UPDATE ON FAST ION INSTABILITY SIMULATIONS FOR THE CLIC MAIN LINAC

G. Rumolo, D. Schulte
CERN, Geneva

Abstract

The specification for vacuum pressure in the CLIC electron Main Linac critically depends on the fast ion instability. In fact, the maximum tolerable pressure value in the pipe of the Main Linac is dictated by the threshold above which the fast ion instability sets in over a CLIC bunch train. Previous calculation based on ion generation from scattering ionization of the residual gas alone showed that, due to the loss of the trapping along the linac caused by the beam size shrinking from acceleration, a pressure as high as 10 nTorr could be accepted, higher than the tolerable value in the long transfer line.
However, since the accelerated beam becomes transversely very small, its electric field can reach values above the field ionization threshold. When this happens, the whole space region with a sufficiently high electric field gets instantly fully ionized by the first bunch and the effect on the bunch train could be severe. We have modeled field ionization in our simulation code FASTION and re-evaluated the onset of fast ion instability in the Main Linac.

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 static ion/electron clouds around propagating beams. There are two main possible mechanisms through which a beam can ionize the rest gas:

- Scattering ionization. This event has typically cross sections of few unites of MBarn, and can therefore only ionize a small fraction of the full volume swept by the passing beam.
- Field ionization [1]. It only occurs when the beam electric field is sufficiently high (above a certain threshold) and causes full ionization of the volume swept by the beam.

The ions created by residual gas ionization in an electron machine may be either lost or trapped between subsequent bunches. In the latter case, the number of ions around the beam increases linearly with the number of bunches passing through a certain accelerator section and the ion cloud can become so dense as to excite a two-stream instability [2]. In a linear machine, this instability, known as fast ion instability, develops over the length of a bunch train and affects only the tail part of the train.
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 [3]. Trains of 311 very short bunches spaced by 0.5 ns will have to propagate through these structures to reach the interaction point with the required features to achieve the nominal luminosity. Therefore, the basic conditions for a possible fast ion instability could be met both in the long transfer line and in the main linac (for electrons). A full simulation study was presented in [4] under the assumption that the ions would only be produced from scattering ionization. This paper assessed the pressure thresholds both in the transfer line and in the main linac, above which the fast ion instability sets in. The goal of the present paper is to carry on the study for the main linac initiated in [4], taking into account that the CLIC bunches can become so small during acceleration as to create electric fields above the threshold of field ionization. For this purpose the FASTION code has been extended with the option of generating ions via field ionization when the electric field of the beam is found to exceed a threshold value. The model and the implementation in FASTION of field ionization are described in the Section II, the application to the CLIC main linac is given in Section III, and the conclusions are drawn in Section IV.

FIELD IONIZATION

Model

The basic assumption to include field ionization in the analysis of fast ion instabilities in the CLIC main linac can be thus summarized. When the peak electric field of an electron bunch exceeds a given threshold value (typically in the range 10–100 GV/m), the ionization probability becomes 1 and the beam is able to ionize all the molecules of residual gas that it sweeps along in its motion. Therefore, when a train of bunches propagates along a beam line, the first bunch ionizes the whole of the residual gas molecules present in the volume through which it goes, but all the subsequent bunches will only be able to ionize the molecules that could diffuse into that volume during the interbunch time. To quantify the possible impact of field ionization on the development of a fast ion instability, we can evaluate the ion production per unit length of the accelerator for simple scattering ionization and compare it to the rates (first bunch and other bunches) with field ionization. The ions per unit length produced via scattering by a bunch of N_b electrons traveling at speed of light through a mixture of gases having pressures P_n are given by

$$\frac{dN_{ion}}{ds} = kN_b \sum_n \sigma_n^{ion} P_n \quad , \qquad (1)$$

where σ_n^{ion} are the ionization cross sections of the different components of the residual gas, and k is a constant (3.22×10^{-9} if P and σ^{ion} are expressed in nTorr and MBarn, respectively). For instance, a bunch of $N_b = 10^9$ electrons will ionize 3.22 molecules per unit length of a gas at 1 nTorr and having a ionization cross section of 1 MBarn. The ions per unit length produced via field ionization by a bunch of N_b electrons traveling at speed of light through a mixture of gases having pressures P_n are given by

$$\frac{dN_{ion}}{ds} = k \cdot 4\pi\sigma_x\sigma_y \sum_n P_n \quad , \qquad (2)$$

