# MULTIPACTING IN AN RF WINDOW: SIMULATIONS AND MEASUREMENTS

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## Abstract

Electron guns are used in the accelerators of the European XFEL and FLASH. They are operated at 1.3 GHz. The RF peak power is 5 MW at 650 $\mu$s pulse width and 10 Hz repetition rate. In order to understand the multipacting that occurs during conditioning, it was simulated in the RF window type that is used for the electron gun in the XFEL. The reduction in secondary emission yield associated with conditioning was taken into account. Since the RF windows are tested with high power on a test stand before their use, without the electron gun, measurement results are available which are compared with the simulation results. The main advantage of the simulation compared to the measurement is that the locations of multipacting can be determined in the RF window. This could be helpful for the development of high-power RF components in the future, in order to detect pronounced multipacting resonances even before production and to avoid them by design changes.

## INTRODUCTION

The RF power of the XFEL's electron gun is fed via the window (Fig. 1 and 2). Between the window and the gun coupler there is a 100 mm long spacer which brings the ceramic into the field minimum of the standing wave which is formed by the RF power reflected from the gun [1]. On this spacer, there is a vacuum pump which monitors the residual pressure. On the window, light detectors are mounted to diagnose multipacting or other discharges.

Since a window replacement would cause a long interruption of operation, the windows are tested on a test stand prior to their use. These tests are carried out with up to 6.5 MW peak power, 900 $\mu$s pulse length and 10 Hz repetition rate, which corresponds to a maximum average power of 58.5 kW and thus clearly exceeds the current power in XFEL operation (5 MW / 650 $\mu$s / 10 Hz). During conditioning on the test stand, light and variations in residual pressure could be observed which were evaluated as signs of multipacting. The power ranges in which this multipacting was found were recorded and compared with simulations.

## NUMERICAL SIMULATION

The simulations were carried out with CST Microwave and Particle Studio. First, the RF fields were simulated.
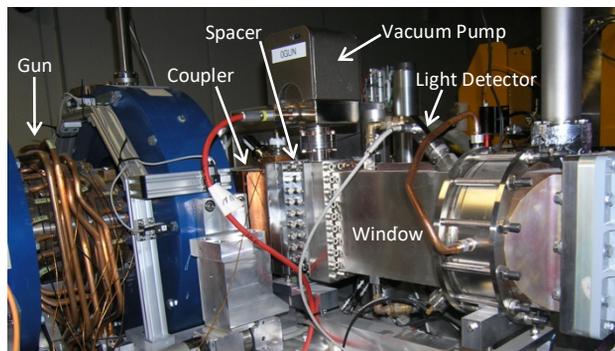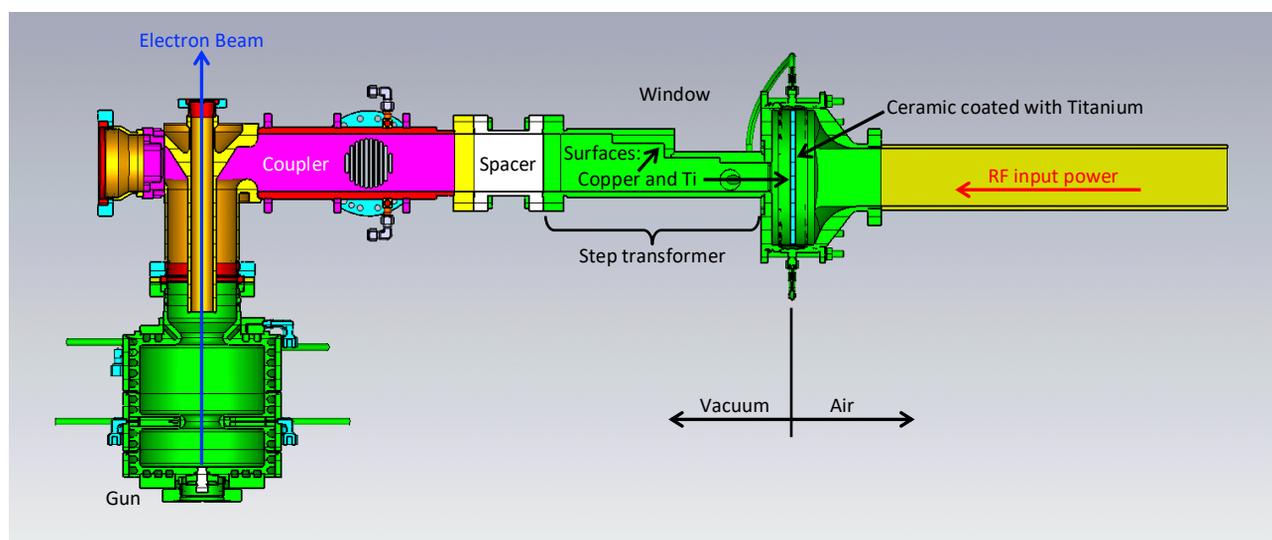


Figure 1: XFEL gun with RF window.



Figure 2: Cross-section through the XFEL gun and the RF window.

