SIMULATION OF MULTIPACTING WITH SPACE CHARGE EFFECT IN PIP-II 650 MHz CAVITIES*

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Abstract

The central element of the Proton Improvement Plan -II at Fermilab is a new 800 MeV superconducting linac, injecting into the existing Booster. Multipacting affects superconducting RF cavities in the entire range from high energy elliptical cavities to coaxial resonators for low-beta part of the linac. The extensive simulations of multipacting in the cavities with updated material properties and comparison of the results with experimental data are routinely performed during electromagnetic design at Fermilab. This work is focused on multipacting study in the low-beta and high-beta 650 MHz elliptical cavities. The new advanced computing capabilities made it possible to take the space charge effect into account in this study. The results of the simulations and new features of multipacting due to the space charge effect are discussed.

INTRODUCTION

Proton Improvement Plan-II [1] at Fermilab is a plan for improvements to the accelerator complex aimed at providing a beam power capability of at least 1 MW on target at the initiation of LBNE (Long Base Neutrino Experiment) operations. The central element of the PIP-II is a new 800 MeV superconducting linac, injecting into the existing Booster. A room temperature (RT) section of the linac accelerates H- ions to 2.1 MeV and creates the desired bunch structure for injection into the superconducting (SC) linac. The superconducting part of the linac explores five superconducting cavity types operating at three different frequencies

Multipacting can affect practically all accelerating RF cavities and their components in the entire range energies and frequencies. Therefore we routinely perform the extensive simulations of multipacting (MP) as a part of RF design in each SC and RT cavities and other RF components under development (excepting SC half wave resonators since they are developed for PIP-II by other institution [2]). Also we use every opportunity to compare MP simulations with experimental data to evaluate overall reliability and accuracy of our simulation technique.

In present simulations of MP in high beta (HB, β=0.9) and low beta (LB, β=0.6) 650 MHz cavities with the use of CST Particle Studio we followed in general our practical approach described in [3]. At the same time the new advanced computing and software capabilities made it possible to take space charge effect into account in this study.

It is shown in [4] that the space charge effects play a prominent part in the secondary electron resonance discharge, i.e. multipacting. In the elementary theory of multipacting and in the most MP simulation codes the space charge effect is neglected, which results in infinite growth of electron number in the calculations or in the simulations (a growth is typically exponential, but not always). Such MP dynamics is representative for the initial stages of multipacting development, and, actually, the multipacting thresholds predicted by the models without space charge effect usually are in a good agreement with the experiments. However, for the quantitative parameters of developed multipacting process such as discharge current, power, energy spectrum etc. the predictions of the elementary theory are not reliable or even cannot be done.

In principle developed multipacting is essentially a space charge limited process, and its first phenomena is a saturation of the discharge current density. During developed multipacting there are one or several bunches of electrons in RF device volume (number depends on MP order), which are well formed by phase focusing mechanism. Space charge of an electron bunch pushes peripheral particles out from phase stability interval (and possibly from area where dynamic conditions for multipacting exist). Therefore, a number of electrons constantly go out of the game. This loss of electrons is compensated by secondary electrons re-emitted at each RF cycle. Finally a dynamic equilibrium is established between losses and re-emission, and the process comes to the steady state regime in which discharge current density stops at certain level, and no infinite growth of particle number occurs [4, 5, 6].

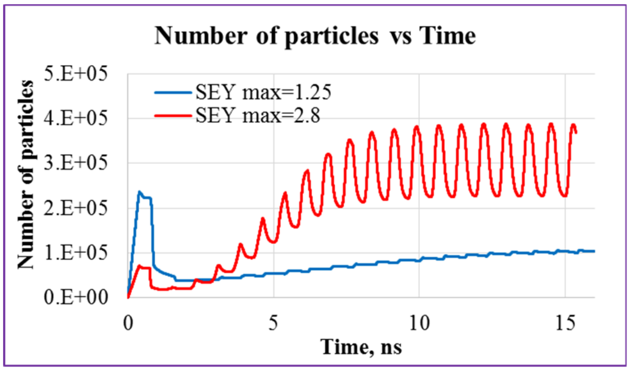

Figure 1: Typical behaviour of particle number in PIC simulations of multipacting with space charge ON. Level of particle number saturation depends on maximal SEY of the walls (simulated in PIP-II low beta 650 MHz cavity).

