ANALYZING MULTIPACTING PROBLEMS IN ACCELERATORS USING ACE3P ON HIGH PERFORMANCE COMPUTERS*

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Abstract

Track3P is the particle tracking module of ACE3P, a 3D parallel finite element electromagnetic code suite developed at SLAC which has been implemented on the US DOE supercomputers at NERSC to simulate large-scale complex accelerator designs [1-3]. Using the higher-order cavity fields [4] generated by ACE3P codes, Track3P has been used for analysing multipacting (MP) in accelerator cavities [5]. The prediction of the MP barriers in the ICHIRO cavity at KEK was the first Track3P benchmark against measurements. Using a large number of processors, Track3P can scan through the field gradient and cavity surface efficiently, and its comprehensive post-processing tool allows the identifications of both the hard and soft MP barriers and the locations of MP activities. Results from applications of this high performance simulation capability to accelerators such as the Half Wave Resonator (HWR) [6], Quarter Wave Resonator (QWR) for FRIB [7], 704 MHz SRF gun cavity for BNL ERL [8] and the Muon cooling cavity for Muon Collider [9] will be presented.

INTRODUCTION

Multipacting (MP) is an undesired, resonant built-up of electrons inside RF structures. It can cause wall heating and high power RF components like couplers, windows, etc. breakdown. There are also other bad effects, such as significant power loss, low achievable field gradient and thermal breakdown in superconducting structures.

Due to the critical role of multipacting effects on accelerator design, much work has been done on multipacting studies to identify potential MP activities and their locations and to mitigate MP effects using different methods such as modifying geometry to eliminate MP barriers, changing surface conditions to reduce secondary emission yield (SEY) and imposing external DC biasing field.

In recent years, with more computing power, first 2D, then also full 3D simulation tools have been developed to investigate potential multipacting activities in RF-structures [10]. There are several requirements for realistic multipacting simulation, namely, 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.

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ACE3P CODE SUITE

For more than a decade, SLAC has been developing the conformal, higher-order, C++/MPI based parallel finite element suite of electromagnetic codes [1-3]. ACE3P consists of the following modules: 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 multipacting 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.

There are several strengths of the parallel finite-element method used in ACE3P. First, high-fidelity geometry modelling can be achieved using curved quadratic tetrahedral elements. Second, higher-order field interpolation functions (p = 1-6) improve field accuracy as shown in Fig. 2 when using linear, quadratic and cubic basis functions for solving the eigenmode of the cavity shown in Fig. 1. Third, parallel processing speeds up the computation by taking advantages of the code scalability. The calculation took less than 1 minute to obtain the mode frequency within 0.001% using a mesh with 67k quadratic elements on 16 CPUs with 6GB memory. All these factors are important for multipacting simulation as will be seen later in this paper.

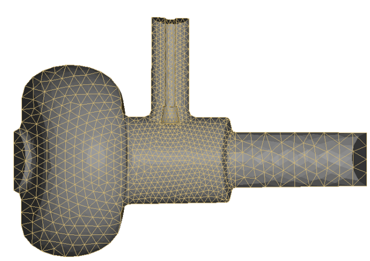

Figure 1: End cell cavity with input coupler.

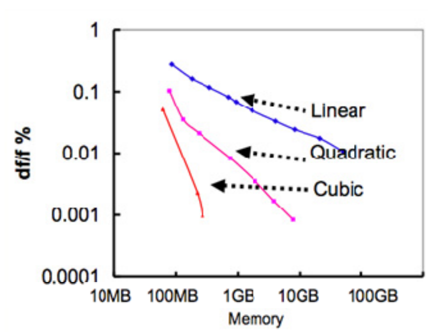

Figure 2: Convergence study for using linear, quadratic and cubic basis functions.

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ACE3P has been installed and runs on the supercomputers at NERSC (National Energy Research Centre) of Lawrence Berkeley National Laboratory. One of the NERSC machines, hopper, has 153,216 compute cores, 217 terabytes of memory and 2 petabytes of disk storage. Its peak performance is 1.28 Petaflops/sec. More information can be found at [11].

TRACK3P

Track3P is a 3D parallel high-order finite element particle tracking code for multipacting and dark current simulations. For multipacting simulation, Track3P can load EM fields calculated by Omega3P, S3P and T3P, which are high resolution EM solvers to calculate standing wave, traveling wave and transient field solutions as input for particle tracking. High-fidelity geometry representation built inside ACE3P allows realistic modeling of particle emission on cavity surface. Realistic SEY curves provided by experiments can be used to construct multipacting maps. The versatile post-processing capabilities help users to identify onset of multipacting through various parameter scans.

