VACUUM SPECIFICATIONS FOR THE CLIC MAIN LINAC

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Abstract

The maximum tolerable pressure in the vacuum of the CLIC electron Main Linac is determined by the threshold above which the fast ion instability sets in over a bunch train. With micro-metric beam sizes, the macroscopic electric field of the bunches reaches values above the field ionization threshold, thus producing more ions than the classical scattering ionization. In this paper we first discuss the extent of the transverse areas that gets fully ionized along the ML. Then, we show the results of the instability simulations made with the FASTION code using the new model, and consequently review the pressure requirement in the ML.

INTRODUCTION

The residual gases (H_2, H_2O, CO, N_2, etc.) present in the vacuum chamber of an accelerator are ionized by the beam and form ion/electron clouds. The rest gas can be ionized by a beam via scattering ionization, or field ionization. The latter phenomenon only occurs when the beam electric field is sufficiently high [1] and causes full ionization of a certain volume around the beam. In an electron machine the ions can be trapped between subsequent bunches and accumulate to a level capable to excite a two-stream instability [2]. In a linac, this instability, named fast ion instability, develops over the length of a bunch train and affects mostly the tail of the beam train.

CLIC is an electron-positron linear collider made of two main linacs of about 20 km, and of equally long beam transfer lines between the central production complex and the head of the linacs [3]. The main beam trains are made of 312 very short bunches of $N = 3.7\,10^9$ particles spaced by 0.5 ns . The basic conditions for the possible onset of the fast ion instability could be met at several stages for electron beams. A simulation study for the Main Linac was presented in [4] with ions produced only by scattering ionization. Subsequently, field ionization was recognized as a possible main actor in the ion production. A first model was put in place to check its effects on the previously determined threshold of instabilities [5]. This model assumed that, for electric fields above the field ionization threshold, only the volume swept by the beam was fully ionized. In this paper, we consider a more refined model in which the ionized volume is self-consistently calculated from the field map associated to the transverse shape of the beam bunches. The FASTION code has been extended to include this model. We then present the results of our numerical simulations for the CLIC electron main linac. Some conclusions are drawn in the last Section.

FIELD IONIZATION

Model

The probability p [1/s] for an atom or molecule of ionization potential ξ [eV] to be ionized in a electric field E [GV/m] is [1]

$$p(\xi, E) = \frac{1.52\;10^{15}\times 4^n \xi}{n\Gamma(2n)} \left(\frac{20.5\xi^{3/2}}{E}\right)^{2n-1} \exp\left(-\frac{6.83\xi^{3/2}}{E}\right) \qquad (1)$$

with $n = 3.69\xi^{-1/2}$ for a singly ionised event. With a nearly constant r.m.s. bunch length $\sigma_z = 44\ \mu$m , and considering a probability of ionization per bunch $p_b = (2\sigma_z/c) \times p(\xi, E) = 0.1$, we get the threshold electric fields $E_{\rm th}$ listed in Table 1 for different gas species. The transverse area inside which $E > E_{\rm th}$ is obtained by building the field map along the linac using the Bassetti-Erskine formula for a bunch ellipsoid $\sigma_x \times \sigma_y \times \sigma_z$ [6].

Table 1: Gas species, ionisation potential and threshold electric field for a probability of ionisation of $p_b = 10\%$ per CLIC main beam bunches.

Gas	ξ [eV]	$E_{\rm th}$ [GV/m]
C	11.26	15
H_2O	12.6	18.5
H,O	13.6	21.5
CO	14.0	22

Figure 1 shows the fully ionized area for electric field thresholds $E_{\rm th} = 18$ and 24 GV/m, respectively. The bands inside which the sizes oscillate are associated to the FODO optics. The main driving parameter is the horizontal beam size. Mean beam sizes are typically $\sigma_x = 2\,\mu$m and $\sigma_y = 0.4\,\mu$m. An inspection of Fig. 1 shows that except for the early part of the linac the ionized area is approximately constant and quite larger than the beam sizes. For $E_{th} = 18$ GV/m, $a_{\rm ion} = 6\,\mu$m and $b_{\rm ion} = 4\,\mu$m. With $p_b > 10\%$ inside these area, all atoms/molecules are ionized after the passage of ten bunches. All the 300 subsequent bunches ionize the molecules that diffuse back into this area during the interbunch time. Using the average thermal speed of the gas molecules we find that these freshly diffused molecules only fill a corona of about 1μm at the border of the fully ionized area and are produced at a rate:

$$\frac{dN_{ion}}{ds} = k_1(\sigma_x + \sigma_y) \cdot T_b \cdot \sum_n \frac{P_n}{\sqrt{A_n}} \ , \qquad (2)$$

where T_b [ns] is the interbunch gap, $\sigma_{x,y}$ [μm] the beam r.m.s transverse sizes, P_n [nTorr] the partial pressures of the different components of the residual gas, A_n their atomic mass numbers. The factor k_1 is ≈ 130 at room temperature. A simulation indicates that over the whole train, the 're-fill' process increases by a factor eleven the amount of ions which were produced during the passage of the first ten bunches.

