CONDITIONS FOR THE EXISTENCE OF 1- AND 2-POINT MULTIPACTOR IN SRF CAVITIES *

V. Shemelin†
Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE), Ithaca, NY 14853

Abstract

One- and 2-point multipactor (MP) in RF cavities are well-known phenomena. Here, we define conditions when this or the other type of discharge develops. An explicit description of these two types of the MP is presented, geometrical parameters, or figures of merit, responsible for initiation of the MP defined, and areas of their existence delineated. Small sizes of trajectories in the MP require a very precise calculation of fields for simulations. On the other hand, due to these small sizes, fields can be presented as the Taylor expansions and trajectories can be found solving ordinary differential equations of motion. Conditions of the phase stability define the boundaries of the MP zones.

INTRODUCTION

Electron multipactor is a well known phenomenon that can be met in many radio frequency (RF) devices. It is especially important to avoid this phenomenon in the superconducting (SC) RF cavities when their best advantage, low losses, is compromised by the avalanche increase of the electrons bombarding the cavity walls which can lead to the loss of superconductivity.

1-point and 2-point MP are distinguished in the RF devices. Here we will try to find physical explanation when this or another kind of the discharge exists in an RF device. Shortly, in the 2-point MP the electrons are oscillating in a cavity in such a manner that they impinge the surface every half-integral (1/2, 3/2, 5/2, . . .) number of the RF period. In the 1-point MP, the electrons hit the surface after an integer number of periods. This number of incomplete periods in the case of 2-point MP or complete periods in the case of 1-point MP is called the order of MP. Between collisions with walls the electrons are subjected to comparable forces from both electric and magnetic fields. After the collision, depending on the energy of the electron at this moment, some quantity of secondary electrons are released from the wall. If this quantity is more than one per an impacting electron in average and conditions for the newly appeared electrons are appropriate, they can be again accelerated in the inner space of the cavity and newly hit out secondary electrons. So, the number of electrons can increase exponentially and lead to a significant loss of the energy of the cavity. The multipacting electrons can increase the temperature of the wall that can be registered by the thermometers installed on the outer surface of the cavity [1].

* Supported by NSF award DMR-0807731
† vs65@cornell.edu

Simulations can reveal the necessary conditions for the MP. But the kind of the MP is defined *a posteriori*, as a result of the simulation. Understanding conditions of existence of this or another kind of MP can give a clue to prevent it.

The commonly used superconducting cavity shape is a result of evolution from a pillbox RF cavity with the beam pipes added and rounded wall corners – to decrease the peak electric field – to a shape consisting of elliptic arcs to prevent multipacting [2]. However, even with the rounded shape of the equator as, for example, in the TESLA cavities, MP appears sometimes and requires certain time for processing. Our simulations show that resonant motions of electrons are possible in this cavity, but that particles have low impact energy (32 eV) at which the secondary electron yield should be less than unity. Nevertheless, the RF processing is required to get rid of multipacting in this area.

The most radical way to avoid MP is to decrease the secondary emission yield (SEY) below unity. For this goal the surface can be covered by materials having SEY<1, for example a soot or TiN. Unfortunately, this cannot be done for superconducting cavities. Additional magnetic or electric, static or RF, fields are also unacceptable in this case. So, the choice of the shape stable against MP appears the only way to avoid it.

As it is said above, the shape consisting of elliptic arcs helps to avoid MP on the surface remote from the axis and alleviate the problem near the cavity equator where the MP though happens but can be easily processed. The principle of the electric field minimum for MP proposed in [3] explains why the equator stays the place where the 2-point MP occurs and helps to avoid it in the transitions between cavities and beam pipes. It appears that in the 1-point MP the electrons also move to a minimum of the electric field.

FROM SIMULATIONS BACK TO ANALYTICS

Although simulations can help in many cases, they require special programs which are time consuming and they cannot give a clear hint on how to change the cavity shape to obviate multipacting.

On the other hand, the results of simulations prompt a possible way of better understanding of the phenomenon. For example, let us consider the trajectory obtained in multipacting calculations for a cavity [4], Fig. 1. The calculations were performed with MultiPac [5]. One can see that the dimensions of the trajectory are very small compared with the cavity dimensions. It is clear that the magnetic

