MULTIPACTING SIMULATION OF ACCELERATOR CAVITIES USING ACE3P*

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Abstract

ACE3P [1] is a 3D parallel finite element code suite for cavity design and optimization including electromagnetic, thermal and mechanical effects. Taking advantages of the power of computing on multi processors, ACE3P's particle tracking module Track3P allows efficient multipacting (MP) simulation by extensive scanning in field gradient and on cavity surface to identify the occurrences of MP activities. The output from Track3P simulation includes the determination of resonant trajectories and their locations, the calculation of electron impact energy on cavity surface, and the evaluation of the electron enhancement counter as a function of field gradient. The sensitivity of MP on secondary emission yield can be readily obtained through post processing. The basic capabilities of Track3P for MP simulation will be presented.

INTRODUCTION

Multipacting (MP) is an undesireable, resonant built-up of electrons inside RF structures. It can cause wall heating and high power breakdown of RF components, prolong processing time and limit the achievable design field gradient. While most of the soft MP barriers could be processed through RF, the presence of a hard MP barrier prevents a RF component from reaching its design power or field gradient level.

Much work has been done on MP studies to identify potential MP events and to mitigate MP activities. In recent years, with more computing power, full 3D simulation tools have been developed to investigate potential MP activities. High resolution EM field, correct representation of particle emission from curved surface, realistic SEY curve for surface material and comprehensive post-processing of particle data to identify MP events are the basic requirements for accurately simulation of MP. Furthermore, the use of high performance computing allows efficient MP simulation by making use of hundreds to thousands of CPU cores running in parallel, by which the speedup in computation time facilitates extensive parameter scans. Track3P, a 3D parallel particle tracking code, provides a MP simulation tool with these advanced modeling and computational features. It has been extensively benchmarked against experiments and applied to model and predict MP activities for the design of many accelerator cavities and RF components.

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MULTIPACTING SIMULATION USING ACE3P

ACE3P

ACE3P (Advanced Computational Electromagnetics 3D Parallel) is a comprehensive set of conformal, higher-order, parallel finite-element electromagnetic codes with two unique features. First, it is based on higher-order curved finite element method for high-fidelity modeling and improved solution accuracy. Second, it is implemented on massively parallel computers for increased memory (problem size) and speed. The six modules of ACE3P cover a wide range of simulation capabilities for accelerators: Omega3P for calculating cavity modes and damping, and S3P for transmission in open structures in frequency domain; T3P for calculating wakefields and transients in time domain; Track3P for MP and dark current studies using particle tracking; Pic3P for RF gun design with particle-in-cell (PIC) method; and TEM3P for multi-physics analysis including EM, thermal and mechanical effects.

Track3P Characteristics

Track3P provides accurate and efficient simulation for MP by tracking particle trajectories under the influence of RF fields or external static fields. The RF field in an accelerator structure is first solved by Omega3P or S3P, which calculates the EM field to high accuracy using higher-order basis functions (up to 6th order), and then loaded into Track3P for particle tracking. In a similar manner, external static electric and magnetic fields can be read into the code as input field data. The high-fidelity geometry representation built in the finite-element method allows realistic modeling of particle emission on cavity wall. Track3P constructs the MP map by identifying resonant particle trajectories. With a realistic secondary electron yield (SEY) curve provided by experiments, Track3P can calculate the particle enhancement counter and locate MP regions. This is achieved using the versatile postprocsing tools that have been developed to identify the onset of MP through various parameter scans.

MP Module in Track3P

The following describes the procedure for modeling MP in Track3P. Electrons with specified kinetic energy and emission direction are launched from specific surfaces at different phases over a full RF period. The initial launched electrons follow the electromagnetic fields in the structure and eventually hit the boundary,

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where secondary electrons are emitted. The tracing of electrons will continue for a specified number of RF cycles, after which MP trajectories are determined and the MP types (order: # of RF cycles to return to the original site; point: # of sites on the wall) are identified. The necessary condition for MP is when the trajectory traced out by consecutive emissions is in resonance with the RF cycle. These particles impact on the surface at the same locations with the same impact energy. When the impact energy falls in the range with SEY greater than unity, the resonant trajectory is considered as a MP event. One can also estimate the strength (soft or hard) of the MP event by the value of the SEY.

