# MULTIPACTING IN THE 150 MHz FLAT-TOP CAVITY OF HIPA: SIMULATION, VERIFICATION, AND MITIGATION STRATEGIES

T. G. Lucas[*], J-Y. Raguin, M. Pedrozzi, M. Schneider, P. Craievich
PSI Center for Accelerator Science and Engineering, Villigen, Switzerland

*Abstract*

Local X-ray production, beam losses, and surface discolouration in colloidal graphite coated regions of the cavity indicate that multipacting continues to affect the operation of the 150 MHz flat-top cavity of the HIPA Ring Cyclotron. Particle-in-cell simulations were performed to confirm the phenomenon driving the issues and identify the specific operational conditions where it is driven. Simulations at the nominal cavity voltage show resonant electron trajectories between the electrodes and cavity wall, producing stable multipacting patterns consistent with observed surface discolouration. Guided by these results, the cavity geometry was modified to flatten the field minimum near the backplane, which demonstrated effective mitigation of multipacting under various operational conditions.

## INTRODUCTION

The 150 MHz flat-top cavity of the PSI Ring Cyclotron at the Paul Scherrer Institute is being redesigned to support operation at an increased beam current of up to 3 mA, as the existing cavity is limited by its RF power capability [1]. The upgraded design targets a peak voltage of 700 kV with approximately 140 kW of average dissipated power, while maintaining compatibility with the current mechanical layout and integration constraints.

The present cavity has long been suspected to exhibit multipacting, with indications such as localised X-ray production, elevated power consumption, and beam losses reported over more than a decade of operation [2, 3]. These phenomena suggest the presence of a resonant electron multiplication process that limits achievable performance and operational stability.

This work presents a detailed numerical investigation of multipacting in the existing flat-top cavity using particle-in-cell (PIC) simulations. The study aims to confirm that the observed operational limitations are the result of multipacting, and to identify the regions and conditions under which it occurs. In addition, potential mitigation strategies will be explored in the context of the upgraded cavity design to ensure reliable operation at higher beam currents.

## FLAT-TOP CAVITY OF HIPA AND HISTORY OF MULTIPACTING

The flat-top cavity is a normal-conducting aluminium resonant structure operating at 150 MHz, corresponding to the third harmonic of the Ring cyclotron RF frequency (Fig. 1). Multipacting in the cavity has long been suspected due to observations of anomalous power absorption, beam losses, and localised heating, which motivated this study. Over the operation of the machine, several attempts to mitigate the multipacting have been attempted including removing the cavity for observation and the application of colloidal graphite to reduce the secondary emission yield (SEY) of the surface expected to be involved. Later in its operational history the cavities in wall was photographed and was used as a motivation for this study.