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In order to achieve the good agreement of the simulated and with the measured S-parameters (Fig. 3), the mesh for curved surfaces had to be optimized and the appropriate value for the relative permittivity of the ceramic had to be found.
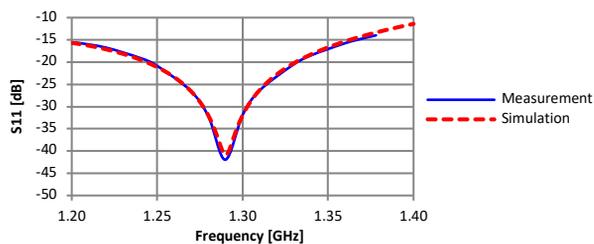


Figure 3: Measured and simulated return loss S11.

Then the field distribution calculated with Microwave Studio was imported into Particle Studio to perform the multipacting simulations. At the beginning of the multipacting simulation, electrons are randomly distributed in the vacuum part of the window and then moved by the electrical RF field. If these electrons hit the ceramic or copper inner walls with a certain amount of energy, secondary electrons are released from the wall and the number of electrons can increase. In the case of a multipacting resonance, the number of electrons increases exponentially.

The assumed secondary emission coefficients (SEY) for untreated copper [2, 3] and the titanium layer on the ceramic [4] are shown in Fig. 4. They represent the material state at the beginning of conditioning. During conditioning, the SEY decreases, which was modelled by a stepwise reduction of the SEY in 5 % increments. The simulation results are presented below and compared directly with the measurements at the test stand.
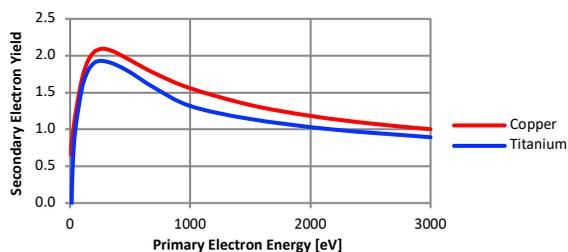


Figure 4: SEY of window interior surfaces.

## MEASUREMENTS AT THE TEST STAND

On the test stand, two windows are connected together via a vacuum waveguide (Fig. 5). To detect multipacting, sensors for light and residual pressure are available. The conditioning starts with short RF-pulses which are then prolonged stepwise from 20 to 900 $\mu$s. Multipacting bands can be determined, as peak performance is regularly increased and decreased during conditioning. With ongoing conditioning, the SEY and also the multipacting decreases, which causes the multipacting bands to change (Fig. 6a).
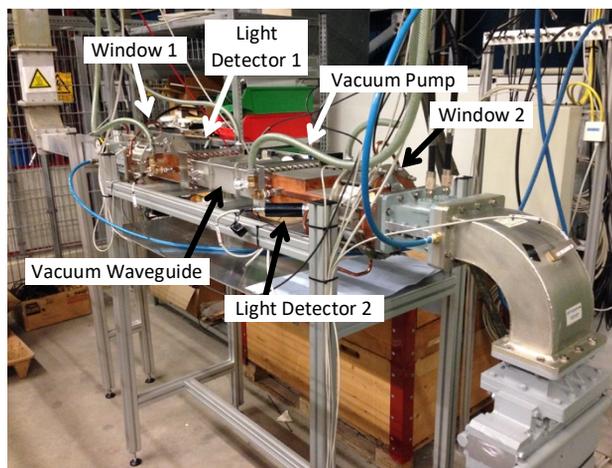


Figure 5: RF window test stand.

## CONDITIONING PROCESS

At the beginning of conditioning, the power was increased from 0 to 6.5 MW and multipacting (light or residual pressure increase) in the range of 0.15 to 6.5 MW was observed in the vacuum section (Fig. 6a). During simulation, the performance could not be continuously increased. Instead, multipacting had to be simulated for concrete power values. 1000 electrons were introduced at the beginning of each simulation and exposed to the RF field for 40 ns. The number of electrons at the end of the simulation can be seen in the graph (Fig. 6b) for power values from 0 to 7 MW. Below 0.08 MW the number of electrons decreased, above it increased. According to the observations at the test stand, however, electron multiplication is only fast enough from 0.15 MW onwards (Fig. 6a) to cause light or a change in residual pressure within a 20 $\mu$s RF pulse. Above 2 MW, very strong resonances occur which lead to the peaks in the graph (Fig. 6b).

Within 2 days, the weak multipacting below 2 MW has largely subsided (Fig. 6a). After 2.5 days, multipacting resonances only survive in 3 bands: 2.5 to 3.2 MW, 4 to 5 MW and 5.9 to 6.5 MW. The two lower bands disappear in the further course and the upper band shrinks considerably, but persistently holds at 6.2 MW. It could only be eliminated by the second part of the conditioning routine, where 20 $\mu$s pulses are fully reflected behind the second window.

