A Study of Multipactor Phenomena in the 52 MHz PETRA II Cavity at DESY

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Abstract

We present the results of a study of multipactor phenomena which have occurred in a 52 MHz cavity which is used for acceleration of protons in PETRA II at DESY. Analytical estimations and computer simulations show that the special distribution of the RF-fields along a ceramic cylinder which is placed in the acceleration gap, together with an extremely high electron re-emission coefficient of the ceramic material, provide favorable conditions for multipactoring.

1. INTRODUCTION

In the PETRA II 52 MHz cavities, which are described elsewhere [1] in more detail, the vacuum in the beam tube is separated from the normal air pressure in the cavities by a ceramic cylinder in the gap. This is also shown in Fig.1. After several years of successful operation a ceramic cylinder had to be exchanged because of a vacuum leak.

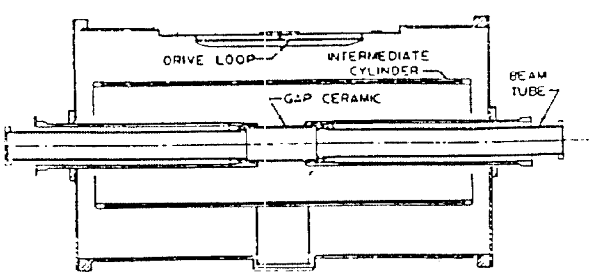

Figure 1. Schematic view of the 52 MHz cavity. This Fig. is taken from[1].

Unlike the original cylinder its replacement showed strong signs of multipactor which made operation practically impossible. The replacement cylinder had been produced by the same manufacturer at the same time as the original one. A difference between the cylinders may arise from the fact that the first one had been installed in the cavity some five years ago only a few weeks after having been manufactured and its inner surface had been subjected to vacuum for almost all the time, whereas our spare cylinders have been stored under normal conditions since then.
As long as there was air of normal pressure in the beam tube operation at all gap voltages up to 100 kV, the specified maximum value, was possible with any of the replacement cylinders. Once the beam tube had been evacuated a threshold below 5 kV gap voltage occurred. Initially it was possible to get through this threshold by some conditioning with pulsed RF. When increasing the RF voltage then, we realized that now much more RF power was needed to reach a particular cavity voltage than before. This effect could be partially cured by conditioning, so that for example 20 kV could be reached without any abnormal increase of transmitter power. But to reach 40 kV, about 5 times as much power was needed than normally, and at higher voltage it become even worse. This effect looked like some kind of non-resonant multipactor since it occurred in a very large range of cavity voltages.
In the following we describe an analysis of the multipactor phenomenon which we have performed in order to improve our understanding and to find possible solutions.

2. ANALYSIS OF THE MULTIPACTOR PHENOMENA IN OUR 52 MHZ CAVITY

As a first step the RF field distribution of the fundamental cavity RF mode has been calculated with the code MULTIMODE [2]. There was good agreement between calculated and measured frequency.
Fig. 2 shows the electric field lines in the region between the ceramic cylinder and the metallic drift tube.
The field distribution is essentially non-uniform, and we can distinguish two regions which are the most probable ones for multipactor to occur. One of them is the region between the ceramic cylinder and the drift tube. Here the radial electric field components are dominating. The other one is the central part of the ceramic cylinder where the electric field lines are parallel to the cylinder's surface.

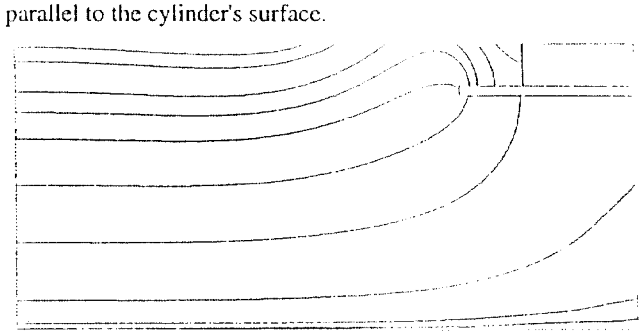

Figure 2. The RF field distribution in the cavity. The field in the region between the ceramic cylinder (upper horizontal line) and the drift tube has been emphasized. The beam axis coincides with the lower horizontal line.

The coefficients for emission of secondary electrons for Al_2O_3 ceramic material which are given in table 1 are taken from experimental data from [3, 4].