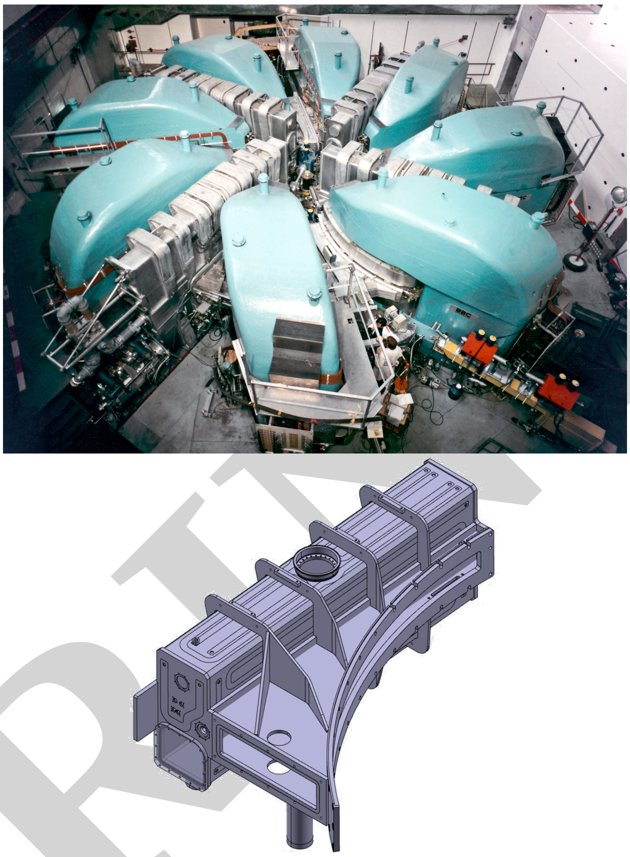

Figure 1: HIPA Ring Cyclotron (top) and flat-top cavity (bottom).

## PARTICLE-IN-CELL SIMULATIONS

To investigate multipacting in the flat-top cavity, simulations were performed using CST Studio Suite, combining the eigenmode solver and the particle-in-cell (PIC) module [4]. First, the eigenmode solver was used to compute the electromagnetic field distribution within the cavity at the operating frequency. These simulations included the adjacent vacuum chamber which is integrated into the cavity's design [1]. These fieldmaps serve as the basis for subsequent PIC simulations.

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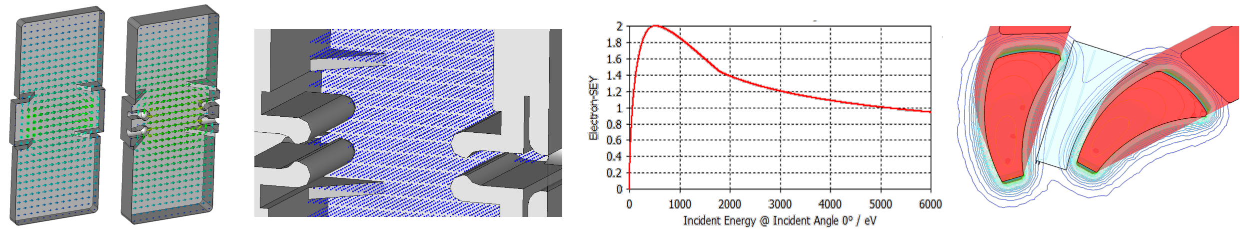
[*] thomas.lucas@psi.ch



1. Electromagnetic Fieldmap
2. Seed Particles
3. Secondary Emission Model
4. Local Magnetic Fields

Figure 2: Key components of the method for performing multipacting simulations in the Particle-in-Cell Solver.

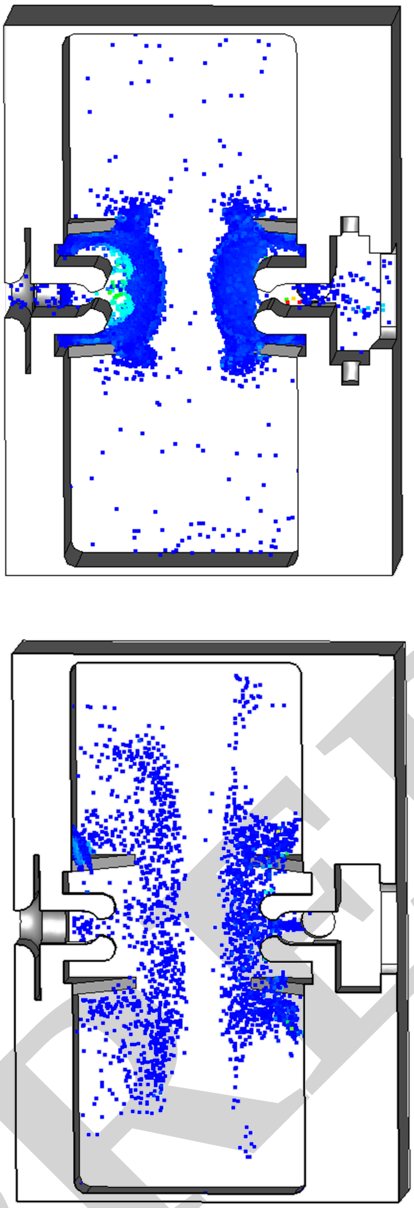


Figure 3: Steady-State (after growth and into saturation) solution of the Particle-in-Cell simulations of the multipacting without (top) and with (bottom) the local magnetic fields of the sector magnets.

