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COMBINED FIELD EMISSION AND MULTIPACTOR SIMULATION IN HIGH GRADIENT RF ACCELERATING STRUCTURES

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Abstract

Field emitted electrons have important consequences in the operation of high-gradient RF accelerating structures both by generating so-called dark currents and initiating RF breakdown. The latter is an important limitation of the performance in such devices. Another kind of vacuum discharge that primarily affects the operation of lower-field RF components, for example those used in space applications, is multipactor. Theoretical simulations using CST Particle Studio, show that field emitted electrons generated in the high field regions of high-gradient accelerating cavities migrate to low field regions under ponderomotive forces potentially triggering multipactor there. This phenomenon is an interplay between high field and low field processes which may have as a consequence that multipactor actually affects to the performance of high-gradient cavities because field emitted electrons might reduce the timescales for the onset of multipactor.

INTRODUCTION

A number of state of the art accelerators envisage the use of high-gradient (HG) linacs For example, in the 3 TeV final energy stage of the Compact Linear Collider (CLIC) [1] the accelerating gradient is 100 MV/m, resulting in peak surface fields in excess of 200 MV/m. Under such high surface electric fields, electrons are pulled out of the metal surface by means of quantum tunneling in a process known as Field Emission (FE). The electronic current is described by the Fowler-Nordheim law [2], which can be expressed with the simplified expression

$$J = a\beta^2 E^2 e^{\frac{-b}{\beta E}} \tag{1}$$

where a and b are constants that depend on the metal work function, E is the electric field and β is the field enhancement factor.

FE electrons are accelerated by the RF fields generating the so-called dark current (DC) [3]. Above a certain accelerating gradient [4], electrons can be captured in RF buckets and then be accelerated over larger distance in the structure. In the case of CLIC structures, the electrons can reach energies of the order of 10 MeV. These high energy electrons produce ionizing radiation when colliding with the material walls. As a consequence, the experimental facilities must be properly shielded for safe operation [5], even without beam.

Multipactor (MP) [6] is an RF discharge that can occur at lower field level applications, for example in satellites [7]. MP is a resonant process in which electrons are accelerated by RF fields and move in trajectories that collide with the metal surface. If these trajectories connect one or more points on the surface with a time between collisions a multiple of half an RF period a resonance occurs. If this resonance condition occurs together with the generation of secondary electrons, providing that the secondary electron yield (SEY) of the material is higher than unity for the primary electron energies (ranging between 100 eV and 1 keV), an electron avalanche known as multipactor discharge is produced.

Field emission occurs in the regions of the cavity with highest surface electric field while multipactor predominantly occurs in regions with relatively low electric fields such as the outer cavity wall. MP has been analysed using tracking simulations of HG linacs [8], showing possible coupling of FE electrons to side cavity multipacting. A recent work developed at MIT [9] showed that MP is present in a 17 GHz HG accelerating cavity, by means of a single-surface B field leaded MP. The resonances they found occur in the sidewall of the cell, where the longitudinal E field is minimum. With only 1% of the maximum field level electrons can still be accelerated up to 1 keV in a 0.1 mm trajectory, giving SEY bigger than unity and having multipactor resonance.

In the present work, a study of the MP discharge in the CLIC/CERN cavities is described, distinguishing between damped and undamped structures. In the first section, CST simulations are presented which track field emitted electrons and also include secondary electron emission (SEE) property in the material walls. The simulations show that FE electrons are pushed by ponderomotive forces to the outer cavity regions after which they enter MP resonant trajectories. A novel experiment to directly measure this effect using a modified TD24 CLIC cavity is proposed. This set-up could also be used for different important measurements related to MP and RF breakdown.

FIELD EMISSION AND MULTIPACTOR SIMULATIONS IN THE CLIC CAVITIES

The RF cavities used in this work are 12 GHz travelling wave CLIC prototype accelerating structures working in the $2\pi/3$ mode, their phase velocity is equal to the speed of light by design [10]. We focus in the transversal DC of a single cell, as the electron share from neighbour cells has not been seen to be relevant. Doing particle simulations of the FE