Table 1

Collision Energy ε	100 eV	200 eV	800 eV	1400 eV	2000 eV	3000 eV	4000 eV
Coefficient δ	.8-.9	3	7	3	2	1.5	1.3

The base of our investigations was the calculation of the electron motion in the cavity with the code TRAJ2. The code calculates the electron trajectories in the axially symmetric cavities and uses either a calculated RF field distribution or the field given in some analytical form. The code solves the system of equations of relativistic electron motion in one symmetry plane, i e. fields which are changing the azimutal electron velocity are not taken into account.
The secondary emission model includes elastic, inelastic and true secondary re-emission processes and uses experimental data for the given materials.
The relative number of electrons, their mean energy of collision with the cavity walls and an integral re-emission coefficient are calculated. These figures characterize a progress or a regress of a multipactor process.
Our calculations indicate the existence of several kinds of multipactoring, but here we will restrict ourselves only to the most probable phenomena.

3. CHARGING OF THE CERAMIC.

Background electrons which may originate from any point in the volume of the cavity have the following mean collision energies with the ceramic:

Table 2

Mean collision energy ε	47 eV	270 eV	3300 eV	7100 eV
Accelerating voltage	2 kV	5 kV	10 kV	20 kV

For accelerating voltages ranging from 4 to 15 kV the simulation shows a multiplication of background electrons due to the high emission coefficient of the ceramic at these collision energies.
Since the number of emitted electrons is larger than the number of incident ones, a positive charge is generated on the surface of the ceramic [4, 5]. The static electric field due to this positive charge provides the return force necessary for non-resonant multipactoring.

4. NON-RESONANT MULTIPACTORING

Non-resonant multipactoring arises when the initial velocity of the emitted electrons becomes significant for their dynamics and can not be neglected. In general, electrons emitted at a given RF phase return to the electrodes within a broad region of RF phase. Therefore the bunch of electrons moving synchronously with the RF field does not exist, but some stable distribution of electrons over the initial phases is formed.
All electrons have different collision energy, so an integral re-emission coefficient $< \sigma >$ is used to characterize the intensity of a re-emission process.
Naturally, a fraction of the electrons is constantly going out of the game. For compensation of these losses the achievable re-emission coefficient must be not less than 3.5-3.7 for the electrons of maximum collision energy at a threshold level of the RF field [5].

The non-resonant one-electrode multipactoring can arise in particular in the presence of the positive surface charge of the highly emitting ceramic or on the surface of an isolated metal electrode which can also be charged and when the RF electric field is parallel to the surface of the electrode. We have this situation in the central part of our ceramic cylinder.
If the value of the electrostatic field E_e is small, then the time of flight between emission of the electron and collision with the wall largely exceeds the RF period.
Since the secondary electrons can leave the surface of the electrode at any RF phase, the distribution of the colliding electrons over the phases of the RF field is practically uniform. In this case the amplitudes of the RF field E_{rf} and the electrostatic one are independent. The energy gain provided by E_{rf} must be sufficient to enable re-emission and the force returning most of the electrons to the electrodes comes from E_e. This kind of non-resonant multipactoring is considered in [5, 6] .
In our case the electrons could not return to the wall immediately if only a weak electrostatic field were present but would be captured by the strong accelerating field and end up far away.
Most electrons are returned to the wall only if E_e is so high that the time of flight of the electrons is less than one RF period. Then the values of E_{rf}, E_e, and $< \sigma >$ are no more independent and there appear well defined relations.
The dependence of $< \sigma >$ on E_e for different values of E_{rf} is shown in Fig. 3.

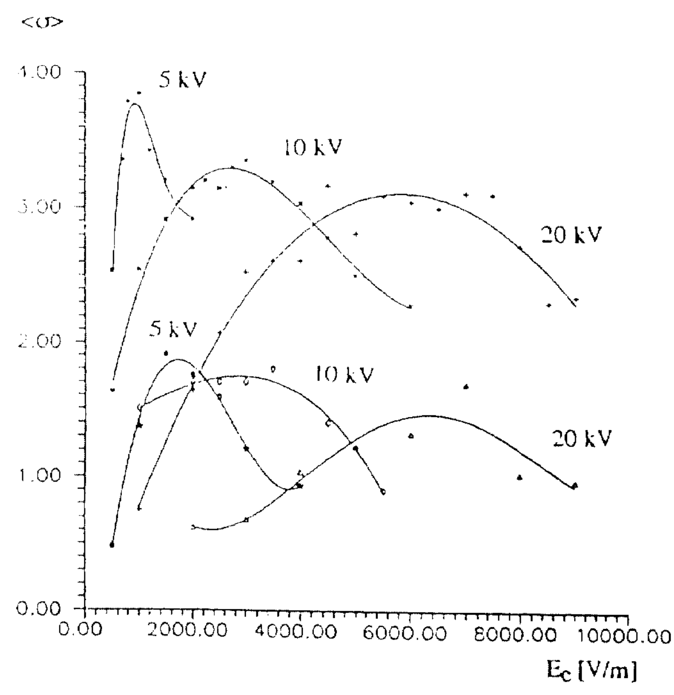

Figure 3. Integral re-emission coefficient $<\sigma>$ as a function of the electrostatic field E_e (see text) for three different accelerating voltages. The upper curves stem from the test simulation, the lower ones from the simulation with the "real" fields.