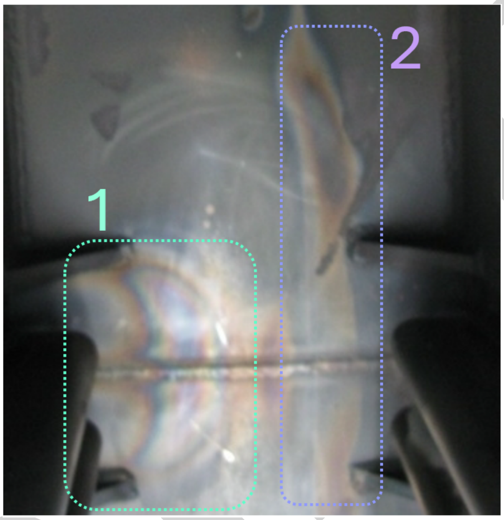


Figure 4: Discolouration of the inside of the flat-top cavity where colloidal graphite had been applied.

In these PIC simulations, seed electrons, those that trigger the multipacting, were placed in regions where multipacting was expected to occur. The region in question was known due to discolouration observed on the surface where colloidal carbon was applied. However, in the absence of visible marks such regions of interest include local field magnitude minima where particles can be trapped through ponderomotive forces [5]. The surface of the cavity is then assigned a SEY based on representative metallic surface properties. The SEY curve was also varied to understand its impact on multipacting as the exact SEY response curve of the surface was unknown and expected to vary over time as the colloidal graphite was removed from the surface due to high power operation. Finally, the PIC simulations had the option to include external magnetic fields originating from the cyclotron sector magnets, which permeate the cavity volume and influence electrons' trajectories. Figure 2 overviews this multipacting simulation process.

The PIC simulation tracks the motion of the initial seed electrons and secondary emission electrons under the influence of RF and magnetic fields. Figure 3 demonstrates the steady-state multipacting patterns for two separate situations where multipacting is expected to occur. We define the steady-state solution as the state where multipacting growth has occurred and eventually saturates leading to a constant number of electrons in the system.

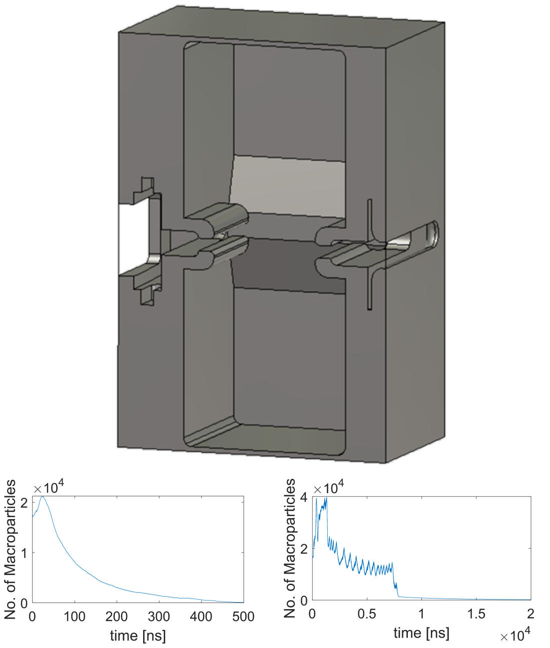


Figure 5: Mitigation of multipacting through a modified backplane.

The first simulation case is that where the fields from the local sector magnet are not included. We observe a strong crescent-shaped distribution in the region between the electrodes and the cavity wall, the region of a local field minimum. This crescent-shape strongly matches the discolouration observed in the cavity (labelled 1 in Fig. 4). For Case 2, which includes the local magnetic fields of the sector magnet, we see that the electrons now migrate away from the region causing a vertical stripe. Similar to Case 1, Case 2 was also observed in the image of the surface discolouration (labelled 2 in Fig. 4). The choice of these two cases was due to each being where the two systems were most expected to operate. With qualitative confirmation of the simulation methodology, this allowed us to move towards mitigation strategies and using the PIC simulations to steer the design of the cavity, in particular the regions where multipacting was known to occur.

