Simulation of Secondary Electron Emission with CST PARTICLE STUDIO™

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Abstract

In accelerator physics and high power vacuum electronics the secondary electron emission (SEE) has in many cases an important influence on the physical behavior of the device. Since its analytical prediction even for simple geometries is extremely cumbersome, numerical simulation is essential to obtain a better understanding of the possible effects and ideas to change the design. The current paper introduces the implementation of SEE within the code CST PARTICLE STUDIO™, which is an easy to use three dimensional tool for the simulation of electromagnetic fields and charged particles.

There are three basic types of secondary electrons, the elastic reflected, the rediffused and the true secondary ones. The implemented SEE model is based on a probabilistic, mathematically self-consistent model developed by Furman and includes the three kinds of secondary electrons mentioned above. The paper presents simulation results with focus on the SEE for the absorbed power within an electron collector of a high power tube. As a second example the secondary emission process is studied within the superconducting TESLA cavity which gives some hints for the understanding of multipactor effects in those cavity and filter structures.

INTRODUCTION

CST PARTICLE STUDIO™ is a software tool for the design and analysis of 3D electromagnetic components for accelerating and guiding charged particles beams. To calculate electromagnetic fields, magnetostatic, electrostatic, eigenmode and wakefield solvers are included in this software package. As all particles can be emitted from rounded surfaces, it is not possible to use a staircase approximation. Instead, our calculations are based on the perfect boundary approximation PBA®. However, the particle tracking is based on the conventional leap-frog algorithm:

$$\mathbf{r}^{n+3/2} - \mathbf{r}^{n+1/2} = \Delta t \mathbf{v}^{n+1} \quad (1)$$

$$m^{n+1}\mathbf{v}^{n+1} - m^n \mathbf{v}^n = \Delta t \left(\mathbf{E}^{n+1/2} + \mathbf{v}^{n+1} \times \mathbf{B}^{n+1/2}\right) \quad (2)$$

In order to take care of dark currents and multipacting effects, the secondary electron emission must not be neglected. These effects have both a parasitic influence on the heating of the device, on the fields and thus on the particle movement. If the worst comes to the worst, the multipacting effect can destroy the device. The workflow of the implemented secondary emission model can be described as follows:

1. Check for each timestep whether an electron collides with solids or faces of the device.
2. If an electron collides, use the implemented, probabilistic emission model [1] to calculate number of secondary electrons and the kind of emission, i.e. elastic, rediffused or true secondary.

As the collision check is based on triangulated surface and triangle-trajectory intersection, it can be a very time-consuming algorithm. To optimize this process, our collision detection uses an axis-aligned bounding box (aabb) test to calculate the intersection.

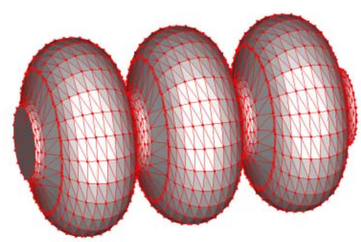

Figure 1: Triangulated surface for the collision detection model.

The well-known parameter to describe the SEE is the secondary electron yield (SEY) or coefficient, which is defined as the quotient of the incident and the secondary or emitted current $\delta = I_s/I_0$. As the detailed physical process is very complex, the SE model used in CST PARTICLE STUDIO™ to calculate the SEY is a statistical model which is based on random numbers (monte carlo) for the emission angle and the kind of emission.

MODEL

The secondary emission model used in CST PARTICLE STUDIO™ is based on a probabilistic, mathematically self-consistent theory by developed Furman and Pivi[1]. There are three basic types of secondary electrons, the elastic reflected, the rediffused and the true secondary ones.

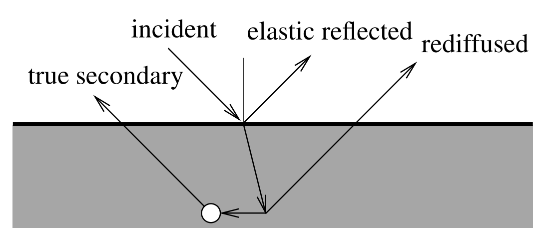

Figure 2: Different types of secondary electrons.

To change model parameters for each type of the secondary electrons, a program interface is implemented, that allows the number of secondary electrons to be specified which one source electron is able to produce. It is also possible to set the maximum number of secondary electron generations and to change the material parameters of the default materials. Thus we require, that our probabilistic model should be material based, energy and angle dependent. Of course, the fulfillment of basic conservation laws should be guaranteed by the model itself, e.g. that the energy of emitted electrons should not exceed the energy of the primary electron.

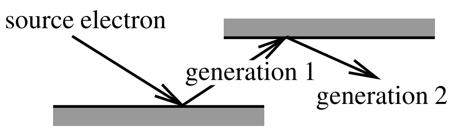

Figure 3: Generation model for secondary electrons.