These curves were obtained by a test simulation of multipactoring near a flat electrode in the presence of a perpendicular uniform electrostatic field E_e and a uniform RF field E_{rf} parallel to the electrode. One can see that there is an optimal value of E_e for which $< \sigma >$ is maximal. A sudden increase of E_e above this optimal value would lead to a decrease of the value of $< \sigma >$ which results in an autoregulation of the positive charge on the electrode.
One sees also that the optimal value of E_e increases with increasing E_{rf}.
The multipactor simulation in our cavity was performed with the calculated "real" RF fields and in the presence of the uniform electrostatic field which was perpendicular to the surface of the ceramic. Here the maximal value of $< \sigma >$ is smaller than in the test simulation because of the additional losses of electrons due to the non uniformity of the real fields. The results of the simulations are presented in Fig. 4.

In uniform fields the multipactor process may begin at the acceleration voltage of 3 kV [5]. Our simulation shows that in the "real" fields stable multipactoring begins around 5 kV. The upper limit can be estimated with the help of diagrams presented in [6] to be at least 100 kV. This estimation does not take into account the relation between E_e and E_{rf}. It expresses rather an energetical possibility. The experimental fact is that from a certain level of the RF field on, the positive potential on the surface of the electrode stops increasing [6]. The reason may be the discharging of the electrode by leakage currents and by the limited multipactor current.
Presently we are not able to simulate this complex process and to determine the upper limit of the potential quantitatively.

5. CONCLUSIONS AND CURE

Our calculations show that the conditions for multipactoring are fulfilled in the central part of the ceramic cylinder and the region between the ceramic cylinder and the drift tube. In particular we find that

1. At the accelerating voltage of 1 kV resonant one electrode multipactor may arise. However, the relative strength of this process seems to be small.
2. Beginning at 5 kV non-resonant multipactoring can take place on the surface of the central part of the ceramic cylinder under the influence of the longitudinal electric RF field and the radial electrostatic field near the ceramic surface. We believe that this is the most important process. The results of its simulation are summarized in Fig. 4.
3. A non-resonant one-electrode multipactor process at the end of the cylinder may accompany the one in the central part.

Experimentally we observe the onset of non-resonant multipactoring at RF voltages between 8 and 20 kV, depending on the state of conditioning. These phenomena strongly increased as a function of RF voltage.
Since the cavities are installed in the PETRA ring our possibilities to work on them were severely limited during the run. One opportunity was used to install corona rings at the ends of the drift tubes, but we had to learn that this would not be the solution of our problems. This is consistent with the results of our simulations which say that the main process takes place in the middle of the cylinder.

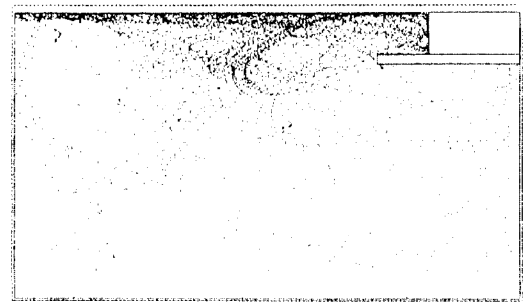

Figure 4. Simulation of one-electrode non-resonant multipactoring at the accelerating voltage of 5 kV and the electrostatic field 1.9 kV/m.

Coating the surfaces of coupling windows or cavities etc. with Ti, or better TiN, has proven to be a reliable cure of multipactoring in many cases because of the low coefficient of emission of secondary electrons.
Therefore we prepared [7] one ceramic cylinder for installation in the cavity during the shut down by coating its inner surface with a layer of TiN of 100 - 200 Angström thickness.
During initial operation, the multipactor process occurred at low RF voltage as previously. After a few hours of conditioning with pulsed RF it disappeared completely, and we could increase the RF voltage up to the maximum value of 100 kV without any further signs of resonant or non-resonant multipactor.

6. REFERENCES

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