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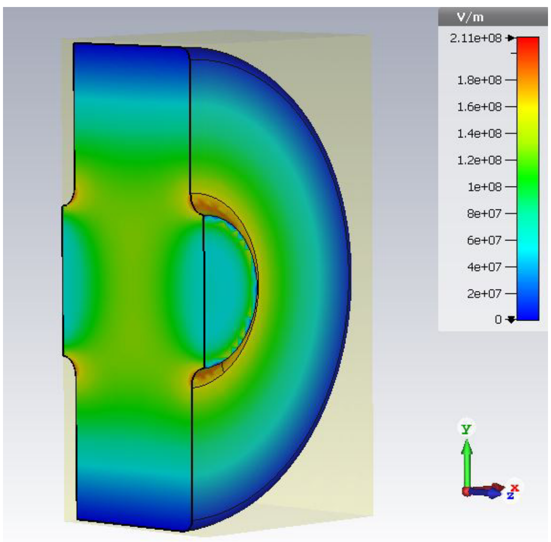
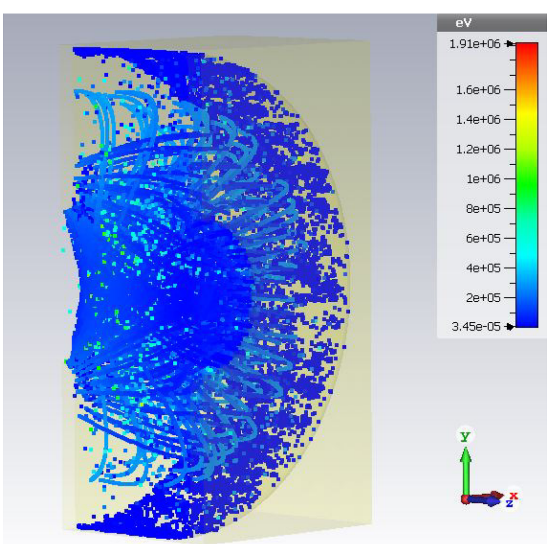
electrons with and without secondary emission, we are able to see the differences and guess if MP actually occurs.

There are mainly two different types of CLIC structures. First we have the T24 prototypes, which are made of cylindrical cells, and later the TD24 prototypes, which include damping waveguides for high order mode (HOM) absorption. Conditioning data of both types of structures has shown that damped structures perform about a 10% worse in gradient. TD24 structures need more power to achieve the same gradient and suffer more from pulsed heating. However, multipactor might be also a differential factor, for that reason a separate analysis is made for each type.

Transversal Dark Current in the T24 Prototype



(a)

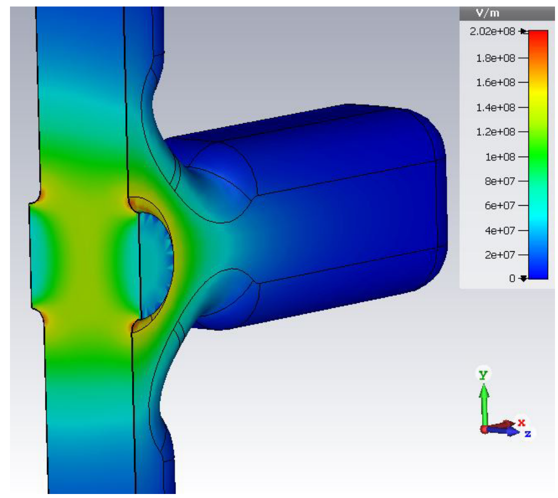


(b)

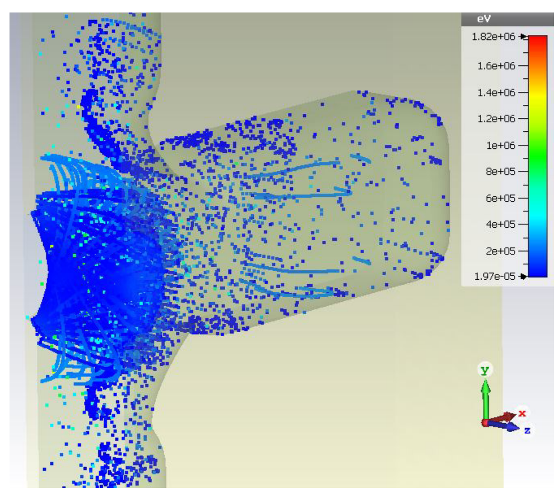
Figure 1: (a) Electric field magnitude in the T24 cell, at 100 MV/m gradient. (b) CST PIC simulation for the same cell.

The T24 is the basic CLIC prototype composed by cylindrical cells. The fields of the first cell are obtained using CST frequency domain eigenmode solver [11], applying periodic conditions with a phase advance of $2\pi/3$. The particle simulation is made with CST particle in cell (PIC) solver, choosing between Secondary Electron Emission (SEE) property and perfect absorbing walls. Figure 1a shows the electric field magnitude at 100 MV/m gradient, whereas the particle simulation with SEE is presented in Fig. 1b. One can see how the FE electrons emitted in the left iris travel to the cavity side causing a MP resonant discharge.

Transversal Dark Current in the TD24 Prototype



(a)



(b)

Figure 2: (a) Electric field magnitude in the TD24 cell, at 100 MV/m gradient. (b) CST PIC simulation.

As previously mentioned in the beginning of the section, there is a set of more advanced CLIC prototypes which include HOM damping waveguides. In our case we have analysed the TD24 structure. The cells have a cross-like shape as it can be seen in Fig. 2. Figure 2a shows the electric field magnitude, and Fig. 2b the particle distribution.