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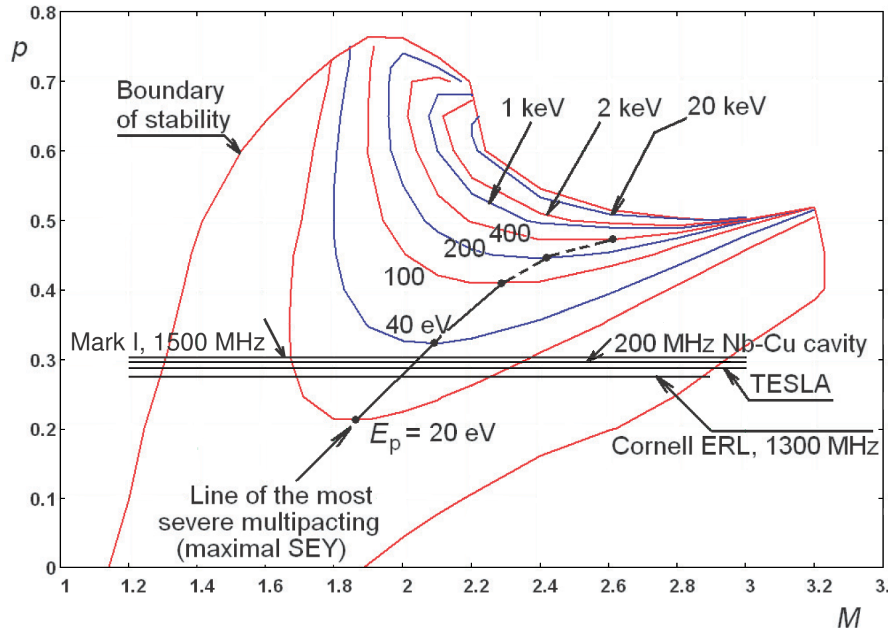

Figure 2: Equatorial crossed-field 2-point 1st-order multipacting zone. Emission energy of the electrons is 2 eV. Examples for several geometries: see references in [6]. E_p is the impact energy. For emission energy of 4 eV all the E_p values should be doubled.

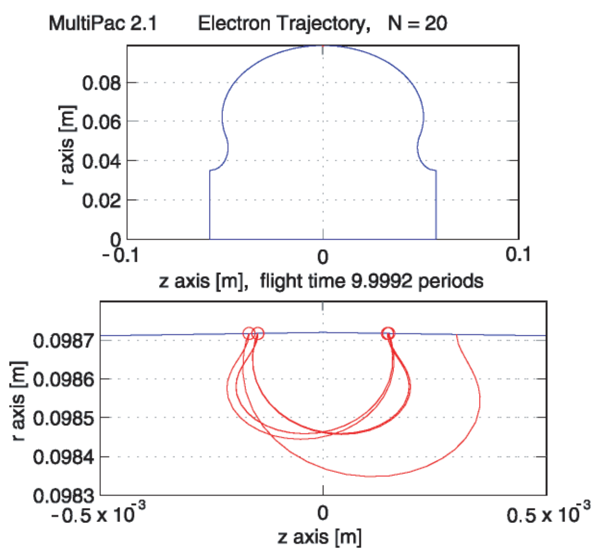

Figure 1: 2-point MP on the cavity equator.

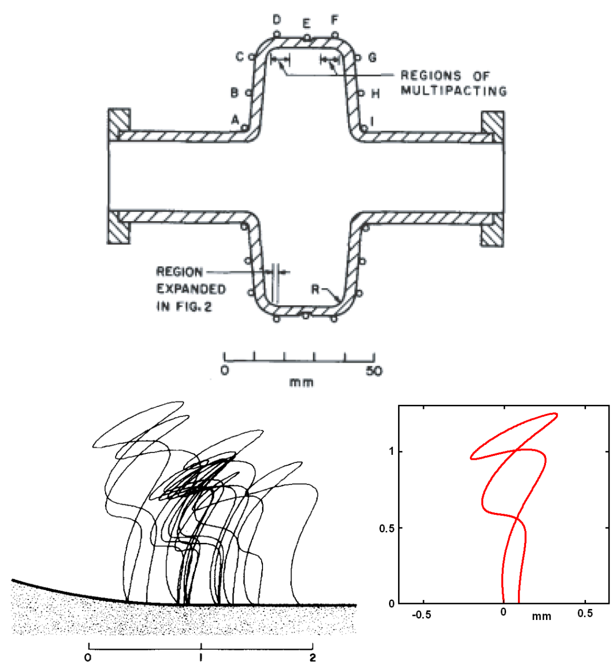

Figure 3: Schematic drawing of the S-band cavity and an example of electron orbits from [1] for the third-order 1-point MP, and a solution of equations (4) for this geometry.

field has as big an influence on the motion as the electric field. At the same time one can assume that the amplitude of the magnetic field is nearly constant within such a small change of coordinates. These features will be used in derivation of the equations of motion. An analysis of the 2-point MP near the cavity equator was presented recently in details [6]. Now we will expand this analysis on the 1-point MP in the SC RF cavities, analyse some existing experimental data and compare these two kinds of the RF discharges.

