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MULTIPACTING STUDIES OF THE COAXIAL COUPLER FOR BNCT DTL*

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Abstract

Multipacting is a phenomenon in which electrons grow sharply under certain conditions in a RF structure. It may lead to the breakdown or even damage to the equipment. Therefore, it is very important to calculate the Multipacting range in the RF equipment design. Since the phenomenon is too complicated to use the formula to fully predict it, numerical simulation is employed. There are many computer codes (such as Track3P, MultiPac, CST PS, etc.) used to simulate the phenomenon, but most of them are not commercial. In this paper, theories used in coaxial line for predicting multipacting are introduced; the CST PS is chosen to simulate the multipacting of coaxial coupler for BNCT DTL; finally, methods of suppressing multipacting are discussed.

INTRODUCTION

Boron Neutron Capture Therapy (BNCT) is considered one of the most promising tools for treating certain types of cancer [1], it's developed and researched by an increasing number of workgroups. Now, a new BNCT facility contains a 75 keV H- Ion Source, a 3.5 MeV Radio Frequency Quadrupole (RFQ) and a solid Li target is under construction in China Spallation Neutron Source (CSNS) campus. Considering the neutron flux and difficulty of target manufacturing, a 3.5 to 10 MeV Drift Tube Linac (DTL) is planned to construct as an upgrade solution after successful obtaining the neutron beam. Preliminary physical design of the DTL shows that the required peak and average power does not exceed 600 kW and 200 kW independently, therefore, the coaxial type coupler is chosen. Preliminary design of the coaxial coupler draws on the successful experience of coupler used in many machines such as ADS injector-1 RFQ, TRASCO RFQ, JPARC DTL and so on, the process of it is quite standard and similar to the design of CSNS DTL coupler [2][3], so the detailed parameters will not be discussed here.

Multipacting in coaxial coupler has been studied for many years and it can be a limit factor of the coupler. Different analytical formulas are used to predict the multipacting barriers; however, they often base on homogeneous electromagnetic fields and the estimated results are rough for complex structures. Therefore, the numerical calculation is quite essential for reliable prediction of multipacting barrier. In this paper, theories commonly used to calculate the multipacting of coaxial coupler are introduced firstly, and the two-point 1st order multipacting point of BNCT DTL coupler is calculated according to the theory. Section 2 introduces the detailed multipacting simulation process with CST Particle studio (CST PS), after that, the results are compared with theory ones. Finally, the suppression of multipacting is simulated and analyzed, which is helpful for the new coupler design.

THEORY

There are many theories to compute the multipacting barrier in coaxial line and the most commonly used one is the Scaling laws. This theory holds that the multipacting in standing wave (SW) coaxial line is only caused by electric fields and the one-point and two-point multipacting both may occur. Based on experience and analysis, it gives the following formulas [4]:

$$P_{\text{one-point}} \sim (fd)^4 Z \qquad P_{\text{two-point}} \sim (fd)^4 Z^2 \tag{1}$$

where f is the operating frequency, d and Z is the outer diameter of the coaxial line and the line impedance respectively. The average impact energy obeys the following laws:

$$Ei \sim (fd)^2 \tag{2}$$

Although the proportional relationship between the multipacting point and the coaxial line parameters is given, the scale factor also needs to be obtained by many computations or simulations; it could be difficult for new designers.

Another concise theory is proposed by Z. Zheng in Facility for Rare Isotope Beams (FRIB). They experienced strong multipacting in high power conditioning of the coaxial coupler for half wave SC resonators (HWR); the first eight resonators used a DC bias insert into the transmission line to suppress the multipacting [5]. However, the number of couplers is quite a lot, suppression of multipacting directly in the coupler is an economical and effective solution. In this theory, the radial electric field (E_r) between the inner and outer conductor is assumed to be constant, the electric field in coaxial coupler is:

$$E = \frac{V}{r}\left(\ln(\frac{b}{a})\right)^{-1} \tag{3}$$

the input power of the coaxial line is:

$$P = \frac{A\pi V^2}{\eta}\left(\ln(\frac{b}{a})\right)^{-1} \tag{4}$$

where b is the inner radius of the outer conductor, a is the outer radius of the inner conductor, V is voltage between

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the outer conductor and inner conductor, for travelling wave A is 1, for standing wave A is 0.25, η is the wave impedance in vacuum.

The electron trajectory is considered to be the difference between the outer and inner conductor radius in a half-integer RF period. So:

$$s\left(t=\frac{(2n-1)\pi}{\omega}\right)=\frac{(2n-1)\pi eE_r}{\omega^2 m}=b-a \Rightarrow E_r=\frac{(b-a)\omega^2 m}{(2n-1)\pi e} \quad (5)$$

E_r can also be represented by V/(b-a), therefore, the two-point multipacting barrier can be given:

$$P_n=\frac{A\omega^4(b-a)^4 m^2}{(2n-1)^2\pi\eta e^2}\left(\ln\left(\frac{b}{a}\right)\right)^{-1} \quad (6)$$

n is the order of two-point multipacting, m and e is the quality and charge of the electron.

