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RF AND MULTIPACTOR SIMULATIONS IN THE PLASMA CHAMBER OF THE SILHI PROTON SOURCE

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Abstract

In the scope of high current protons sources simulations, we tried to simulate the plasma chamber of the SILHI proton source with HFSS. This work focuses on the RF and multipactor simulation close to the boron nitride window.

INTRODUCTION

The CEA Saclay develops and produces ECR sources for various projects. In particular, several sources have been developed for high-intensity proton and/or deuteron beams, as the SILHI and ALISES sources. Currents typically vary between 5 mA (Spiral 2) to 125 mA (IPHI, IFMIF), and several test benches have been assembled, BETSI and PACIFICS, to analyse these sources [1].

ECR sources, in general, require the production of electrons, which, by interacting with the molecules and ions of the gas, produce the ions beam. Part of these electrons are produced by a dielectric window, (here made of boron nitride), possessing very high primary and secondary electron emission coefficients [2].

Electron production is certainly mainly due to secondary emission. Among the different processes that generate secondary emission, the multipactor, under certain conditions, can be one of them. It has been widely described for example on the ceramic windows of high-power RF couplers [3]. The objective for RF couplers is in principle to minimize this phenomenon. Here, we try to show that the multipactor can affect the production of electrons at the ceramic level of an ECR source.

For this, we have simulated the RF field on the boron nitride, in order to describe the field at the dielectric level. Then, we tried, based on some analytical calculations, to estimate the best conditions to get (or to do not get) multipactor.

ABOUT MULTIPACTOR

The multipactor is a potential source of secondary electrons in ECR sources, and Boron Nitride (BN) has a high secondary emission coefficient [2]. So, the primary electrons produced by the BN ceramic can themselves produce new electrons, if their trajectory brings them back on the ceramic.

The primary and secondary electrons follow a trajectory defined by the RF electromagnetic field at 2.45 GHz, at the time of their appearance (or their initial phase), as well as by the external magnetic field. If the kinetic energy of the primary electron acquired thanks to the RF field is sufficient, secondary electrons can be produced.

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The ionization energy (or gap energy) of 5.8 eV for H-BN (Hexagonal) [4] gives an estimate of the minimum energy to produce secondary electrons.

Moreover, if an electron comes back after an whole number of RF periods, the secondary electron starts with the same phase, and thus, follows the same trajectory, and the phenomenon continues indefinitely. The number of electrons increases exponentially until reaching saturation, which depends on the available electrons, the available RF power, and the space charge generated. This phenomenon was known as multipactor.

To test our hypothesis, we modeled the distribution of electromagnetic fields in the cavity with HFSS software and identified potential areas producing multipactor. An analysis of the electron trajectory near the window is proposed.

HFSS SIMULATION

These simulations were realised with the HFSS software. We reproduced the cavity of the plasma chamber of the SILHI source, measuring 45 mm in radius and 100 mm in length, and the boron nitride plate with a thickness of 2 mm. The coupler of SILHI was simulated with its three ridges.

The waveguide was modelled by a 550 mm long line. The ATU (Automatic Tunning Unit) was modelled by a single piston that modifies the coupling of the ECR cavity.

We have calculated the electric field on the BN for several position of piston. For each position of the piston, we have modified its penetration to adapt the cavity by minimizing the reflected power. The frequency remained close to 2.45 GHz ± 100 MHz.

To realize the simulation, we defined a port in TE10 mode at the extremity of the waveguide. In a perfect cylinder in the TE mode theory, the electric field is only axial. Here, due to the coupler, the electric field on the longitudinal axis is not zero on the boron nitride window.

The simulation was made for different distances between the piston and the RF cavity, to observe how the piston position affects the RF field on the window. All field patterns are presented at the resonance frequency of the ensemble, which always remains close to 2.45 GHz.

Figures 1 and 2 show that the electric field at the center of the window is very intense (281 kV/m) at 335 mm, but becomes less intense (11.4 kV/m) when the piston position was at 410 mm, for an injected power of 50 W at the extremity of the waveguide. It seems reasonable to imagine that the multipactor acts differently in both cases.

