DESIGN OF AN RF DEVICE TO STUDY THE MULTIPACTOR PHENOMENON

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Abstract

Multipacting is a parasitic electron avalanche process that may occur in RF devices such as cavities or couplers. As it can be detrimental to the operation of these devices, the accelerator group at LPSC is currently designing a coaxial resonant cavity in order to study this phenomenon.

This paper presents the calculations performed to find the measurable parameters of the cavity. These calculations were confirmed by electromagnetic fields numerical simulations. The results of multipactor simulations performed with a dedicated code, Musicc3D, are also exposed.

INTRODUCTION

In the framework of the SPIRAL2 project, the accelerator group at LPSC had the charge to provide the 28 power couplers for the LINAC cryomodules. During the commissioning of these couplers, some units showed parasitic multipactor emissions [1]. Multipacting can appear in radiofrequency devices operated under vacuum. An electron is accelerated by the electric field and hits the device's wall. Depending on the secondary electron yield, more than one electron can be emitted and accelerated by the electric field, creating a self-sustained electron avalanche. These electron avalanches can degrade the device's performance: a part of the power that must be transmitted to the cavity and the beam is transferred to the electron avalanche. Moreover the electron avalanche can deteriorate the coupler.

In order to better understand the multipactor phenomenon, an experimental device will be built at LPSC. This experiment will operate in the 100 MHz to 1 GHz range. A coaxial geometry was chosen and will be operated such as to be resonant. In order to perform the study at different frequencies, the structure will be modular.

RESONANT COAXIAL CAVITY

Cavity Parameters

The resonant structure will consist of two coaxial lines shorted at one end and assembled in parallel at the other with a tee adapter as shown in Fig. 1. The left line will have a length corresponding to $\frac{\lambda}{2}$ and the right line a length corresponding to λ.

The input impedance Z of a shorted coaxial line can be written as a function of the length l of the line, the propagation coefficient γ and the line characteristic impedance Z_0: $Z = Z_0 \tanh(\gamma l)$. For two coaxial lines assembled in parallel, the total input impedance becomes:

$$Z = \left(\frac{1}{Z_0 \tanh(\gamma(f) x_{\text{right}})} + \frac{1}{Z_0 \tanh(\gamma(f) x_{\text{left}})} \right)^{-1}$$

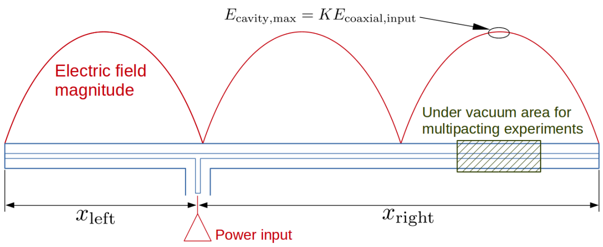

Figure 1: Schematic view of the experiment.

The propagation coefficient γ is equal to $(R + jL\omega)(G + j\omega C)$ with R, L, G and C the resistance, inductance, conductance and capacitance per unit length. The conductance G can be neglected with respect to $j\omega C$. L and C are characteristics of the line but R depends on the frequency f via the skin depth $\delta(f)$: $R(f) \propto (\delta(f))^{-1}$. The propagation coefficient can also be written $\gamma = a + jb$ with j the imaginary unit and [2]:

$$a(f) = \sqrt{2LC}\pi f \sqrt{\sqrt{1 + \frac{R(f)^2}{4\pi^2 L^2 f^2}} - 1}$$

$$b(f) = \sqrt{2LC}\pi f \sqrt{\sqrt{1 + \frac{R(f)^2}{4\pi^2 L^2 f^2}} + 1}$$

In order for the line to be resonant, the impedance has to be matched at the entry: $Z = Z_0$. The total length of the cavity is $x_{\text{right}} + x_{\text{left}} = \frac{3\lambda_0}{2} = \frac{3c}{2f_0}$ with f_0 the working frequency, chosen in the 100 MHz to 1 GHz range. The matching condition yields two relations for the lines lengths x_{right} and x_{left}:

$$x_{\text{right}} = \frac{c}{f_0} \left(1 + \frac{\arctan\left(\frac{1}{k}\right)}{2\pi} \right)$$

$$x_{\text{left}} = \frac{c}{f_0} \left(\frac{1}{2} - \frac{\arctan\left(\frac{1}{k}\right)}{2\pi} \right)$$

with $k \approx \sqrt{\frac{2}{3a(f_0)\lambda_0}} \approx \sqrt{\frac{4Lf_0}{3R(f_0)}}$ [2]. This coefficient k is also approximately equal to the voltage magnification factor of the cavity, i.e. the ratio between the maximum voltage inside the cavity and the input voltage.

