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Multipacting phenomenon at high electric fields of superconducting cavities

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Recently multipacting (MP) recalculation of the TeV Energy Superconducting Linear Accelerator (TESLA) resonator was performed. In addition to the normal MP which occurs at a peak electric field of around 40MV/m for the TESLA cavity, another type of multipacting with resonant electron trajectory that is far from the equator is also seen. It occurs at a gradient around 60MV/m to 70MV/m. This result seems to explain some experimental observations.

Keywords: multipacting, TESLA cavity
PACC: 2915D, 1000

1. Introduction

As we know, multipacting (MP), field emission and thermal breakdown are the three limitations of a superconducting cavity. Since the cavity shape is changed from cylindrical to elliptical, normal MP is no longer a major limitation. Sometimes MP even does not exist. Most times when it occurs, it can be processed after some time. Figure 1 is the typical MP analysis of a TESLA middle cell cavity.[1] We use the electron counter function, enhanced electron counter function, final impact energy and electron trajectory to describe and analyse MP.

The electron counter function (the number of free electrons) and enhanced electron counter function (the number of secondary electrons) are denoted as c_N, e_N (N stands for the maximum number of impacts).

Figure 1 is the MP analysis of TESLA middle cell cavity. From top to bottom, Fig.1(a) shows the electron counter, the average impact energy of the last impact in eV and the enhanced electron counter for the Tesla 1.3 GHz middle cell cavity, respectively. The horizontal axis gives the peak electric field in kV/m. In Fig.1(a), we can see that MP probably occurs around the peak electric field of 40–45MV/m, with which we are familiar from the RF test. At this field level, we call it normal MP. The impact energy is less than 35 eV (see the figure in the middle) and for those impact energies the secondary yield function is less than one, there is no MP. But if the surface of the cavity is not ideal (the secondary yield function may be larger than 1) or the initial energy is greater than 2eV, MP will take place. So MP potential is around the peak surface field of 47MV/m. Fig.1(b) shows a two-point first order electron trajectory near the equator in the TESLA cavity when the peak electric field is 47.5MV/m. On the top is the trajectory in (r, z) coordinates, in the middle is the zoomed plot of the same trajectory and on the bottom is the trajectory in (r, t) coordinates, where t is the time in RF period. The circles indicate impacts on the walls of the cavity. Recently in some cavities at DESY, radiations were observed at the peak electric field higher than 60MV/m during the RF test, and reduced with processing. This phenomenon is usually a characteristic of MP. But it is hard to explain with the normal MP that happens always near the equator and usually around 40 MV/m. The recent calculated high field MP seems to give an explanation.

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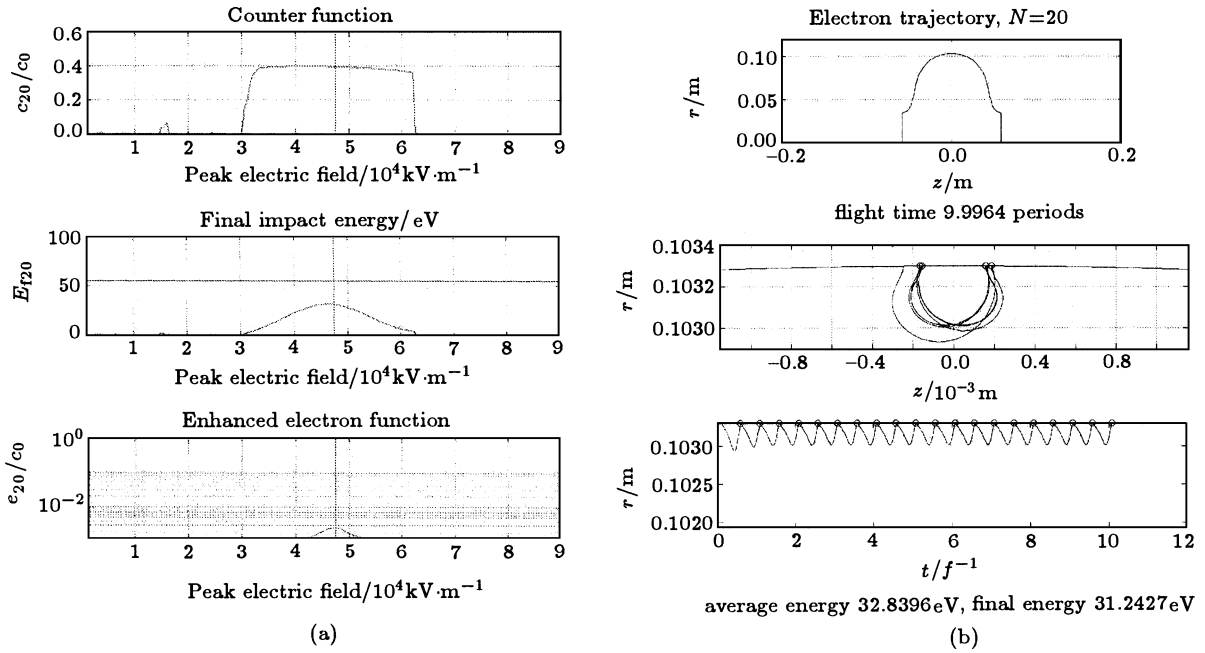