where $\sigma_{x,y}$ are the transverse rms sizes of the bunch. Hence, a round bunch with 1μm rms radius (consistent with a peak electric field of some tens of GV/m with the above charge and a full length of about 200μm) will ionize about 400 molecules of 1 nTorr gas per unit length, i.e. around 100 times more than those that would be ionized via scattering. The second bunch (and all the subsequent ones) can only ionize the molecules of residual gas that have diffused into the volume swept by the beam:

$$\frac{dN_{ion}}{ds} = k_1(\sigma_x + \sigma_y) \cdot T_b \cdot \sum_n \frac{P_n}{\sqrt{A_n}} \quad , \qquad (3)$$

where T_b is the interbunch gap and A_n are the atomic mass numbers of the different components of the residual gas and k_1 is a constant (≈ 130 at room temperature if the pressures are in nTorr, the interbunch gap in nsec and the beam rms sizes in μm). Round bunches with 1μm rms radius in a train with 500 ps spacing will ionize about 30 molecules of 1 nTorr H_2O or 24 molecules of 1 nTorr CO per unit length.

It should be observed that, since field ionization only occurs for small beam sizes, its effect can become less evident than calculated above, because the number of produced ions decreases as the volume swept by the beam becomes smaller. For instance, if we had use transverse beam sizes of 0.1μm, the number of ions produced by the first bunch becomes comparable to that produced by simple scattering, and the subsequent bunches will produce even fewer ions.

Extension of the FASTION Code

The FASTION code was 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 macroparticles. The basic principle of the code was discussed in Ref. [4]. Several interaction points between electrons and ions are selected via a PLACET [5] or MAD-X produced Twiss file. As a train of electron bunches goes through an interaction point, ions (of different selectable species) are gradually produced and they interact electromagnetically with the electrons. Then the electrons are linearly tranported to the next interaction point, where the whole process of ion generation/interaction starts over again. Acceleration/deceleration can be included by means of the variation of the relativistic gamma along the line (also defined in the Twiss file).

Originally, the code was only intended to deal with ions produced through scattering ionization. However, the application of FASTION to the CLIC Main Linac made clear that field ionization had to be also taken into account, because the beam transverse size along the line (in the order of μm) can become small enough as to cause this phenomenon to set in (see next subsection).

FASTION has been therefore extended to include field ionization following the procedure outlined in the following. At each step of the Linac, FASTION scans the beam electric field $E_{x,y}(x, y)$ over the beam area and stops if it finds a value larger than a threshold value set from input. In this case the charge of macro-ions produced by the passing bunches is determined by a field ionization routine. The ions will still be generated in the area of the bunch cross section, but their charges are recalculated according to the field ionization mechanism, as was described above. The volume swept by the first bunch will be fully ionized and the molecules of residual gas that can diffuse into the ionized volume during an interbunch gap will be ionized when each of the following bunches of the train passes. In the case of field ionization, the charges of the macro-ions will be different over the ensemble. In particular, those produced by the first bunch will have a different charge than those generated by all subsequent bunches. Therefore, the distribution of ions on the mesh points will have to be carried out with a routine allowing for distribution of unidentical charges.

APPLICATION TO CLIC

The parameters of the CLIC Main Linac are summarized here below in Table 1.

Table 1: 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)	0.5
Bunch population	N	4×10^9
Number of bunches	N_b	311
Gas pressure	$P_{H_2O,CO}$ (nTorr)	30, 30
Ioniz. cross sect.	$\sigma_{H_2O,CO}$ (MBarn)	2, 2
Threshold E	E_{max} (GV/m)	5, 10, 100
Length	L (km)	20.5

Due to the possible onset of field ionization, the simulations for the Main Linac had to be repeated with the new version of FASTION to find the vacuum specification. A pressure scan from 10 to 50 nTorr was made for three different values for the threshold electric field (E_{max} =5, 10 and 100 GV/m). First of all, it could be seen that a threshold electric field of 100 GV/m translates in no field ionization all across the main linac. The two pictures on the upper row of Fig. 1 show that the number of ions generated for the first and the second bunch are basically the same and their values increase along the linac only because the integration step increases. When the threshold electric field is set to 10 GV/m, the mid plots in Fig. 1 show that only the second half of the main linac is affected by field ionization. The ionization rate of the first bunch grows by a factor 30, whereas for successive bunches it only increases by a factor 2–3. The case $E_{max} = 5$ GV/m is much more critical, as can be seen from the bottom pictures of Fig. 1. Almost all the linac is affected now by field ionization and the ionization rates are therefore 3–30 times higher than those of scattering ionization all along the linac.