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An other way to perform the matching calculations is to use the $S_{11} = \frac{Z-Z_0}{Z+Z_0}$ parameter of the cavity. When $|S_{11}| = 0$, all the input power is dissipated in the cavity. This condition allows to find both the length x_{left} and the frequency f_{matched} needed for the matching. These calculations can be performed with a computer algebra system.

These values offer the advantage to be measurable on the experimental device: a comparison between the calculations, numerical simulations and the experiment will be possible. An other value of interest is the unloaded quality factor Q_0. It is equal to $\frac{2\pi L f}{R(f)}$ for this model. This quantity can also be found by numerical simulations and it will be measurable on the experiment by calculating the ratio $\frac{f_{\mathrm{matched}}}{f_1 - f_2}$ where f_1 and f_2 are the frequencies such as $\Re(Z) = \Im(Z)$. A last interesting value is the voltage magnification factor K as it allows to find the maximum voltage inside the cavity, knowing the input voltage. It is approximately equals to $\sqrt{\frac{4Lf_0}{3R(f_0)}}$ so $K \approx \sqrt{\frac{2Q_0}{3\pi}}$

Computation of the Parameters

In order to validate the calculations made above and implemented with Mathematica, a first comparison was made with numerical simulations performed with Ansys HFSS. Table 1 shows the results concerning the matching frequencies for different design frequencies f_0. Table 2 shows the length of the left coaxial line when the matching condition is fulfilled. We recall that the total length of the cavity is $x_{\mathrm{right}} + x_{\mathrm{left}} = \frac{3c}{2f_0}$. Table 3 shows the unloaded quality factor for the different design frequencies. Finally Table 4 shows the different values of the voltage magnification factor K.

Table 1: Matching Frequencies - obtained with numerical calculations and with electromagnetic simulations performed

Design freq.	**Matching freq.** **Calculation**	**Matching freq.** **HFSS**
100 MHz	99.939 MHz	99.863 MHz
625 MHz	624.62 MHz	624.75 MHz
900 MHz	899.46 MHz	899.39 MHz

Table 2: Left Coaxial Line length at Matching - obtained with numerical calculations and with electromagnetic simulations

Design freq.	**Coaxial length** **Calculation**	**Coaxial length** **HFSS**
100 MHz	1473.1 mm	1472 mm
625 MHz	237.3 mm	237.3 mm
900 MHz	164.9 mm	164.7 mm

Table 3: Unloaded Quality Factor Q_0 - obtained with numerical calculations and with electromagnetic simulations

Design freq.	Q_0 **Calculation**	Q_0 **HFSS**
100 MHz	1475	1426
625 MHz	3698	3509
900 MHz	4439	4125

Table 4: Voltage Magnification Factor K - obtained with numerical calculations and with electromagnetic simulations

Design freq.	K **Calculation**	K **HFSS**
100 MHz	17.74	17.60
625 MHz	28.04	27.49
900 MHz	30.72	30.23

These results show that the calculations are consistent with the simulations and should also be consistent with the experiment. These calculations are quickly performed with a computer algebra system, allowing to predict the characteristic of any cavity length in the desired frequency range. The quantities f_{matched}, x_{left} and Q_0 may be measured on the experiment, allowing to compute the voltage magnification factor K. Knowing this coefficient will allow to know the magnitude of the electric field along the cavity, a fundamental parameter to study multipacting.

