ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-MOPA59

PREDICTION OF GASEOUS BREAKDOWN FOR PLASMA CLEANING OF RF CAVITIES*

S. Ahmed†, Electronics Business Unit, Ansys Inc., San Jose, CA, USA

Abstract

This paper describes the workflow of RF discharge physics implemented in HFSS and illustrates its application to an accelerating cavity. The workflow can be directly applied to multi-cell structures in a complex setting. The entire simulation can be executed in a single run. Full-wave electromagnetic simulations can be performed in HFSS using the modal or terminal solution; the time-domain simulation then takes over to predict the onset of gaseous breakdown. The accuracy and robustness of the simulation can be guaranteed through the full-wave FEM solution in an unstructured mesh and the temporal evolution of plasma density.

INTRODUCTION

With the current state of the art, radiofrequency (RF) cavities are most employed for accelerating electrons (or ions) to achieve high-energy particles for exploring the fundamental nature of the universe [1]. These cavities undergo various steps to qualify the high performance in terms of accelerating gradient, quality factor, etc [2]. However, the performance gradually degrades over the period of use, and hence cleaning such cavities is necessary [2]. The normal procedure adopted in the qualifying stage of the cavity cannot be applied for in-situ cleaning inside the accelerator facility [2]. For in-situ cleaning, the gas processing method known as "helium processing" is commonly used at a cold temperature where the partial pressure of helium gas is much below the breakdown threshold. This technique is a random local ionization process, which may adversely affect cavity performance [2]. Plasma cleaning has been adopted in various accelerator facilities for the removal of surface impurities and contaminants [2, 3].

In plasma cleaning, an ionization discharge of gases inside the cavity volume is induced by the RF or microwave electromagnetic (EM) fields. The development of a procedure for plasma cleaning requires a detailed investigation toward establishing a plasma discharge inside the cavity. Generating an efficient plasma inside a complex cavity structure for a desired frequency and gas type for a given temperature and pressure is challenging. Setting up an experiment is expensive and time-consuming, which may lead to a significant delay in the project. A high-fidelity computer simulation, modeling an arbitrary three-dimensional geometry for tracking the plasma discharge in a complex electromagnetic environment is therefore necessary. Ansys HFSS through its Finite Element Mesh (FEM) for the full-wave EM simulations combined with the electron impact ionization of gases enables the successful prediction of plasma breakdown for an arbitrary configuration for a wide frequency band and gases. The RF discharge analysis feature has been integrated into the Ansys electronics desktop (AEDT); full-wave electromagnetic and RF discharge simulations can be set up in the same design. The breakdown threshold predicted by the solver helps users determine the RF power and gas pressure at a given temperature for any complex configuration. Therefore, the RF discharge package can be reliably used for the onset prediction of plasma discharge for plasma cleaning as well as the safe operation of helium processing.

MODEL DESCRIPTION

For purposes of illustration, we have selected an RF cavity, however, the workflow can be directly applied to any other structure. The RF discharge simulation in HFSS can be combined with the RF design performed either in the "modal" or "terminal" solution type.

RF Simulation

The model illustrated in Fig. 1 has been set up for the "modal" solution type. The RF power has been fed into the cavity using a co-axial feed through the beam pipe and the dual orthogonal modes are excited simultaneously. The RF modeling has been performed for 1 W of input power, which can be simply scaled for any desired power after the execution of the simulation.

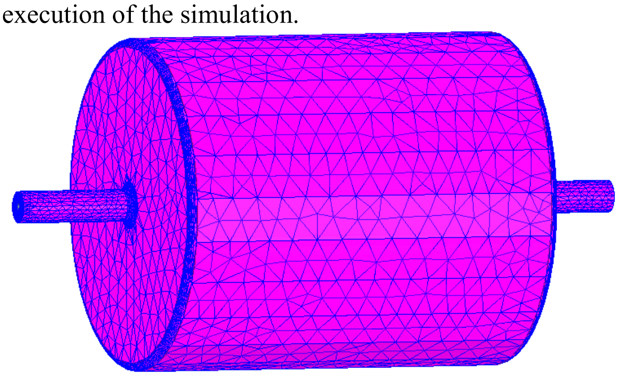

Figure 1: A schematic of the cavity used in the model for operation at 550 MHz.

Figure 2(a-d) shows four eigenmodes excited inside the cavity. The fundamental mode is depicted in Fig. 2a, which represents the accelerating mode. The remaining modes illustrated in Fig. 2(b-d), correspond to the higher-order modes (HOM); the degenerate modes are indeed indicated in Fig. 2(c-d). These eigenmodes due to different EM configurations can create ionization breakdown at different locations and hence play a critical role in the overall cleaning procedure development.

* Work supported by the Electronics Business Unit of Ansys, Inc.
† shahid.ahmed@ansys.com

ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-MOPA59

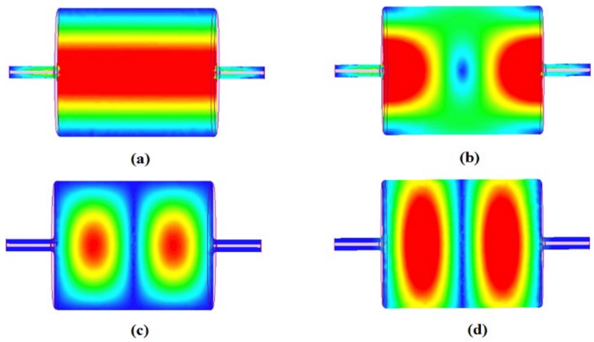

Figure 2: Sub figures (a-d) shows electric field distributions of four modes excited inside the cavity at about 549.82 MHz, 626.7 MHz, 732.44MHz, and 732.47 MHz, respectively.