Fig.1. MP analysis of Tesla middle cell cavity.

2. High energy high field multipacting with resonant electron trajectory

2.1. Parameters of MP calculation

MP calculation of 1.3GHz TESLA cavity was redone with MultiPac 2.1 (Helsinki 2001 version).[1] The input parameters are the following. Mesh constant of the cavity is 5mm. Initial energy of the electrons that are launched from given initial sites on the boundary of the structure is 2eV. The phase step is 5 degrees.

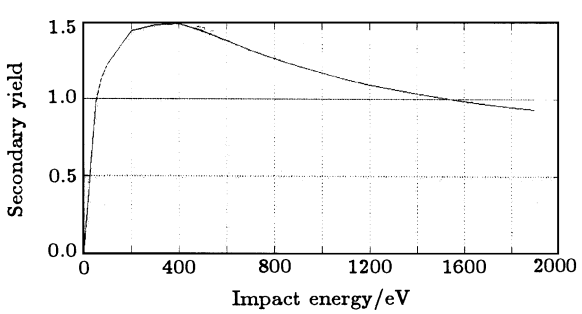


Fig.2. Secondary electron yield at different impact energies for a niobium surface baked at 300°C.

The number of impacts of every initial electron is 20. The program creates initial points whose z coordinates (cavity axis) satisfy $-0.04 \leq z \leq 0$m. All the calculations assume magnetic boundary conditions. A typical secondary electron yield curve for a niobium surface used is displayed in Fig.2.[2]

2.2. MP analysis

2.2.1. Existing normal MP

For the TESLA project, a 9-cell cavity is adopted. The technical design report (TDR) designed geometric parameters of the 9-cell cavity are shown in Table 1.[3] The two end half-cells (Endcup1 and Endcup2) are different from the middle half-cells (Midcup). When MP was analysed on a middle cell of the 9-cell cavity, the result was the same as the previous calculation (see Fig.1). MP analysis was also performed on an asymmetric single-cell cavity formed by cutting off all the middle cells of a TESLA 9-cell cavity. Figure 3 shows the calculation result. We can see that the electron trajectory ends near the equator at the peak electric field of 43 MV/m, and this is the normal MP similar to the middle-cell.

Table 1. Relation between two-point high field MP and cavity geometry parameters.

Name		R_c	Horizontal half axis a	Vertical half axis b	Iris radius R_{iris}	Half cell length L	Y/N
Midcup		4.2	1.2	1.9	3.5	5.77	N
Modification from Midcup	M1	4.221	1.18	1.663	3.7	5.77	N
	M2	4.303	1.081	1.708	3.5	5.77	N
	M3	4.395	1.046	1.464	3.6	5.77	N
	M4	4.03	1.076	1.56	3.6	5.77	Y
	M5	4.138	1.074	1.654	3.6	5.77	Y
Endcup2		4.2	0.9	1.28	3.9	5.7	N
Modification from Endcup2	R1	4.2072	0.8999	1.2798	3.9	5.7	N
	R2	4.2282	0.8576	1.2264	3.9	5.7	N
	R3	4.1250	0.9156	1.2910	3.8	5.7	Y
	R4	4.1505	0.9129	1.2781	3.9	5.65	Y
	R5	4.1704	0.9299	1.3019	3.9	5.68	Y
Endcup1		4.03	1	1.35	3.9	5.6	Y
From Endcup1	R6	4.1259	0.9215	1.2809	3.9	5.63	Y
	R7	4.0673	0.9321	1.2956	3.8	5.65	Y