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During our experiments with SILHI, we observed that the minimal power to see some "pink" light in the H source was around 50 W. It shows that there are interactions between electrons and gas, even without current emission

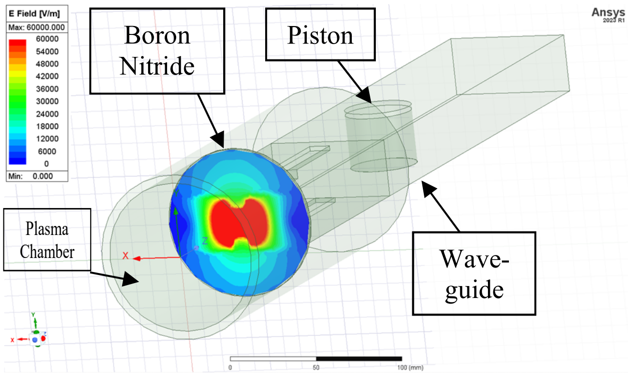

Figure 1: Visualization of E-field at the center of the window for a piston position of 335 mm.

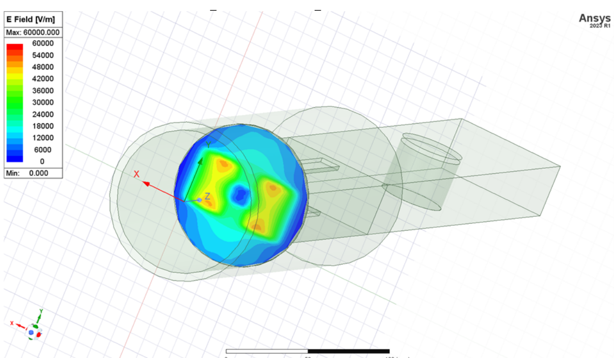

Figure 2: Visualization of E-field at the center of the window for a piston position of 410 mm.

SIMULATION OF THE ELECTRON TRAJECTORY CLOSE TO THE CERAMIC

The general equation of motion of an electron of mass m and charge q in presence of an electromagnetic field is

$$m\frac{d^2}{dt^2}\begin{bmatrix}x\\y\\z\end{bmatrix} = q\left(\begin{bmatrix}E_{rf,x}\\E_{rf,y}\\E_{rf,z}\end{bmatrix} + \begin{bmatrix}0 & B_z & -B_y\\-B_z & 0 & B_x\\B_y & -B_x & 0\end{bmatrix}\frac{d}{dt}\begin{bmatrix}x\\y\\z\end{bmatrix}\right),$$

in our case, the magnetic field $B_{x,y,z}$ includes a DC and an RF component: $B_{x,y,z} = B_{0,x,y,z} + B_{rf,x,y,z}$. While the electric field has only an RF component $E_{x,y,z} = E_{rf,x,y,z}$. The z axis is the longitudinal axis, and the x axis is the radial axis where E_{rf} is maximal in average. φ defines the initial phase between the electron and the electric RF fields in the resonant cavity

$$E_{rf,i} = E_{1,i}\cos(\omega t + \varphi),$$
$$B_{rf,i} = -B_{1,i}\sin(\omega t + \varphi).$$

We therefore have a first-order differential equation in $\frac{d}{dt}\begin{bmatrix}x\\y\\z\end{bmatrix}$, with constant and sinusoidal terms. The general analytical solution to this type of equation is not developed here.

If B_0 is oriented along the z axis, and E_1 along the x axis, if $\omega \neq \omega_c = \frac{qB_z}{m}$, and the initial speed is zero, the analytical solution is given by

$$\frac{d}{dt}\begin{bmatrix}x\\y\\z\end{bmatrix} = \begin{bmatrix}\cos(\omega_c t) & \sin(\omega_c t) & 0\\-\sin(\omega_c t) & \cos(\omega_c t) & 0\\0 & 0 & 1\end{bmatrix}\begin{bmatrix}C_x\\C_y\\C_z\end{bmatrix} +$$
$$\frac{a_c}{\omega^2-\omega_c^2}\begin{bmatrix}\omega\sin(\omega t+\varphi)\\\omega_c\cos(\omega t+\varphi)\\1\end{bmatrix},$$

with $a_c = \frac{q \cdot E_0}{m}$, and C_x, C_y, C_z are integration constant.

In normal conditions, at $t = 0$, the velocity is close to the electron's thermal velocity, which is given by

$$\sqrt{< V_{th}^2 >} = \sqrt{\frac{3k_BT}{m}} = 115\,000\ \mathrm{m.s^{-1}}.$$

The corresponding kinetics energy is 0.038eV.

In this specific case, the speed along the z axis is constant, thus, primary electrons cannot go back and there is no multipactor. This is the "perfect case", where the B field is longitudinal and the E field is transverse.

However, in an imperfect case, where the longitudinal electric and transverse magnetic fields are different from zero, the multipactor phenomenon can appear.

In this case, the longitudinal electric field tends to accelerate electrons on the z-axis, and the rotation plan of the electrons is not parallel to the window anymore.