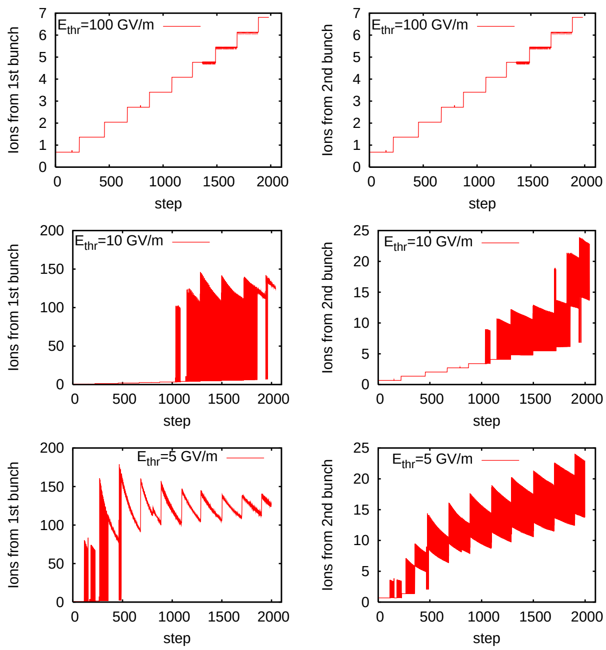

Figure 1: Ionization rates for first (left column) and second bunch (right column) with the threshold eletric field for field ionization set to 100 (top row), 10 (middle row) and 5 GV/m (bottom row).

The next point is to assess how field ionization will affect the electron beam stability under the effect of the ions. Figs. 2 confirm the intuitive guess explained above. We show the results of the simulation of a beam through the main linac with pressures of 30 nTorr for H_2O and CO.

While the difference in beam stability between the two cases $E_{max} = 100$ GV/m and $E_{max} = 10$ GV/m is hardly perceptible both in terms of vertical coherent centroid motion of the bunches in the train and their emittance growth, the case $E_{max} = 5$ GV/m is significantly more unstable with a strong coherent motion affecting almost all the train, and large emittance growth. Intuitively, $E_{max} = 10$ GV/m could be expected to marginally affect much the beam stability. In fact, field ionization appears only all through the second half of the linac, where electrons have higher energy and ions are not trapped. The case $E_{max} = 5$ GV/m, where field ionization appears at the beginning of the linac could be expected to lower the instability threshold by a factor as high as 2–3 due to the enhanced number of produced ions all along the linac.

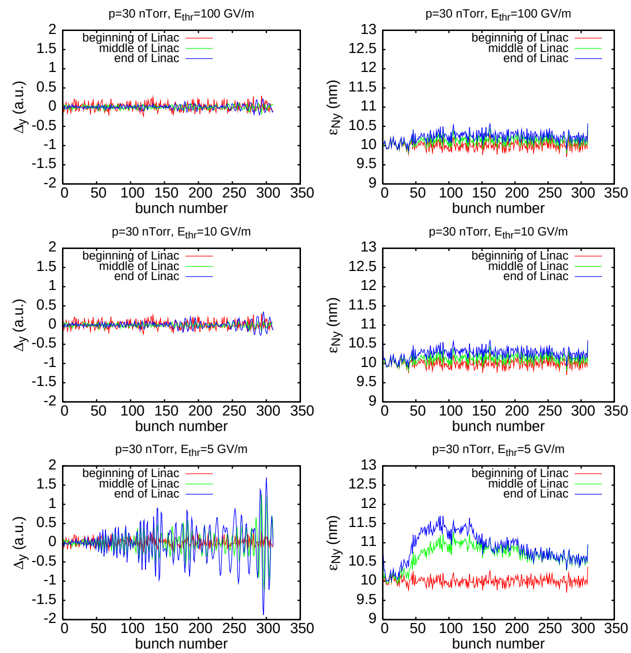

Figure 2: Bunch-by-bunch centroid vertical position (left column) and emittance (right column) at three different points along the linac (as labeled) with the threshold eletric field for field ionization set to 100 (top row), 10 (middle row) and 5 GV/m (bottom row).

CONCLUSIONS

The vacuum specifications of the CLIC Main Linac needed to be reviewed taking into account field ionization, which was implemented in the FASTION code. The new fast ion instability simulations have shown that the influence of field ionization depends on its threshold electric field value. If the threshold value lies between 10 and 100 GV/m, as should be for H_2, CO, N_2 and H_20, field ionization appears only in the second part of the linac and its destabilizing effect is marginal. A pressure of 10 nTorr would be acceptable in terms of beam stability. Only if the threshold value of the electric field were found to fall below 10 GV/m, field ionization would cover most (or all) of the main linac, causing the beam to become unstable at lower vacuum pressures.

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