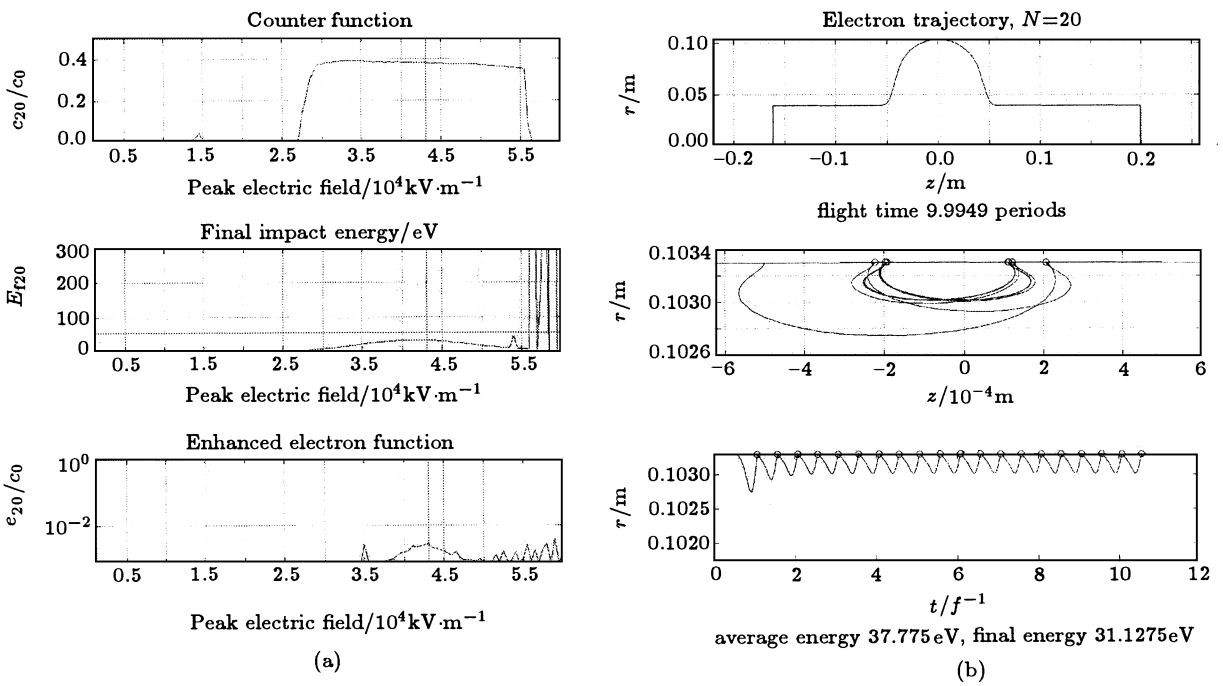


Fig.3. Asymmetric single-cell cavity made by two end half-cells of a TESLA 9-cell cavity. (a) E_p is from 1–60MV/m and field step is 500kV/m. (b) Electron trajectory when E_p is 42.5MV/m (similar to that of the Tesla middle cell).

2.2.2. Zoom of high field trajectory

Besides the normal multipacting, we still can see some high-energy peaks in the middle graph of Fig.3(a). These high-energy peaks appear at the peak electric field of more than 55MV/m. Figure 4(a) is zoom view of Fig.3(a) when the peak electric field is from 30 to 70 MV/m. Under most gradients, the energy of the simulated electrons for the first few impacts is very high and then gradually becomes lower and lower; eventually the electrons stop at the equator (see Fig.4(b)). But under some other fields, the electron trajectory can be resonant between two points of the cavity wall far from the equator (see Fig.4(c)). This is different from the normal MP.

In Fig.4, the final impact energy can reach 1MeV; MP trajectory may take place far from the equator and can even be stable between two points of the cavity wall under some electric field. This kind of MP occurs at higher field compared to the normal multipacting. So we call it high field multipacting.