According to this theory, the multipacting power of the main transmission part in BNCT coupler is 90 kW for the standing wave. Also, we can get the 1st order multipacting power as a function of impedance by reducing the inner radius and increasing the outer radius (Figure 1); it could be helpful for the design and modification of the coupler.

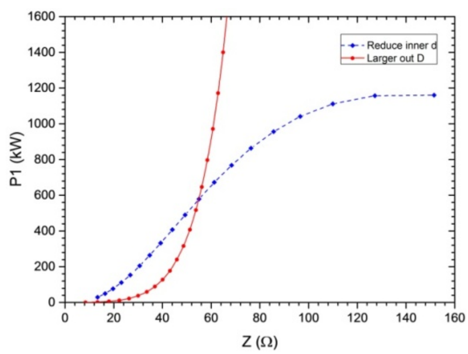

Figure 1: P1 vs. coupler impedance.

SIMULATION AND RESULTS

There are two solvers in CST PS studio, one is Tracking Solver (TRK), another is Particle In Cell Solver (PIC). The difference of the two solvers is that only the PIC solver considers the interaction between the electric field and the particles, it determines that more powerful computing resources are needed in PIC Solver than TRK Solver, but the TRK Solver is proved to be useful in Ref [6], so the solver used in this paper is TRK Solver.

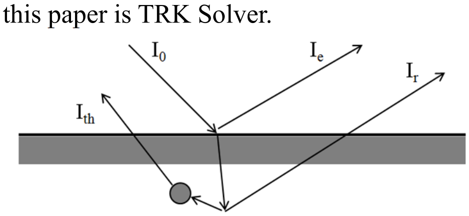

Figure 2: Different components of Secondary emission.

In our simulation, the material is chosen to be SEE-Copper and the secondary emission model is Furman-Pivi. This model was first proposed by Furman and Pivi in 2002 [7]. The whole process can be shown in Figure 2.

To ensure the simulation accuracy, the EM field is calculated in EM Solver before the TRK Solver setup (as shown in Figure 3). First, the mode of interest is import into the TRK Solver as the base for calculation, the amplitude scaling factor and phase of the field can be changed in this process. Since the Eigen-mode fields are normalized to 1 J in simulation, the scaling factor s can be evaluated by the ratio of the actual average electric field in the axial direction of the cavity and the simulation electric field at the same location. Next, we define the particle source on the target surface, in this step, the initial emission energy and spread angle can be set, the number of fixed points is defined according to the size of the emission face and the computation resources. Thirdly, the mesh properties, the frequency range, the background properties and the boundaries conditions are defined, it must be noted that if the mesh lines per wavelength are too small, the particles will increase indefinitely and may lead to the software crash. Finally, in the TRK Solver menu, we select the fields which will be used in the simulation and run the project, we generally run for 30-200ns.

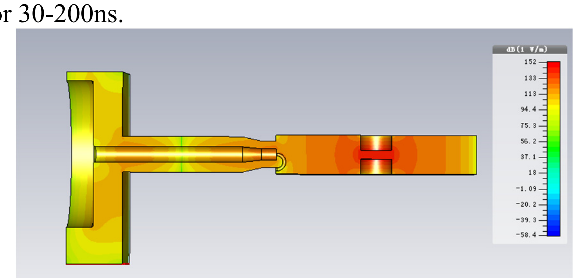

Figure 3: Electric field distribution.

We can identify the multipacting phenomenon from the simulation results, and the most intuitive method is to observe the particle vs. time curve and fit the curve with $e^{\alpha t}$, thus we can get the growth rate α and time interval T

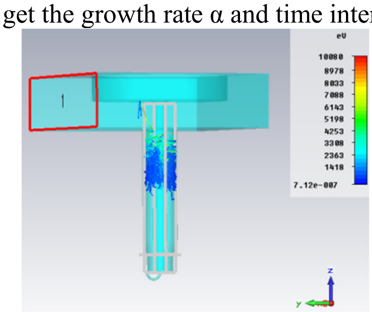

Figure 4: Electron Trajectories plotted after simulation.

between two occurrences of multipacting, the secondary emission yield (SEY) can be easily got by $e^{\alpha T}$ [8]. Another method is to calculate the average SEY in CST post-processing, and this method will be used in our simulation. Also, the trajectories plotted in results will be helpful for determining the type and location of the multipacting, as shown in Figure 4.

According to the methods and settings described above, six different places of the BNCT coupler are simulated, and the initiation SEY line of multipacting is set to 1.2; due to the limit of article length, three of the six results can be seen in Figure 5.