The emitted secondary electrons are characterized by their probability distribution functions PDF's [1]. The PDF for the elastic reflected electrons is Gaussian chosen:

$$f_{1,\mathrm{e}}(E) = \theta(E)\theta(E_0 - E)\delta_\mathrm{e}(E_0,\theta_0) \times \frac{2\exp\left(-(E-E_0)^2/\left(2\sigma_\mathrm{e}^2\right)\right)}{\sqrt{2\pi}\sigma_\mathrm{e}\mathrm{erf}\Big(E_0/\left(\sqrt{2}\sigma_\mathrm{e}\right)\Big)} \quad (3)$$

Integration of the PDF over energy E yields the secondary emission yield which is defined here as:

$$\delta_\mathrm{e}(E_0,\theta_0) = \delta_\mathrm{e}(E_0,0)\left[1 + e_1(1-\cos^{e_2}\theta_0)\right] \quad (4)$$

$$\delta_\mathrm{e}(E_0,0) = P_{1,\mathrm{e}}(\infty) + \left[\hat{P}_{1,\mathrm{e}}(\infty) - P_{1,\mathrm{e}}(\infty)\right] \times \exp\left(-\frac{|E_0 - \hat{E}_\mathrm{e}|^p}{pW^p}\right) \quad (5)$$

The secondary emission yield (SEY) δ_e is dependent of the incident energy E_0 and angle θ_0. All other parameters are material parameters which are based on fitting and measurements.

The rediffused electrons are described in an analog way but the PDF is chosen as exponential distribution:

$$f_{1,\mathrm{r}} = \theta(E)\theta(E_0 - E)\delta_\mathrm{r}(E_0,\theta_0)\frac{(q+1)E^q}{E_0^{q+1}} \quad (6)$$

The angle dependency behaves in the same way as the dependency for the elastic reflected electrons:

$$\delta_\mathrm{r}(E_0,\theta_0) = \delta_\mathrm{r}(E_0,0)\left[1 + r_1(1-\cos^{r_2}\theta_0)\right] \quad (7)$$

$$\delta_\mathrm{r}(E_0,0) = P_{1,\mathrm{r}}(\infty) + \left[1 - \exp\left(-(^{E_0}/_{E_\mathrm{r}})^r\right)\right] \quad (8)$$

The probability $P_{n,\mathrm{ts}}$ for the true secondary electrons is chosen to be binomially distributed. Only due to true secondary emission more than one, namely M electrons, can be emitted during on electron-wall interaction:

$$f_{n,\mathrm{ts}} = \theta(E)F_n E^{p_n-1}\exp(-E/\epsilon_n) \quad (9)$$

$$F_n^n = \frac{P_{n,\mathrm{ts}}(E_0)}{\left[\epsilon_n^{p_n}\Gamma(p_n)\right]^n P(np_n, E_0/\epsilon_n)} \quad (10)$$

$$\delta_\mathrm{ts}(E_0,\theta_0) = \hat{\delta}(\theta_0)D\big(E_0/\hat{E}(\theta_0)\big) \quad (11)$$

$$\hat{\delta}(\theta_0) = \hat{\delta}_\mathrm{ts}\left[1 + t_1(1-\cos^{t_2}\theta_0)\right] \quad (12)$$

$$\hat{E}(\theta_0) = \hat{E}_\mathrm{ts}\left[1 + t_3(1-\cos^{t_4}\theta_0)\right] \quad (13)$$

$$D(x) = \frac{sx}{s-1+x^s} \quad (14)$$

The function $D(x)$ is a weighting function for the secondary yield that allows good fitting of the measured data.

At each particle-wall interaction detailed collision information is calculated, i.e. current, energy and power. If one needs additional information about the particle/trajectories so-called particle monitors can be defined.

DEPRESSED ELECTRON COLLECTOR

The depressed electron collector is a device for collecting electrons in such way that the surface is not damaged by high energetic electrons. This is possible as the electrons are decelerated by an electric field before they reach the collector's surface and collide.

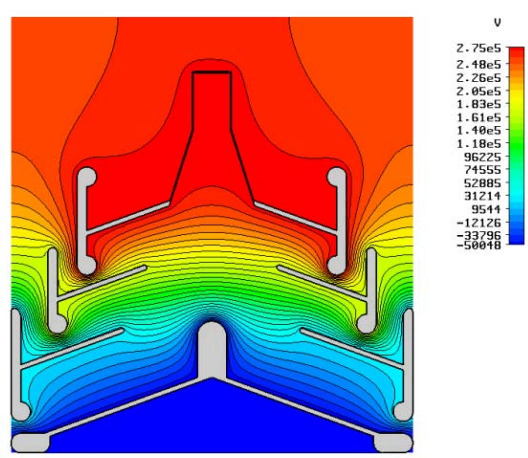

Figure 4: Potential field of the depress collector.