2.3. Independence on cavity mesh size, boundary step size and field step size

In order to see whether this happens occasionally or not, effect of field step size, mesh size of the cavity and step size of the cavity boundary were studied on this asymmetric single-cell cavity.

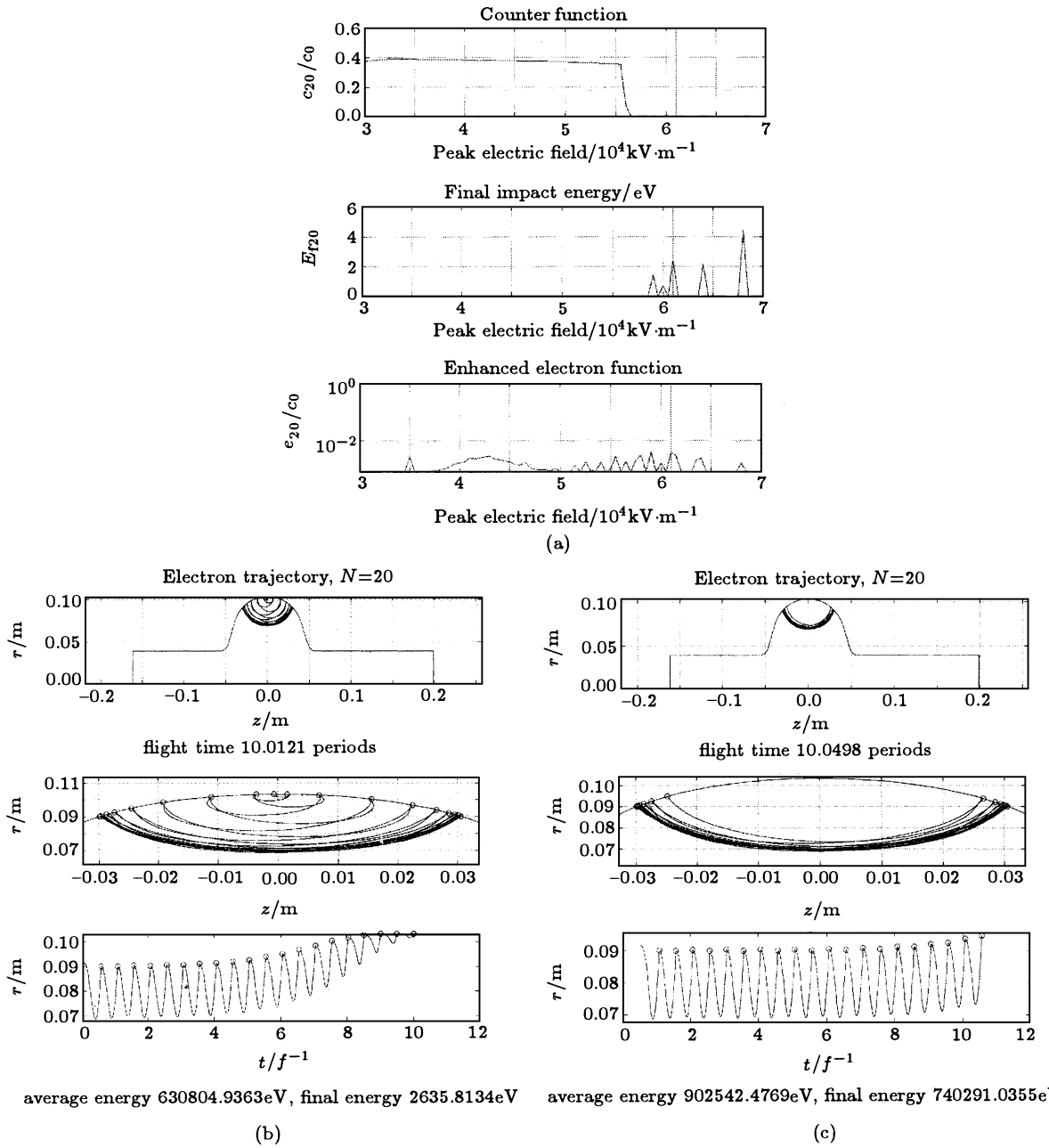


Fig.4. Zoomed MP analysis of Fig.3. (a) Zoom from Fig.3(a), E_p is from 30–70MV/m, field step is 500kV/m. (b) Electron trajectory at E_p=60MV/m, final energy E_f=2.6keV. (c) Electron trajectory at E_p=61MV/m, final energy E_f=740keV.