Following this speculation discharge current density saturation level should depend on secondary emission yield of material – the higher SEY, the higher current density. Indeed, one can see that in the simulations (see Fig.1), and that was confirmed in the experiments [7]. There is also a global limit of discharge current density, which cannot be

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overcome at any big SEY. When the strength of electrostatic field generated by space charge becomes comparable with driving RF field, then the interval of phase stability starts shrinking and that prevents further current density increase [6]. One more noticeable feature of space charge limited multipacting found in the experiments [7] is much lower energy of collision compare to the elementary theory predictions. As a result, MP bands with space charge effect are shifting toward higher field levels, and they are narrower than the ones without it [4]. Of course, when the charge tends to zero, the limits of the multipacting domain are found as determined by the elementary theory.

MODELS AND WORKFLOW DETAILS

The simulations were performed for the single central cells of 650 MHz cavities (the full length models are shown in Fig.2). As usual a particular attention was given to quality of the field maps and accuracy of particle tracking which both depend strongly on mesh density. For particle tracking we used CST Particle-in-Cell (PIC) solver exclusively because of its capability to handle space charge effect, and, as an additional advantage, because it can use GPU acceleration. The RF field maps were calculated by CST eigenmode solver (EM) and then imported into PIC solver. In the model equator area susceptible to MP, the minimal mesh cell size of tetrahedral mesh, which is exploited by EM solver, was 0.2 mm, while the one of hexahedral mesh used by PIC solver was 0.35 mm.

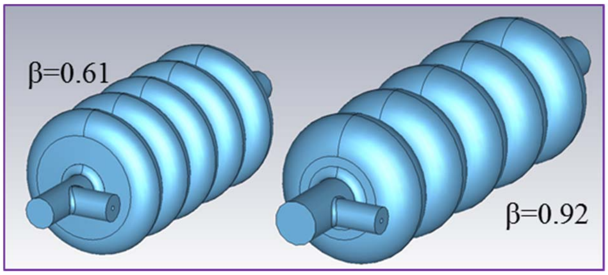

Figure 2: The models of PIP-II 650 MHz cavities.

One more important advantage of the CST PIC solver are time dependent sources of initial particles, which allows distributing the initial particles over phases of RF fields. We used “Particle Area Source” with Gaussian emission model, which seems to be the most flexible and convenient for MP simulations. The details on Gaussian particle source setting are given in [8].

The CST Particle Studio has an advanced Furman-Pivi model probabilistic emission model along with other ones in its library [9]. This emission model includes the stochastic properties of secondary emission and adds elastic and re-diffused reflection of primary electrons from the surfaces into simulations. The inclusion of the probabilistic factors of re-emission along with elastic scattering and rediffusion makes the simulation predictions much closer to the experimental data [10], and their usage is preferable. But in the present simulations we use the GPU acceleration of calculations, and unfortunately the GPU based PIC solver does not support Furman nor any other emission model from the library yet. Therefore, we had to import and use the primitive deterministic emission models in which number of secondary electrons depends only on the energy of primary electrons. The SEY curves used in the simulations are shown in Fig.3. They are conventionally called “Niobium baked”, “Niobium discharge cleaned” and “Niobium wet”, since actually they are true SEY data for niobium baked at 300°C, argon discharge cleaned niobium and wet treated niobium . The limited number of simulations were performed (without GPU acceleration) with the Furman emission models to compare with. These simulations showed that for niobium the difference between probabilistic models and deterministic ones is not large, because re-emission for niobium due to the elastic and diffusion scattering is very low in the Furman models. Anyway, this discrepancy is not that important, because there is no relation to the actual condition of the cavity material, and different SEY data were used just to evaluate impact of surface finish.

