf fields on the ions and the effect of field ionization, which can be specially important in the second part of the linac.

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