MULTIPACTOR SIMULATIONS

To study the multipactor phenomenon in any kind of radiofrequency structure, a dedicated code called Musicc3D was developped and tested at the IPN d'Orsay [3, 4]. This code has been used to predict which frequencies and electric field magnitudes will create multipactor in the experiment. As an input, Musicc3D requires a map of the structure's electromagnetic field, obtained with a numerical simulation software. Other inputs are the secondary electron yield of the material used for the device, the working frequency, the location and the intensity of the initial electron emission. The maximal value of the electric field in the cavity can be varied to perform a scan in electric field.

Musicc3D uses the particle in cell (PIC) model to perform the simulations [4]. It gives as an output a text file containing the intensity of the multipacting discharge for each value of the electric field simulated.

In order to know if the devised experiment will allow to see multipacting discharges, Musicc3D simulations were performed with three different copper cavities working at 100 MHz, 625 MHz and 900 MHz. For each one the electric field boundary values where multipacting was present have been plotted in Fig. 2. The hatched area represents the couples electric field/frequency were multipacting might appear, deduced from the three simulations.

Figure 2 shows that the multipactor phenomenon should be observable in desired frequency range. The two different bands represent two different orders of multipactor: for

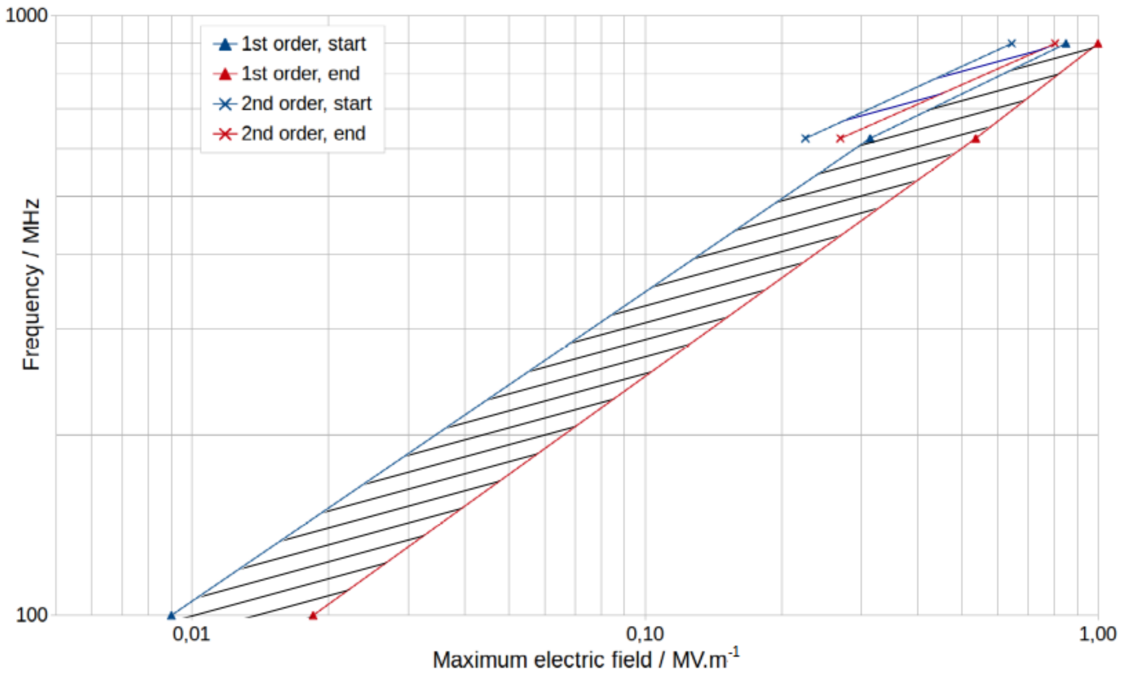

Figure 2: Values of electric field and frequency where multipacting might appear in the coaxial cavity.

frequencies of at least 625 MHz, second order multipacting becomes also observable.

CONCLUSIONS

The calculations done for the resonant coaxial cavity emphasized which parameters will be measurable on the experiment. They also gave indicative values which were consistent with numerical simulations. The multipacting simulations performed with three different set-ups showed that multipacting should be observable in the coaxial cavity and in the desired range. Thus these two studies validated the experiment principle.

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