Mesh size of the cavity is changed from 5mm to 3mm, 4mm and 6mm. Field step size of the simulation is changed from 25 to 500 kV/m. The electron counter functions, final impact energy and electron trajectories give similar graphs (see Fig.5).

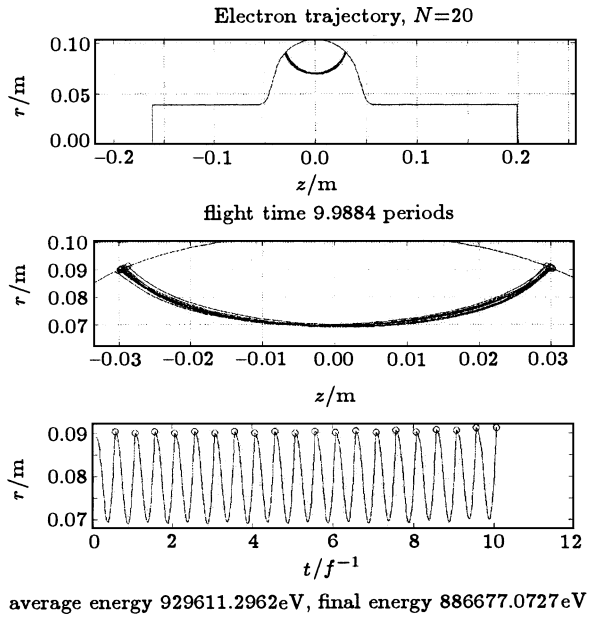


Fig.5. Mesh size=6mm, field step size=100kV/m, at $E_{\rm p}$=61.5MV/m, the final energy $E_{\rm f}$=890keV.

The coordinate of the cavity boundary is given by (r, z) for the input geometry file of the MP program. The input file has about 80 points to form the boundary of the cavity in the previous calculations. Here we change the step size in order to have different total boundary points (45 points, 60points, and 100 points) for the input file. The MP analysis shows that the two-point high-energy multipacting with resonant trajectory can still happen when the peak electric field is in the range of 50–70MV/m.

These analysis show that the high field multipacting with resonant electron trajectory is independent of the cavity mesh size, field step size and boundary step size.

3. High field high impact energy MP depends on cavity geometry

As we mentioned before, high field MP does not exist in the TESLA TDR designed middle cell. Calculations of the designed single-cell cavity at DESY, which is symmetrically fabricated according to the parameters of Endcup2 of a 9-cell cavity (see Table 1), shows no high field MP either (see Fig.6(a)). But it exists in the single-cell cavity made by symmetric Endcup1 of a 9-cell cavity (see Fig.6(b)).