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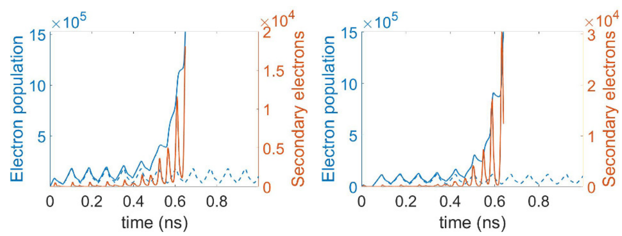
The simulations were made with the same settings as the T24 case. We have observed again that the FE electrons act as a seed for MP. It is also visible that the rounded surface of this design helps for multipactor mitigation in that area, which was mentioned previously in [8]. On the other hand, the damping waveguides have a broader area susceptible of discharge, presenting a full range of field levels where the evanescent wave diminishes towards the end of the waveguide. This behaviour makes these waveguides susceptible to sustain different MP modes.

Simulation Statistics

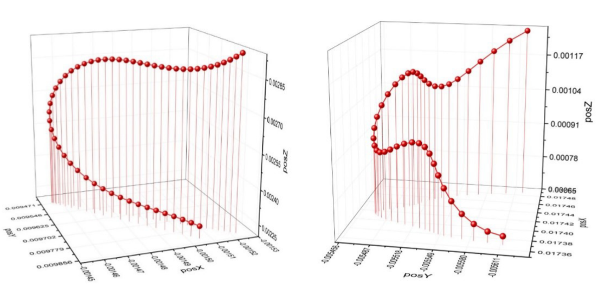
The simulation statistics of the T24 are presented in Fig. 3a, whilst Fig. 3b shows the case of the TD24. The electron population as function of time is the continuous blue line, showing the exponential growth characteristic of MP, and the FE contribution is the dashed blue line. Finally, the secondary electrons are accounted in the right axis with the brown line, showing clearly that SEE is the cause of the discharge.



(a) (b)

Figure 3: Simulation statistics for the T24 (a), and the TD24 (b): Electron population as a function of time considering SEE (continuous blue) and without SEE (dashed blue). The right axis accounts for the number of secondary electrons created during the discharge (brown).

Multipactor Trajectories



(a) (b)

Figure 4: (a) Fundamental mode of the single-surface two-points MP. (b) Resonance of a higher order MP mode.

To complement the previous results, we investigate the 3D shape of the multipactor trajectories for the T24 simulation case, which are obtained exporting the 3D position monitor from CST, and filtering two different particles. Figure 4 shows these trajectories, where one can imagine that the metal surface is vertically oriented in the right side of the pictures, showing how these electrons bounce and go back to the walls. In Fig. 4a the fundamental mode is presented, whereas Fig. 4b shows the case of a higher order MP resonance, where the RF field changes polarity several times before the electron manage to go back. Figures 3a and 3b show that the secondary electron spikes are separated by half RF period, which leads us to think that the fundamental MP mode is dominating the discharge.

FUTURE EXPERIMENT

At this moment no experimental measurements can support this theoretical work because we cannot perform transversal DC measurements in the CLIC cavities that are currently available. Figure 5 shows the mechanical design of a modified TD24 CLIC structure. In this design, the damping waveguides of the central cell have been open to air and new waveguide taper transitions have been brazed, ending in a standard vacuum flange. This design allows the connection of Faraday cups in the four central ports, in addition to the upstream and downstream ports that we have in all CLIC structures. Moreover, this device is also designed for hosting a microwave probe for MP and BD characterisation.

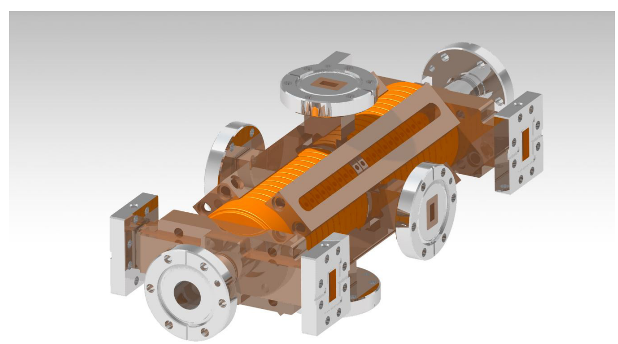


Figure 5: Mechanical design of the modified CLIC structure for multipactor and breakdown analysis.

CONCLUSIONS

In this work, a brief explanation of the field emission and multipactor processes is given in the context of the CLIC accelerating structures. Following that, CST simulations are shown to highlight the potential presence of multipactor discharge in the CLIC cavities working at 100 MV/m gradient. This might be currently affecting to the performance of the structures although we are not able to measure it directly. No difference has been found so far between the T24 and the TD24 prototypes, as the discharge equally appears in both cases. Finally, a novel cavity design is presented, where an open middle cell allows the transversal dark current measurements using standard Faraday cups, as well as breakdown characterisation by means of a microwave probe.

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