PIC simulation with space charge ON requires more iterations per time step. But due to the saturation and therefore limited number of particles it turned out to be surprisingly faster than the one without space charge effect.

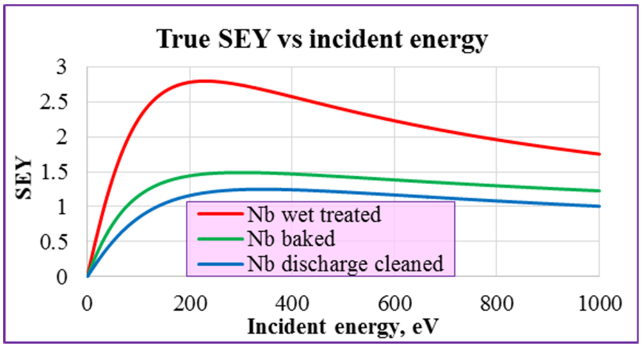

Figure 3: Secondary emission yield data used in the simulations.

IMPACT OF SPACE CHARGE

How space charge effect changes MP dynamic was studied during simulations in the central cell of low beta 650 MHz cavity (the multipacting with space charge ON developed in typical for all elliptical cavities location is shown in Fig.4).

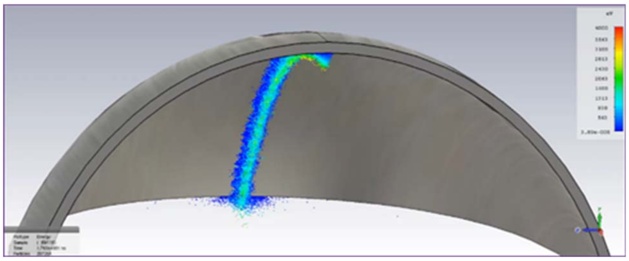

Figure 4. Snap shot of steady state multipacting with space charge effect. Particle colours indicate their energy.

Direct comparison of multipacting intensity with and without space charge effect is not possible. For saturated regime a growth rate is zero, therefore it cannot be an indication of multipacting at all. An effective secondary emission yield is not a convenient indicator either, since it always equals 1 during multipacting regardless intensity of discharge [11]. Instead a total steady state re-emission current was used as MP characteristic in case of active space charge effect and compared with effective secondary emission yield <SEY> obtained in simulation without space charge. The result of simulations expresses the MP re-emission current and <SEY> as functions of cavity energy gain is shown in Fig.5. The average energies of collisions can be compared directly and are shown in Fig.6.

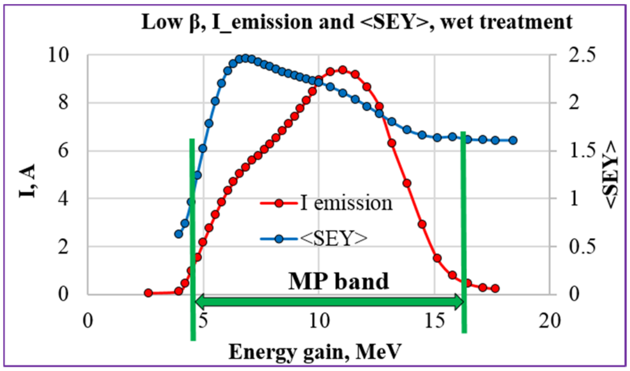

Figure 5: Comparison of MP simulations with space charge (I emission) and without one (<SEY>).

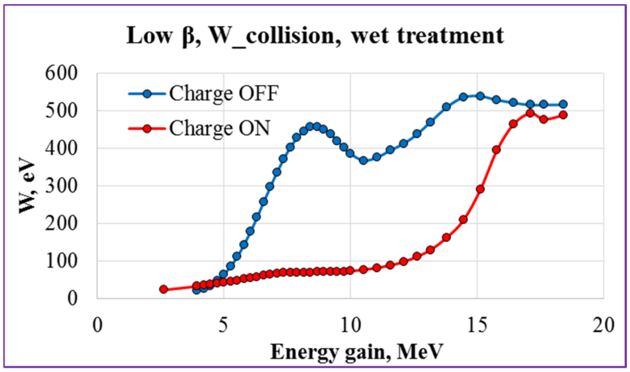

Figure 6: Average energy of collisions in simulations with space charge and without one.