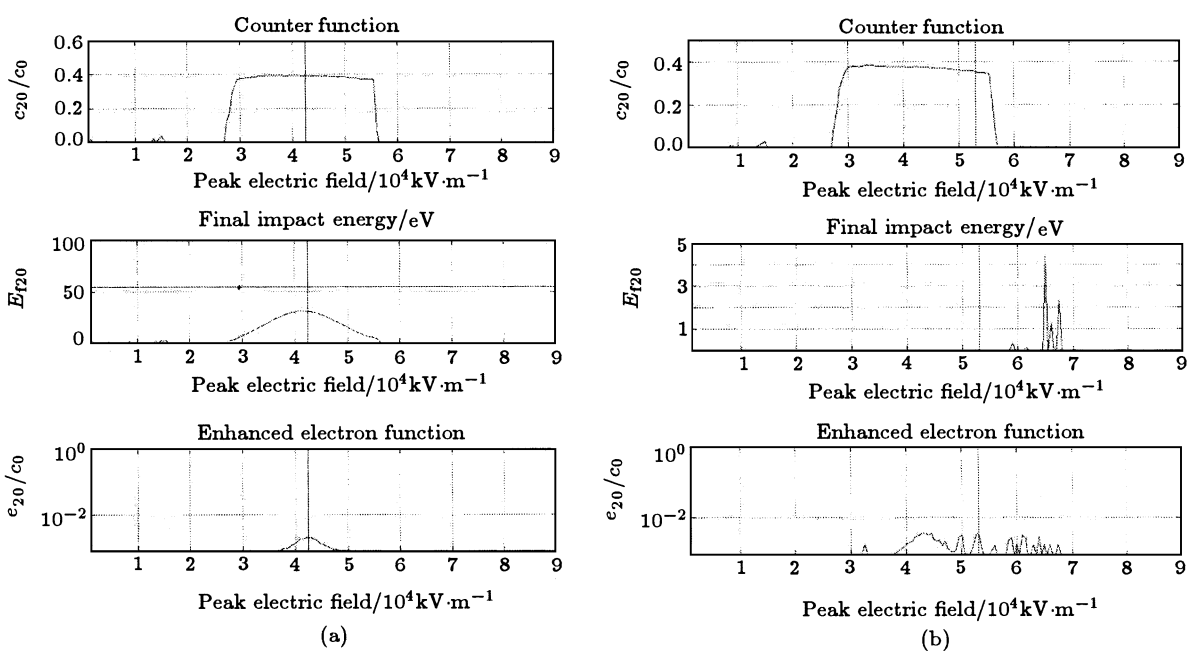


Fig.6. Electron counter functions and final impact energy at peak electric field (1-90MV/m) (a) Single-cell cavity made from symmetric Endcup2. (b) Single-cell cavity made from symmetric Endcup1.

In order to find when this kind of MP takes place, MP analysis was done on a number of cavities by slightly changing the geometry from TDR parameters. Table 1 lists the calculated cavities. The name of a cavity starting with M is a symmetric middle-cell cavity with parameters changing a little from the Midcup

of the TESLA 9-cell cavity. The name of a cavity beginning with R means a symmetric single-cell cavity produced by changing parameters a little from the Endcups of a TESLA 9-cell cavity. In Table 1, the last column "Y/N" stands for whether this high field MP occurs in the cavity or not. All dimensions are in cm.

From the calculations, we can see that high field high impact energy MP depends on cavity geometry parameters, just like the normal MP. Many middle-cell cavities and single-cell cavities produced by changing a little from the Midcup or Endcup of a 9-cell TESLA cavity can also have this high field MP, and the peak electric field range is 60–70MV/m. Table 1 shows that the radius of the circle R_c is the most effective parameter among all geometry parameters. The high field high impact energy MP occurs when R_c is smaller than 4.2cm.

4. Discussion

MP analysis was calculated with the algorithm Multipac 2.1. Calculations show that there exists another kind of MP with resonant trajectory at high electric fields (to date, we have seen no publications about this kind of MP). High impact energy and trajectory far from the equator are its two distinct characteristics. From Fig.4(a), we can see that the maximum of the enhanced electron counter function under high fields is on the same level as that under the normal MP field. It seems that if the normal MP could occur, this high field MP could also occur. To understand it better, let us first have a look how MP takes place. As we know, MP requires two conditions:

(1) An electron emitted from the cavity wall is driven by the electromagnetic field and returns back after an integral number of RF cycles to the same point of the cavity wall.

(2) The impacting electron produces more than one secondary electron, which means the secondary electron yield should be larger than one.

This high field MP fulfils the first condition. For the second, there are no published measured values of the second electron yield δ in the impact energy level of about 1MeV. The program takes a value of a little smaller than 1 for δ when impact energy is this high.

The calculations also indicate this high field MP is independent of the field step, mesh size of the cavity and step size of the boundary, but depends on the cavity geometry. To avoid this kind of MP, the cavity needs proper design. At DESY, both TESLA TDR designed 9-cell cavity and single-cell cavity designed from symmetric Endcup2 do not have this type of MP from the analysis. However, it still may be observed during some cavity RF tests, because the geometry changes during fabrication or tuning and may have a smaller radius of the circle. In order to make sure that the observed γ or x rays from the experiments are caused by this high field MP, we need more quantified measurements of the radiation and to know the precise high temperature places of the cavity wall.

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