The magnetic field for simulations is $B_{0,z} = 78.75$ mT (90% of the ECR magnetic field, 87.5 mT @ 2.45 GHz). The value of the electric field $E_x = 300$ kV/m corresponds to figure 1. Then we applied an x component to the magnetic field $B_{0,x} = 23.3$ mT and a small z component to the electric field $E_z = 10$ kV/m to force multipactor.

Figure 3(abc) shows the results along x, y and z axes at different phases. Figure 3c shows that, for a phase $\varphi = 1.1220$ rad, the electron hits the wall after exactly one RF period. The dotted lines represent also the trajectory of electron. Figure 4 shows that the speed of the electrons after one period was around 10 000 km/s. This correspond to an energy about 310 eV, enough for secondary emission.

This demonstrates that, in these conditions, multipactor is likely to appear.

EXPERIENCES WITH SILHI [5]

We have carried out some experiments with the SILHI source to observe the influence of the pistons position on the beam generation.

We have used the following components (see Figure 5): a 2.45 GHz magnetron (1) and its circulator (2), several waveguides with different lengths (3), a bidirectional coupler (4), a 3-pistons ATU (5), a 3-pistons MTU (6) and the SILHI source (7).

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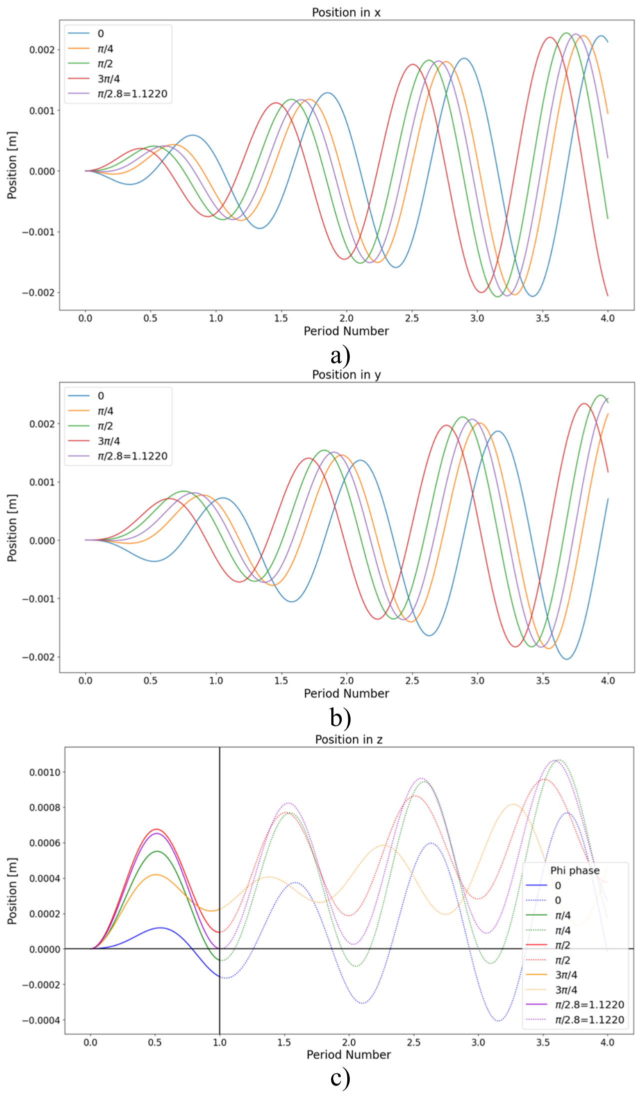

Figure 3: Electron positions in x, y and z as a function of the number RF periods. If the electron hits the window after 1 period, multipactor can appear.

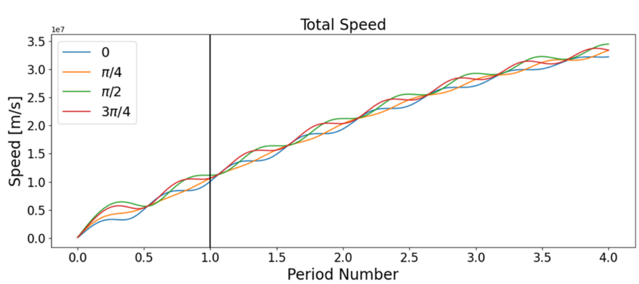

Figure 4: Total speed as a function of period number.

We minimized the reflected power with presence of plasma with the ATU for different configurations of the MTU (Manual Tunning Unit). Figure 6 shows an example of beam current exiting the cavity.