Our simulation result for an incident beam with 275 MeV (figure 5) shows a good agreement with a simulation made by van der Geer and de Loos[2]. The small differ-

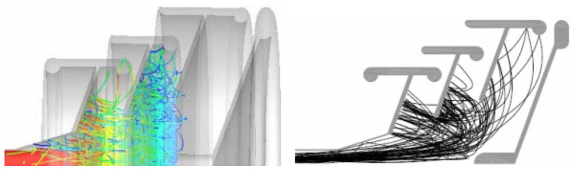

Figure 5: Trajectories of an electron collector with incident beam energy of 275 MeV compared to a simulation of van der Gerr and de Loos.

ences in the trajectories can be traced back to the different device and/or potentials.

In another example two simulation results for the depressed collector [2] are compared in order to analyze the influence of the secondary electrons on the absorbed/emitted current and power. During the first simulation the secondary emission is disabled, whereas in the second simulation the secondary emission is active. The

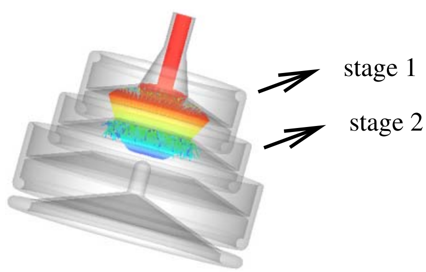

Figure 6: Trajectories of the simulated depressed electron collector.

incident beam in our simulation has a fixed energy of 250 keV and a current of 12 A. To analyze the simulation results, a total current and total power are introduced. They

surface	current in A		power in MW	
	incident	emitted	incident	emitted
stage 1	2.629	0	0.660	0
stage 2	9.371	0	1.360	0
stage 1	8.819	4.417	1.602	0.580
stage 2	18.260	10.680	1.978	0.795

Table 1: Emission and incident magnitudes for a depressed electron collector.

are defined as incident (or absorbed) minus emitted current/power. The total current is equal to 12 A in both cases as it should be. Whereas the total power has an increase of 10% in the simulation with secondary emission compared to the one without. This increase can be attributed to the fact that the secondary electrons are accelerated by the electric field. Thus the secondary emission is a heating process for the depressed collector, here especially for stage 1.

TESLA CAVITY

The TeV-Energy superconducting linear accelerator (TESLA) cavity is a device to for accelerating particles. Due to secondary electron emission there is a parasitic effect called multipacting. Two-point multipacting means

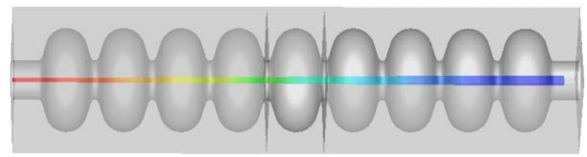

Figure 7: Accelerating particles in a TESLA cavity. The velocity of the particles is nearly speed of light.

that a lot of secondary electrons trace periodically between the two sides of one TESLA cell, see also figure 8. This can lead to thermal damage of the device and/or to noise fields. In our simulation we show the multipacting effect exemplarily for one single electron. Thus a single source electron with an emitting energy of 40 eV is placed close to the equator of one TESLA cell. The eigenmode at 1.3 GHz is used as electro-magnetic source. The peak of the electric field is chosen to be 45 MV/m.

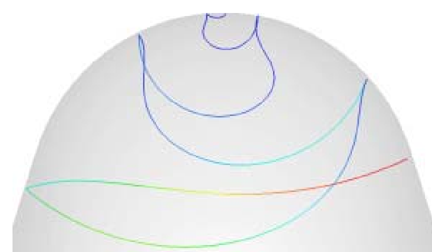

Figure 8: Two-point multipacting trajectories caused by one primary electron. The scattering angle is a statistically distributed magnitude.

The results show that the multipacting effect can be calculated with the probabilistic model we use. The time the electron needs to move from one side of the cell to the other takes a half periodic time of the eigenmode. At the termination point of the trajectory the electron has an energy of a few MeV. During these simulations we also figured out that accurate emission parameters are very important to obtain realistic simulation results.

SUMMARY AND OUTLOOK

A secondary electron emission model based on Furman and Pivi[1] is successfully implemented in CST PARTICLE STUDIO$^{\mathrm{TM}}$. Thus the multipacting effect (two-point and one-point) in a TESLA cavity can be calculated. It could be also shown that the secondary electron emission is a heating mechanism for the depressed electron collector. However, as mentioned above, well-known emission parameters are very important. Therefore measurements for various materials are needed to calculate the fitting parameters for the emission model.

For the future a post processing analysis of the secondary electron emission heating with a thermal solver is planned.

REFERENCES

[1] M.A. Furman and M.T.F. Pivi. Probabilistic model for the simulation of secondary electron emission. Physical Review Special Topics, Accelerators and Beams, Volume 5. 2002.

[2] M.J. de Loos, S.B. van der Geer. The general particle tracer code applied to the fusion free-electron maser. Nucl. Instr. and Meth. in Phys. Res. B, Vol 139, 1997.