Due to small sizes of the electron trajectories it is possible to present fields near the MP site as the first terms of the Taylor series and solve the differential equations of motion in the nearest vicinity of this site. Parameters of these

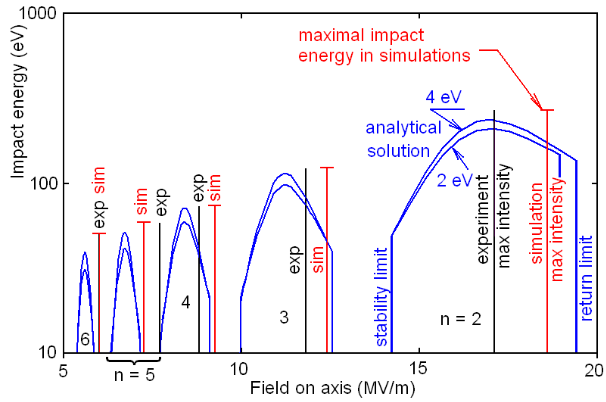

Figure 4: Simulations and experimental results from [1] and analytical results for 2 – 6 orders of 1-point MP.

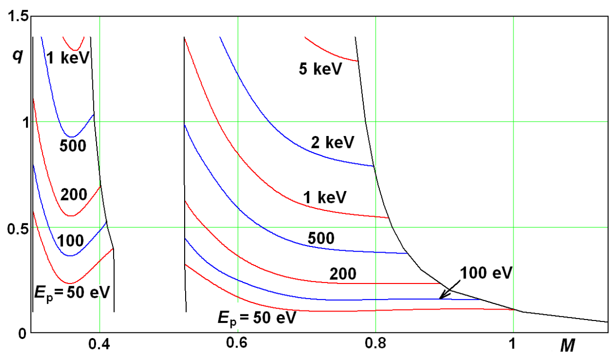

Figure 5: 1-point 1st and 2nd MP zones. Emission energy of electrons is 4 eV.

equations become the figures of merit of the MP and the control of them gives a possibility to avoid MP.

In the case of the 2-point MP near the equator (Fig. 1), the electric and magnetic fields can be presented in the form

$$E_x = \alpha y \sin\theta,\ E_y = -\beta x \sin\theta,\ B_z = -B_0 \cos\theta. \quad (1)$$

Here $\theta = \omega t$, ω is the circular frequency, t is time, and α and β are coefficients describing linear only terms of the Taylor expansion of the fields near the equator. The origin of the coordinates x, y, z is on the equator. The coordinate axis x is parallel to the axis of the cavity; the coordinate $y = R_{eq} - r$ is directed from the equator with radius R_{eq} to the axis of the cavity, the axis z is supplementing this right-hand system of coordinates. Equations of motion,

$$e\left(E_x + \dot{y}B_z\right) = m\ddot{x},\ e\left(E_y - \dot{x}B_z\right) = m\ddot{y} \quad (2)$$

after simple transformations, can be written as

$$\begin{aligned} x'' &= M[(1-p)y\sin\theta - y'\cos\theta], \\ y'' &= M(-px\sin\theta + x'\cos\theta). \end{aligned} \quad (3)$$

The geometrical parameter p can be easily found with any program used for the cavity design as $p = \beta/(\alpha+\beta)$ if E_x and E_y are calculated for small values (from 0 up to 1 – 2 mm) of x and y used in (1). The magnetic field defines the field parameter $M = eB_0/m\omega$. Solution of these equations with account of stability conditions [6] gives the area of MP, Fig. 2.

In the case of the 1-point MP, the normal component of the electric field has the same direction within the trajectory of the electron at any given moment of time. So, if the E_y-component doesn't change too much within the limits of a separate trajectory, we can present the electric and magnetic fields in the form

$$E_x = -\alpha y \sin\theta,\ E_y = E_0 \sin\theta,\ B_z = B_0 \cos\theta. \quad (4)$$

Equations of motion after normalization in this case attain the form

$$\begin{aligned} x'' &= M[-y\sin\theta - y'\cos\theta], \\ y'' &= M(qx\sin\theta - x'\cos\theta), \end{aligned} \quad (5)$$

where $q = E_0/\omega B_0$ can be named the geometrical parameter of 1-point MP, depending on the cavity shape but not on the field amplitude. An example of the orbit calculated with the equations (5) is presented in Fig. 3 together with the geometry and results obtained with a MP simulation software in [1]. Bands of MP found for this geometry with $q = 0.605$ mm are presented in Fig. 4. A map in q, M parameters analogous to the p, M map (Fig. 2) is presented in Fig 5.

CONCLUSION

The maps of multipacting zones for 1- and 2-point MP are presented. It is shown that the MP discharge can be described in terms of two parameters: the geometrical and the field parameter. The parameter p on the equator or the parameter q along the profile line of the cavity and the value of the field parameter M at these points define the conditions when 1- or 2-point MP will occur. No simulations of MP are needed, calculations of fields only. Results are very close to the simulations and experimental data.

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