TRACK3P SIMULATION CAPABILITIES

Track3P has been extensively benchmarked against theories and measurements [2-7]. In a typical MP run, Track3P generates a large amount of particle and field information data such as the position and momentum as a function of time and the history of particles in a resonant trajectory. Various diagnostics and postprocessing tools have been developed to provide simulation capabilities for modeling MP in realistic cavities for accelerator projects. The basic capabilities are as follows.

Determination of Resonant Trajectories

MP activities are due to the resonant built-up of electrons inside an RF structure. The first step to identify the occurrences of MP is the formation of resonant particle trajectories. Based on the resonant particle information, one can identify potential MP locations, types (order and points), and determine impact energies. Fig. 1 shows the locations of resonant particles in the HOM coupler of the SNS SRF cavity at the field level of 4.22 MV/m. The resonant particles are located at the coupler gap region. By drawing out one typical resonant trajectory, the MP type is found to be first order and two point, with impact energies 490 eV and 650 eV on the inner and outer walls of the gap, respectively [8].

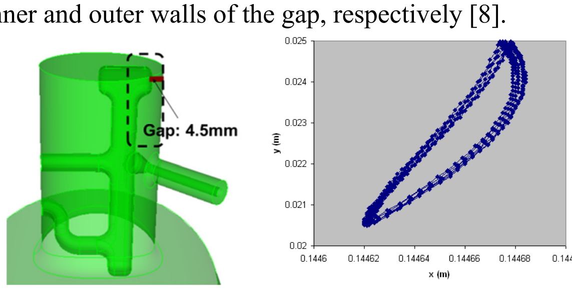

Figure 1: MP simulation of SNS HOM coupler. Left: Locations of particles with resonant trajectories; Right: A resonant trajectory at 4.22 MV/m field gradient.

Construction of MP Susceptible Zones

The main objective of MP simulation is to determine the field levels at which potential MP activities occur. In Track3P simulation, the tracking of particles will be carried out by scanning a range of field levels at a prescribed field step increment. Resonant particles are identified at each field level, and based on this information it is possible to construct potential MP zones. Fig. 2 shows the impact energy as a function of field level for the FRIB Quarter Wave Resonator (QWR) and the locations of the impact positions of resonant particles at all field levels [4]. A hard barrier MP band is found at low field levels from 800V to 7.5kV, with impact energies corresponding to SEY values near its peak. The simulation result agrees well with the high power test data which showed a processing barrier at 1.2kV ~ 7.2kV.

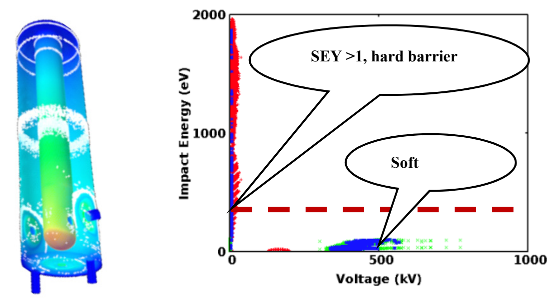

Figure 2: MP simulation for FRIB Quarter Wave Resonator. Left: Resonant particle impact positions at all field levels; Right: Impact energy vs. accelerating voltage for particles with resonant trajectories. Red color indicates resonant particles at the top region of cavity, and green at the middle and blue at the bottom.

Calculation of Enhancement Counter

One parameter to quantify MP is the enhancement counter, which is given by

$$ec = \delta_1 * \delta_2 * \cdots \delta_m$$

where $\delta_1, \delta_2 \cdots \delta_m$ are the number of secondary electrons generated at the 1st, 2nd, … mth impacts determined by the SEY curve. Generally, when ec > 1, there will be potential MP activities. The larger the ec is, the harder the MP barrier. In Track3P simulation, the calculation of the enhancement counter is treated in postprocessing by applying the SEY on the impact energies of resonant particles, and thus one can use different SEY curves to estimate the effects of different surface material properties from a single computer run. Fig. 3 shows the MP simulation results for the MICE 201 MHz cavity [9]. Three enhancement counters are plotted using three different SEY curves [10]. Although the SEY curves have different magnitudes for the range of electron impact energies, the peak enhancement counter is found in the same region at the field levels of 2~4 MV/m. As a result, this MP event is believed to be a hard barrier.