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It should be noted that the simulated value of the on-axial electric field corresponds to the target value when s is 0.314. As can be seen from Figure 5, the multipacting phenomenon is more likely to occur in the upper part of the coupler. From the simulation in Figure 5a, the SEY is unstable when s is larger than 0.25. If we fit the SEY

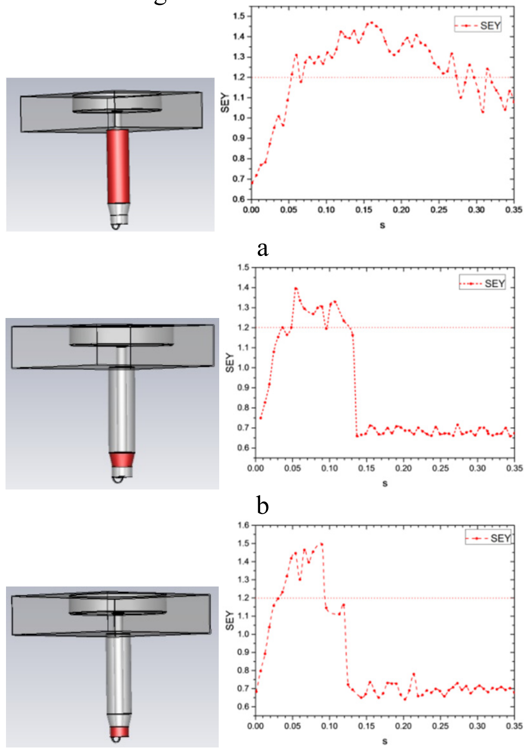

Figure 5: The particle source of different places (left) and their corresponding SEY curve with s (right).

curve in this range, the SEY is less than 1.2 when s is larger than 0.26, thus multipacting may not occur on target power; but the multipacting range is quite wide and it may extend the high power conditioning time. In the taper and down part of the coupler, the multipacting range is narrow and no multipacting will happen on the operation power. We also simulate the outer surface of the inner conductor; the SEY curve is quite similar to that of outer conductor. Due to the electric field of inner conductor is larger than that of the outer conductor; the multipacting range of it is narrower than that of the outer conductor.

The maximum SEY of Figure 5a is 1.46 while s is 0.16, we can calculate the forward input power is about 79 kW, which is quite close to the calculation results, the difference between the theoretical and simulation results may be due to the theoretical results only considering the first order multipacting. Although the multipacting may occur in some power range, we can judge that they are soft barriers, and the suppression of multipacting in couplers for room temperature cavities are not very difficult (such as adding bias on the coupler when high power conditioning), the maximum SEY can be accepted.

From the design perspective, another simulation is carried out to research the suppression of multipacting. Generally speaking, the multipacting barrier can be suppressed by changing the impedance of the coupler; this method will totally change the design of the coupler and is very complicated. So we try to enlarge the outer diameter, reduce the inner diameter or add choke structure to the coupler while maintaining the impedance to 50 ohms. After every change, the electric field is re-simulated and the coupling coefficient is re-optimized. The position of particle source is defined as that of Figure 5a and the comparison is shown in Figure 6.

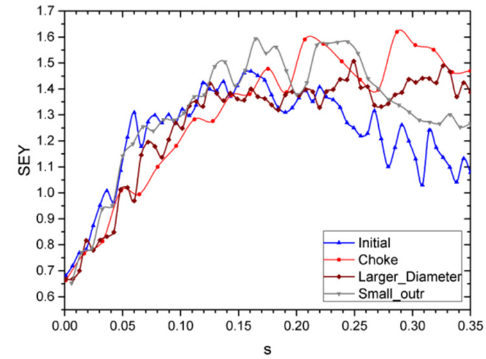

Figure 6: The comparison of different methods to suppress the multipacting barrier.

From Figure 6, in low power level (about s<0.17), we can see that adding a choke structure on the outer conductor is the most obvious method to suppress multipacting, and the least method is to reduce the radius of the coaxial line. Both the method of adding choke structure and increasing the radius, their essence are to reduce the electric field of outer conductor on multipacting position. Theoretically speaking, we can increase the radius infinitely and add a choke large enough to suppress multipacting in all conditioning power level for the BNCT DTL coupler. However, considering the limit of size, the structure stability, the price and many other aspects, the impact of these two methods is limited. Meanwhile, we can see that all these methods have improved the SEY value to some extend when s is larger than 0.21. In high power level, if these methods are all invalid, the most effective way for multipacting suppression is to use the design of multiple sections with different impedance according to Ref [5]. Finally, it can be conclusion that the method of adding choke and increasing radius can suppress multipacting obviously by improves the multipacting power in low power level while increasing the SEY in high power level. It could be helpful to the design of a new coupler.

CONCLUSION

The theoretical and simulation analysis of the BNCT DTL coupler is described and methods of suppressing multipacting are discussed in this paper. The theoretical calculation results show that the two-point 1 order multipacting power is 90 kW which is quite close to the simulation results. The comparison of different suppression methods shows that two of them are quite useful in low power level. However, this is just a step in the coupler design, the mechanical and thermal analysis will be done in the near future.

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