We observed that the required power to launch the source could vary significantly from one configuration to another – from 450 W to 900 W, to get a stable beam – for the same reflected ratio. In some configurations, the source did not work at all.

We also observed that, in some cases, having an inhomogenous B field (there are two coils that can be separately driven with current sources), with a radial component, reduced the required input RF power.

This does not demonstrate that the multipactor comes into play, but it at least shows that the shape of the RF field on the boron nitride wall could be critical.

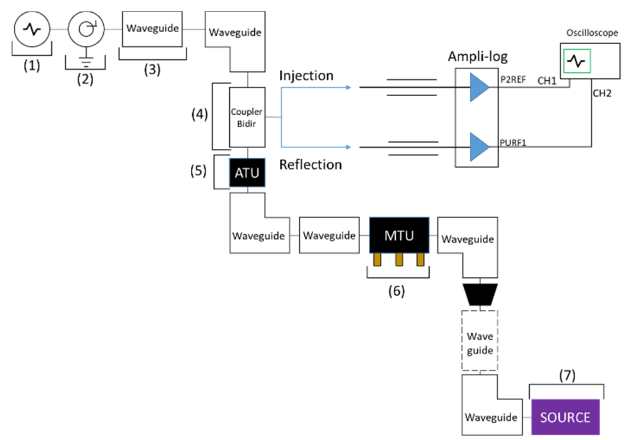

Figure 5: Diagram of the SILHI source test.

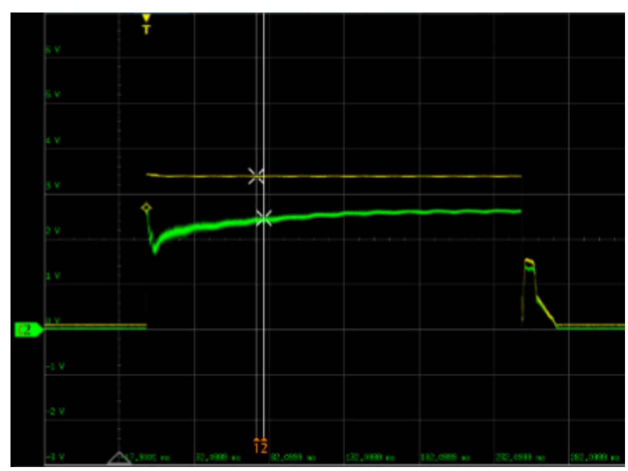

Figure 6: Magnetron pulse gate (yellow signal). Beam current (green signal). Time abscissa is 50 ms per division. Arbitrary ordinate unit.

CONCLUSION

Thanks to the simulations realised with HFSS, we were able to show that the electric field on the boron nitride can greatly vary with the source settings. The analysis showed that this could affect the appearance of multipactor on the window.

Indeed, we observed experimentally with the SILHI source that the position and adjustment of the ATU and MTU have a significant impact on the required RF power.

The next step will be to develop a source, with potentially different window geometries, targeting to maximize the multipactor in simulation and observe the effect on the ion beam.

REFERENCES

[1] O. Tuske, G. Adroit, O. Delferrière, D. De Menezes, Y. Gauthier, "BETSI, a new test bench for ion sources optimization at CEA SACLAY," *Rev. Sci. Instrum.*, vol. 79, no. 2, Feb. 2008. doi:10.1063/1.2805625

[2] L. Huang and Q. Wang, "Study on Secondary Electron Yield of Dielectric Materials," *J. Phys. Conf. Ser.*, vol. 2433, no. 1, p. 012002, Feb. 2023. doi:10.1088/1742-6596/2433/1/012002

[3] G. Devanz, "Multipactor simulations in superconducting cavities and power couplers," *Phys. Rev. Spec. Topics - Acc. Beams*, vol. 4, no. 1, Jan. 2001. doi:10.1103/physrevstab.4.012001

[4] M. J. Powers and M. C. Benjamin, "Observation of a negative electron affinity for boron nitride," *Appl. Phys. Lett.*, vol. 67, no. 26, pp. 3912–3914, Dec. 1995. doi:10.1063/1.115315

[5] R. Gobin, P.-Y. Beauvais, D. Bogard, G. Charruau, O. Delferrière, D. De Menezes, A. France, R. Ferdinand, Y. Gauthier, F. Harrault, J.-L. Jannin, J.-M. Lagniel, P.-A. Leroy, P. Mattéi, A. Sinanna, and J. Sherman, "High intensity ECR ion source (H+, D+, H−) developments at CEA/Saclay," *Rev. Sci. Instrum.*, vol. 73, no. 2, pp. 922–924, Feb. 2002. doi:10.1063/1.1428783