The result of simulation is consistent with theoretical and experimental results from [4, 6]: a maximum of MP band moves toward higher fields when space charge is ON; the MP band itself is narrower and energy of collision is lower compare to the simulations with zero space charge. But it is important to notice that the lower boundary of MP is predicted very accurately by the simulations based on the elementary theory without space charge effect.

RESULTS OF SIMULATIONS

For both low beta and high beta models the simulations were performed with every given SEY data. The secondary emission current I_emission averaged over last 5 RF periods was calculated as the function of energy gain of a cavity. The results of simulations are presented in Fig.7-8. As contrasted to the <SEY> calculated in the simulations without space charge effect, steady state emission current in the simulations with space charge is not proportional to SEY of material, and its maximum moves toward higher fields with increasing of SEY. As it was mentioned above, the lower SEY, the closer the results obtained with and without space charge effect, since MP steady state regime is achieved at smaller space charge for low SEY.

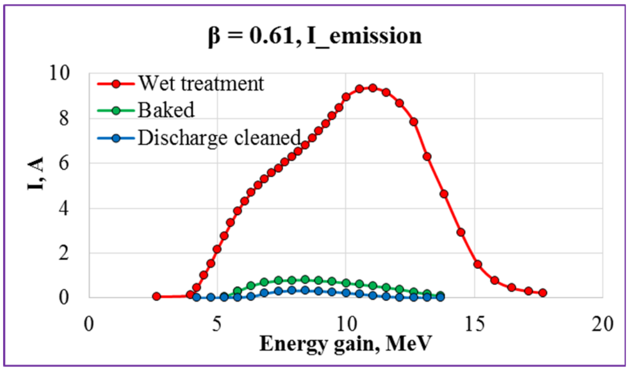

Figure 7: Multipacting barriers in the central cell of low beta 650 MHz PIP-II cavity at different surface cleanness.

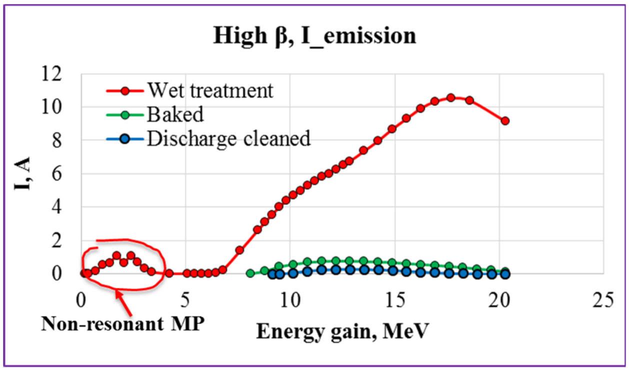

Figure 8: Multipacting barriers in the central cell of high beta 650 MHz PIP-II cavity at different surface cleanness.

In general the present results are in a good consistency with the previous simulations and experiments. The MP barrier in the low beta single cell simulated in [12] with Furman-Pivi SEY model is 4.9÷11.4 MeV. The experiments with single low beta cells in [13] demonstrated the MP activity in 4.9÷5.6 MeV interval - apparently the cells were pretty clean and RF conditioning eliminated the MP barrier very quickly. The power tests of 5 cell high beta cavity at Fermilab [14] had the MP problems in the interval of 10.6÷17 MeV.

CONCLUSION

The inclusion of space charge effects in MP simulations does not result in significant changes of MP barriers. On the other hand the energy of collision and the power deposition in the simulations with space charge effect are apparently very different compare to classic theory. That is interesting phenomena, which requires further study.

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