RF Discharge Simulation

The RF discharge simulation in HFSS is based on the impact ionization of electrons with the ambient gas. Therefore, the details of gas breakdown physics have been taken into consideration. A full-time-domain continuity equation governing the evolution of electron density $n(r,t)$ has been solved:

$$\frac{\partial n(r,t)}{\partial t} = D\nabla^2 n(r,t) + (\nu_i - \nu_a)n(r,t)$$

where the diffusion coefficient (D), ionization coefficient (ν_i), and attachment coefficient (ν_a) are the functions of the electric field.

The RF discharge simulation in HFSS can be performed in the “modal” or “terminal” solution type. A set of discrete frequencies can be defined for predicting the ionization breakdown of gases for multiple frequencies. HFSS offers a convenient workflow for the RF discharge simulation together with the RF simulation in the same design. This means there is no need to perform manual import of data from the EM model to the RF discharge model. There are many built-in gases, however, the users can import their own gas parameters. A GUI-based RF discharge analysis setup helps users define the operating parameters such as RF power, gas pressure, gas temperature, etc. Once the setup for RF discharge analysis is completed, we can analyze all. The RF discharge simulation starts automatically as soon as the execution of the RF simulation finishes. The users can start visualizing the simulation output during the run process because the RF discharge analysis is performed in the time domain.

Figure 3 shows the breakdown prediction for gases (He, Ar, H2, N2) at room temperature for the accelerating mode depicted in Fig. 2(a). These curves can be used to predict the RF power required for the corresponding gas pressure.

Figure 4 shows the breakdown curves for Ar gas for frequencies 550 MHz, 627 MHz, and 733 MHz, respectively at room temperature. We observe that higher frequencies require higher RF power to cause the breakdown. This is because the efficiency of energy transfer from the RF EM wave to the electrons is inversely proportional to the frequency. Another important point to note is that all the four modes illustrated in Fig. 2 are excited at 733 MHz, so the discharge at 733 MHz is a multimodal RF breakdown.

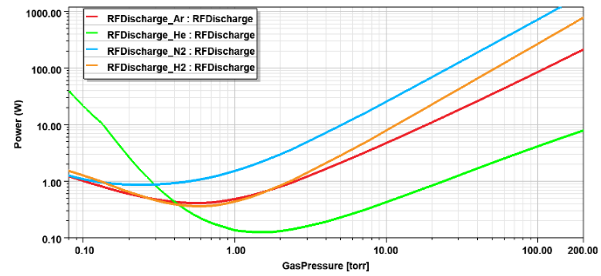

Figure 3: Paschen curve showing the breakdown of gases at room temperature corresponding to the accelerating mode (see Fig. 2(a)).

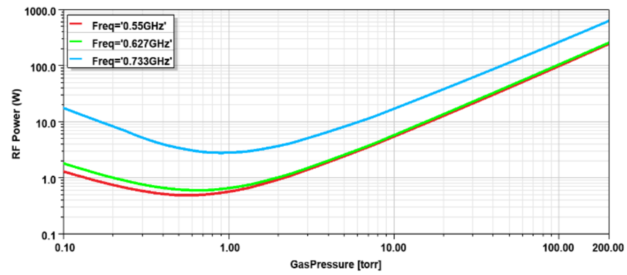

Figure 4: RF breakdown prediction for Ar gas for frequencies 550 MHz, 627 MHz, and 733 MHz, respectively at room temperature.

CONCLUSION

In this paper, the application of AEDT for the successful prediction of plasma discharge inside an arbitrary cavity structure has been outlined. The RF discharge feature of HFSS can be used to minimize the human effort in developing the procedure for plasma cleaning. Having a complete physics module in a single computer code is an advantage. The accuracy and robustness of the simulation can be assessed through the accurate extraction of EM fields in an unstructured mesh and tracking of the swarm of particles (electrons/ions) for the ionization process.

ACKNOWLEDGMENTS

This manuscript has been supported by the electronics business unit of Ansys, Inc. The author likes to thank Hsueh-Yung Chao for his noteworthy contributions to the RF breakdown physics in HFSS and his valuable support.

REFERENCES

[1] S. Ahmed *et al.*, “Beam dynamics studies for transverse electromagnetic mode type rf deflectors,” *Phys. Rev. Accel. Beams,* vol. 15, p. 022001, Feb. 2012. doi:10.1103/PhysRevSTAB.15.022001

[2] S. Ahmed and J. D. Mammosser, “Microwave induced plasma discharge in multi-cell superconducting radio-frequency cavity,” *Rev. Sci. Instrum.,* vol. 86, no. 7, p. 073303, Jul. 2015. doi:10.1063/1.4923295

[3] P. Berrutti *et al.,* “Plasma ignition and detection for in-situ cleaning of 1.3 GHz 9-cell cavities,” *J. Appl. Phys.*, vol. 126, p. 023302, Jul. 2019. doi:10.1063/1.5092235