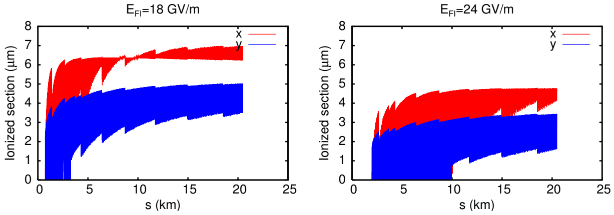

Figure 1: Horizontal (red) and vertical (blue) distances limiting the field ionization areas, as a function of the longitudinal coordinate s along the CLIC Main Linac. The ionized surfaces are approximately elliptical.

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 ion-electron control points are selected via a PLACET [7] or MAD-X Twiss file at different locations s_i along the linac. As a train of electron bunches goes through a control point, ions of different selectable species are gradually produced and they interact electromagnetically with the electrons. The process is iterated at successive control points with linear transportation of the electrons between them. Acceleration/deceleration can be included by means of the variable relativistic gamma along the line as defined in the Twiss file.

Originally, the code was only intended to deal with ions produced through scattering ionization. However, it became clear that the application of FASTION to the CLIC Main Linac shall include field ionization because of the micrometric beam sizes.

FASTION was first extended to include field ionization with the model explained in Ref. [5]. However, following the arguments discussed in the previous Section, this model is now improved. We first calculate the volume in which the beam electric field $E_{x,y}(x, y, s)$ becomes larger than a set threshold value , i.e. the volume inside which field ionization sets in. While tracking the electrons, the produced ions and the charge of the macro-ions produced by the passing bunches, which is determined by default through a scattering ionization routine, can now be computed through a field ionization generation routine after field ionization has set in. For example, the left plot in Fig. 2 displays the charge of the macroions produced by the first 10 bunches or the following ones in the CLIC Main Linac. The ions from scattering ionization are generated inside the beam area according to their cross section, while those from field ionization are generated in the previously determined area in which $E > E_{\rm th}$, see previous section. The charges are recalculated assuming that all the molecules in this space (first 10 bunches) or only the molecules in a 1 μm corona (from the 11-th bunch on) are ionized. Figure 2, right plot, shows the initial distributions of the produced ions with scattering and field ionization. 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.

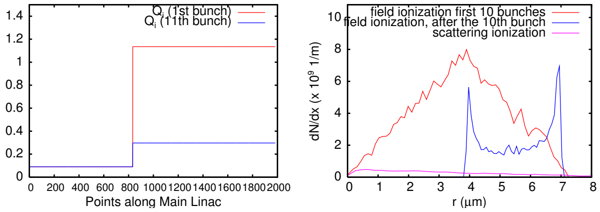

Figure 2: Left : Charges of the macro-ions produced by the first ten bunches and by the 11-th bunch as a function of the longitudinal position along the Main Linac (in non-uniform steps). Right : distributions of the ions at the time of their production, red : field ions, first 10 bunches; blue : additional field ions produced by each bunch from 11th to 312th; purple : scattering ions.

APPLICATION TO CLIC

The parameters of the CLIC Main Linac are summarized 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	$2\sigma_z$ (ps)	0.15
Bunch spacing	ΔT_b (ns)	0.5
Mean transv. size		
$\sigma_{\rm x,y}$ [μm], $s = 0$	12	1.5
$\sigma_{\rm x,y}$ [μm], $s = 20\,$km	2	0.3
Bunch population	N	4×10^9
Number of bunches	N_b	312
Gas pressure	P$_{H_2O,CO}$ (nTorr)	scanned
Ioniz. cross sect.	$\sigma_{H_2O,CO}$ (MBarn)	2, 2
Threshold E	E_{max} (GV/m)	18-30
Length	L (km)	20.5

Analyzing the expected electric field of the beam, as it propagates in the linac, we find out that field ionization is likely to appear from about $s = 4$ km and onwards along the linac. By scanning the electric field around the beam at several locations in the linac, we also find that field ionization, quickly after it appears, will cover an elliptical area with semi-axes $a = 6-7$ and $b = 3-4$ μm. Assuming then that the ionization mechanism switches at $s = 4$ km as described in the previous Section (see Fig. 2), a pressure scan from 0.5 to 20 nTorr (as partial pressures of a two component gas made of H$_2$O and CO) is made in order to determine the threshold for instability. Figure 3 show that for gas pressures of 10 to 20 nTorr the beam exhibits a strong coherent instability in both the horizontal and the vertical plane, along with some incoherent emittance growth in the vertical plane alone. Figure 4 shows that the instability actually appears near 5 nT already.