## MITIGATION STRATEGIES

Mitigating multipacting is essential for reliable operation of the upgraded flat-top cavity at higher beam currents and RF power levels. To suppress this effect, investigations of a modified cavity geometry were performed where the gap between the cavity wall and electrodes was reduced through adding a local bump in the region. This aimed to reduce the field minimum with the aim of disrupting the resonance electron trajectories or, more specifically, mitigating ponderomotive forces of electrons into regions where secondary electron emission occurs.

Particle-in-cell simulations of the modified geometry showed strong suppression of multipacting in the absence of external magnetic fields (Fig. 5). In our simulation, it took less than 100 RF periods to completely remove all particles from the system.

When the magnetic fields from the nearby sector magnets were included, the suppression of multipacting remained but was less pronounced as the magnetic field partially confined the electrons. Nevertheless, the electrons gradually migrated away from the region at a given point reaching a region where secondary emission could no longer be triggered. This point is seen as the strong drop in particles after approximately 7 µs (Fig. 5).

In addition to geometric optimisation there are other mitigation strategies possible. These include reducing the secondary electron yield (SEY) of the device. Through surface conditioning or coatings including colloidal graphite, one can reduce the SEY. Additionally, choice of cavity material is also crucial with materials such as copper having low SEY. Such surface considerations provide complementary strategies to mitigate multipacting.

## CONCLUSION

Particle-in-cell simulations have been used to investigate multipacting in the 150 MHz flat-top cavity of the HIPA Ring Cyclotron. The simulations reproduced stable resonant electron trajectories in regions consistent with the observed surface discolouration and localised heating inside the cavity, providing strong evidence that multipacting is responsible for the anomalous power absorption and operational limitations reported during long-term operation.

The study also demonstrated the important influence of the external magnetic fields from the nearby sector magnets on the multipacting dynamics, significantly modifying the electron trajectories and resulting impact regions. Guided by the simulation results, a modified cavity geometry was investigated in which the local field minimum near the backplane was reduced through a modification of the cavity wall. Simulations of the modified geometry showed strong suppression of multipacting under nominal operating conditions, with complete removal of electrons in the absence of external magnetic fields and substantial mitigation when magnetic fields were included. These results demonstrate that particle-in-cell simulations provide an effective tool for identifying and mitigating multipacting in CW normal-conducting RF cavities.

## REFERENCES

[1] J.-Y. Raguin *et al.*, “Progress in the Design of a New 150-MHz Flat Top Cavity for the PSI Ring Cyclotron”, in *Proc. Cyclotrons'22*, East Lansing, MI, USA, pp. 241–243, 2022. doi:10.18429/JACoW-CYCLOTRONS2022-WEPO018

[2] A. Lüdeke, A. C. Mezger, M. Schippers, and M. Seidel, “Operation of the PSI Accelerator Facilities 2013”, PSI, Villigen, Switzerland, 2014. https://www.psi.ch/sites/default/files/import/gfa/FacilityOperationReportsEN/Operation_of_the_PSI_Accelerator_Facilities_2013.pdf

[3] F. Armborst *et al.*, “Operation of the PSI Accelerator Facilities 2022”, PSI, Villigen, Switzerland, 2022. `https://www.psi.ch/de/media/81412/download?attachment`

[4] Dassault Systems, CST Studio Suite, SIMULIA, Dassault Systems, 2025. `https://www.3ds.com/products/simulia/cst-studio-suite`

[5] M. A. Gaponov and V. I. Miller, “Potential Wells for Charged Particles in a High-Frequency Electromagnetic Field”, *Soviet Physics JETP*, vol. 7, pp. 168–169, 1958.