In which part of the window the multipacting occurred could not be observed on the test stand. Here, the simulation provided interesting insights. If the SEY is not reduced (= conditioning start), multipacting resonances occur in front of the ceramic and the two nearest steps of the step transformer (Fig. 7). One-sided multipacting occurs only at the steps, is particularly pronounced and the main cause of the high peak values in Fig. 6b. However, the more the SEY is reduced, i. e. the conditioning progresses, the less resonance occurs at the steps until they disappear completely over the entire power range.
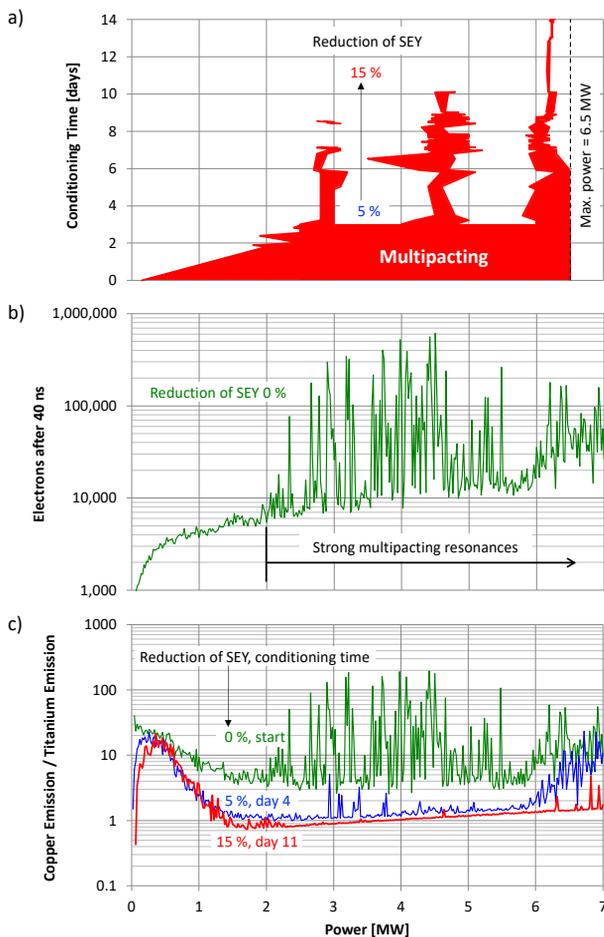
Figure 6: a) Observation: Multipacting at the test stand. b) Simulation: Electron increase at the beginning of conditioning. c) Simulation: Relation between electron emission of copper and titanium surfaces at different stages of conditioning.

If only the weaker, two-sided multipacting occurs between the ceramic and the directly adjacent copper surfaces, then the electron emission of both surfaces is approximately equal in magnitude. This is due to the fact that the copper and ceramic surfaces involved are approximately the same size. In this case, the ratio of the emitted electrons from the copper surface to those from the ceramic is approximately 1, which is only valid for powers > 1.5 MW, because below this limit no or only very weak resonances occur. If the SEY is not reduced, multipacting also occurs on the steps (Fig. 7) in the complete power range from 2 to 7 MW, therefore the ratio is continuously > 2 (Fig. 6c). Especially with regard to the peak values, resonances at the steps play a dominant role. This can be clearly seen from the correlation of the graphs in Fig. 6b and 6c (both green).

After the reduction of the SEY by 5 %, the picture changes significantly. At the steps, the first multipacting resonance now occurs at 2.94 MW, which corresponds

well with the conditioning level after 4 days (Fig. 6a). Below 2.94 MW there are no more resonances at the steps. Between 4 and 5 MW, multipacting is still present at the stages but not as pronounced as above 5.9 MW. If the SEY is reduced by 15 %, the position of the first resonance at one step is shifted upwards to 6.32 MW. This simulation result also corresponds well with observation on the test stand after 11 days of conditioning (Fig. 6a). The small deviation from the measured value 6.2 MW lies within the measuring accuracy of the setup.

From the simulation results it can be concluded that after successful conditioning of the step transformer, the complete RF window is also conditioned. Although there is still weak multipacting in the area of ceramics, the electron growth is no longer fast enough to generate light or a pressure increase at a pulse length of 900 $\mu$s and a repetition rate of 10 Hz.
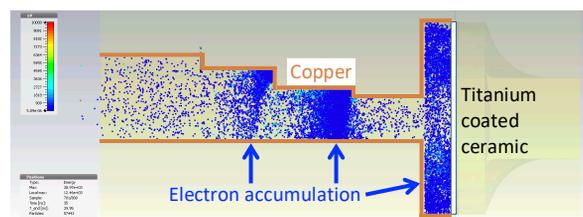


Figure 7: Typical electron distribution at the beginning of conditioning here at a power of 6.36 MW after 35 ns.

## SUMMARY

The presented multipacting simulations can be used to determine power values in which multipacting resonances occur and their spatial position within an RF structure. In addition, the conditioning process can be followed by a stepwise reduction of the SEY. The good correspondence of the simulations with the measurements on the RF window test stand suggests that the simulation model is a good representation of reality and that the multipacting algorithms in Particle Studio work properly.

## OUTLOOK

Since there is now software available for multipacting simulation, it is reasonable to use this in future developments of RF vacuum components. For example, it would be conceivable to optimize the shape of an RF window in such a way that less multipacting occurs from the beginning.

## ACKNOWLEDGMENTS

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07 Accelerator Technology

T06 Room Temperature RF

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