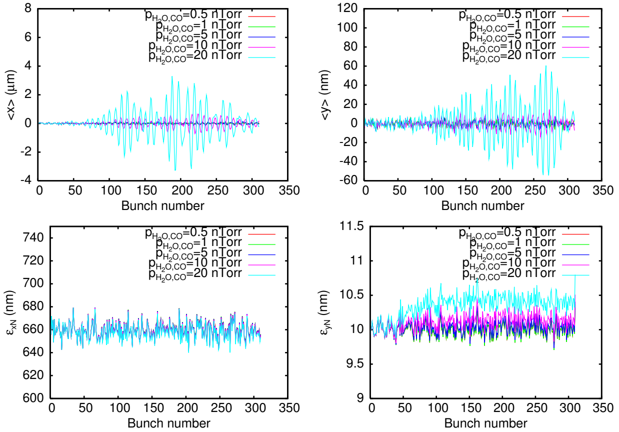

Figure 3: Snapshots of the bunch by bunch centroid ($\langle x\rangle$ and $\langle y\rangle$, top pictures) and of the bunch by bunch emittance (ϵ_x and ϵ_y, bottom pictures) at the end of the Main Linac

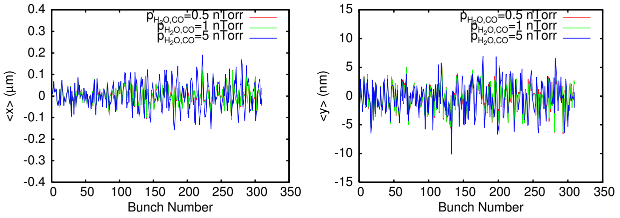

Figure 4: Snapshots of the bunch by bunch centroid ($\langle x\rangle$ and $\langle y\rangle$, top pictures) at the end of the Main Linac

To study the sensitivity of these results to some model assumptions, we have first tried to change the starting point of the onset of field ionization. In particular, we have fixed the gas pressure at 10 nTorr and then "switched on" field ionization starting at different longitudinal locations from the beginning of the linac up to its end. Figure 5 shows snapshots of the bunch by bunch horizontal centroid motion at the end of the linac for these different cases (as labeled). It is clear that the resulting instability is not much affected by the choice of the starting point for field ionization between $s_0 = 0$ and 4 km. Secondly, we have checked the sensitivity to the composition of the residual gas. We have changed the relative fractions of H_2O and CO, keeping the total pressure constant at 10 nTorr. As Fig. 6 depicts, when one of the two species becomes dominant on the other one, the beam tends to become more unstable. The case of equal partial pressures is the most stable, probably because the damping from the different oscillation frequencies is most efficient in this configuration.

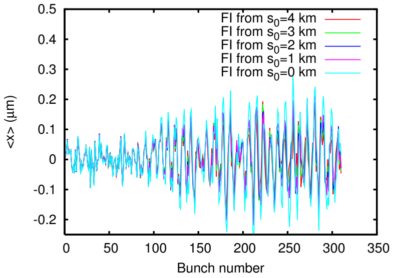

Figure 5: Snapshots of the horizontal bunch by bunch centroid, $\langle x\rangle$, for different starting points of field ionization along the linac.

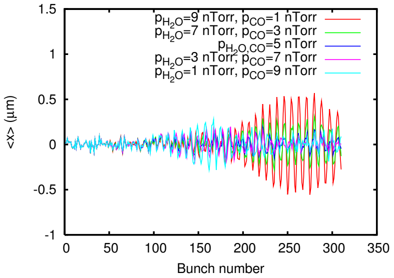

Figure 6: Snapshots of the horizontal bunch by bunch centroid, $\langle x\rangle$, for different compositions of the residual gas.

CONCLUSIONS

The vacuum specifications of the CLIC Main Linac is reviewed with taking into account a more realistis model for field ionization, which is now implemented in the FASTION code using the procedure outlined here above. The new fast ion instability simulations show that the influence of field ionization for a threshold electric field value between 18 and 30 GV/m, which covers the common gas species H_2, CO, N_2 and H_20, makes the beam unstable for partial pressures above 5 nTorr. Therefore, a pressure of 1 nTorr must be specified in order to ensure beam stability. In the future, we plan to simulate the fast ion instability for a more realistic composition of the residual gas (based on molecular dynamics simulations of the dynamic vacuum in the RF structures) and to scan the beam parameter space in order to determine how this strong requirement on the vacuum pressure in the Main Linac can be mitigated.

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