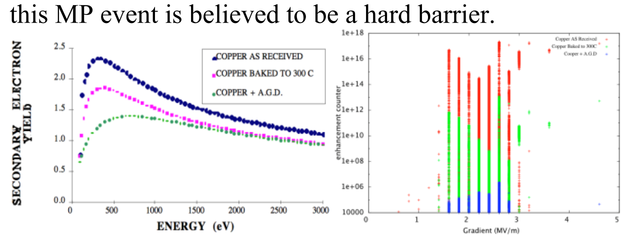

Figure 3: MP simulation for MICE 201 MHz cavity. Left: Three SEY curves; Right: Enhancement counters calculated using the three SEY curves.

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Effects of External Magnetic Field

In addition to loading Omega3P or S3P field, Track3P can load external magnetic field as input. This feature has been applied to improve the designs of the 805 MHz and 201 MHz Muon cooling cavities by studying external magnetic field effects [6]. Fig. 4 shows the location of resonant particle activities around the coupler iris of the prototype 805 MHz Muon cooling cavity without external magnetic field and with 3T solenoid magnetic field. It can be seen that MP activities appear at different locations of the coupling iris.

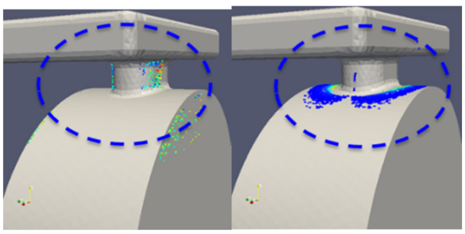

Figure 4: Resonant particle activities around coupler iris for the prototype 805 MHz Muon cooling cavity. Left is with 3T external magnetic field; Right is without external magnetic field.

Modeling of RF Window

The study of ceramic windows such as in couplers requires the implementation of emission on internal surface of the model [2]. Fig. 5 shows the simulation result for the TTFIII coupler with a ceramic window. A 2-point resonant trajectory occurs between the ceramic window and the inner conductor on the cold side of the coupler.

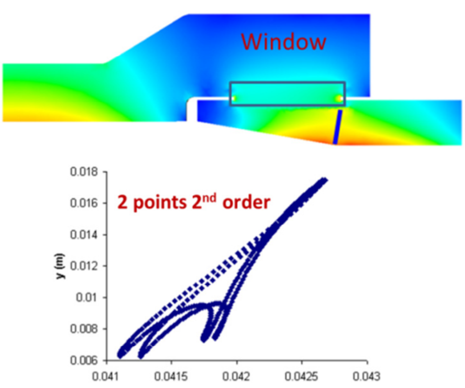

Figure 5: Resonant particle activities in the window region of the TTFIII coupler. Top: the electric field pattern; Bottom: a close-up of the resonant trajectory between the window and the metal wall.

Mitigation of Multipacting

Once MP activities are found in a cavity design, their effects can be mitigated by modifying the geometry where they occur [6]. In conjunction with Omega3P for calculating the RF fields, Track3P can evaluate MP effects at each iteration of the geometry change. For example, the original 805 MHz Muon cooling cavity suffered from severe gradient degradation and surface damage. Through simulation, a new design is achieved which significantly reduces the peak surface field by rounding the coupling slot and using an elliptical disk (see Fig. 6).

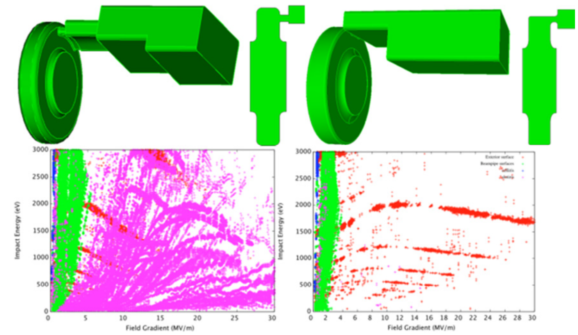

Figure 6: MP studies for 805 MHz Muon cooling cavity. MP locations: Windows (green); Disk rounding (blue); Coupling iris (magenta); Others (red).

SUMMARY

Track3P is the particle tracking module of the parallel finite-element code suite ACE3P and has been applied to study multipacting in accelerator cavities. Running on massively parallel computers, Track3P provides an efficient simulation tool in identifying multipacting barriers, locations and types of trajectories during the design or operation process of cavities. Track3P has been extensively used to study multipacting activities in many accelerator cavities and helps successfully mitigate multipacting effects and thus improve cavity designs.

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