Parallelization of Track3P

In Track3P, the whole geometry mesh and EM fields are loaded in individual processors. Particles are divided evenly among the processors, so no communication is required between processors and thus excellent load balancing is achieved. For a typical MP simulation, for example, the FRIB Half Wave Resonator (HWR), the total number of field level scans is 300 and the estimated number of particles per field scan is 8 millions (with initial particles distributed on all exterior surfaces). It took about four hours with 9600 CPUs to finish the simulation.

Multipacting Simulation in Track3P

In a typical MP simulation, electrons are launched from specific surfaces of a cavity at different phases over a full RF period. The initial launched electrons follow the electromagnetic fields in the structure and eventually hit the boundary, where secondary electrons are emitted based on the secondary emission yield (SEY) of the surface material. The tracing of electrons will continue for a specified number of RF cycles. The process described above is repeated for a set of combined launching parameters: RF field level and phase, launching location energy and angle. After all the calculations for various launching conditions are finished, resonant particle trajectories are identified. Not all of these resonant trajectories contribute to multipacting, and only those with successive impact energies within the right range for secondary emission yield bigger than unity will be treated as multipacting events. Finally a MP susceptible zone is constructed. A post-processing tool is also included in Track3P for the effective extraction of MP events. The tool not only enables to determine the multipacting order and type, which are defined as the number of cycles per impact and the number of impacts per multipacting cycle, respectively, but also includes enhancement counter functions to crosscheck the MP barriers determined using the information from the SEY curve.

Benchmark of Track3P

Track3P has been extensively benchmarked with theories and measurements. During high power RF processing, the KEK ICHRIO cavity experienced low achievable field gradient and long RF processing time. To understand these processing limitations, Track3P was used to study potential MP barriers in the cavity cell and beam pipe step region as shown in Fig 3.

Figure 3: KEK ICHIRO cavity.

Track3P simulation on the ICHIRO cavity cell shows that there are resonant trajectories near the cavity cell equator. Fig. 4 shows examples of the resonant trajectories at three different field levels. The impact energy ranges from 20 eV to 55 eV, based on the SEY curve provided by KEK. This MP barrier is soft, which agrees with RF tests as some radiation signals were observes at these field levels but the tests can be processed through them.

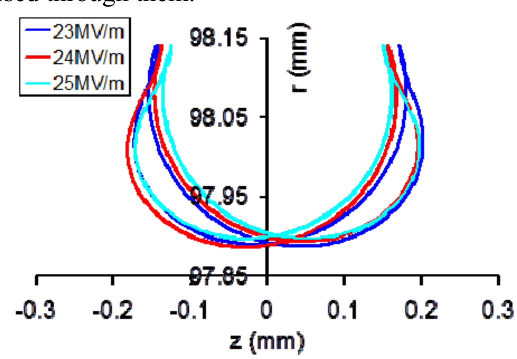

Figure 4: Resonant particle trajectories at three different field gradients: 23 MV/m, 24MV/m and 25MV/m.

Table 1: MP Barriers in the Beam Pipe Step Region of the KEK Ichiro Cavity

Track3P MP simulation		ICHIRO #0 (K. Saito,KEK)
Impact Energy (eV)	Gradient (MV/m)	X-ray Barriers (MV/m)
300-400	12	11-29.3 12-18
200-500	14	13, 14, 14-18, 13-27
300-500	17	(17, 18)
300-900	21.2	20.8
600-1000	29.4	28.7, 29.0, 29.3, 29.4

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Multipacting simulation on the beampipe step shows there are several MP barriers. Table 1 shows the comparison of the simulated and measured MP bands for field levels up to 30 MV/m. Track3P predicted all the MP bands observed in measurements, and, in particular, the hard barrier at 29.4 MV/m at which the cavity could not be processed through.

MULTIPACTING STUDIES FOR ACCELERATOR STRUCTURES

Track3P has been used to study multipacting in many accelerator structures. Its applications on the Half Wave Resonator (HWR), the Quarter Wave Resonator (QWR) for FRIB, the Muon cooling cavity for the Muon Collider and the 704 MHz SRF gun cavity for BNL ERL will be presented in this paper.

Multipacting Study for HWR Cavity of FRIB

The driver linac for the Facility for Rare Isotope Beams (FRIB) will use superconducting cavities to accelerate heavy-ion beams [12]. There are two kinds of superconducting accelerating cavities, the Half Wave Resonators and Quarter Wave Resonators. Multipacting is an issue of concern for the design of these superconducting resonators.

The HWR is being developed at Michigan State University (MSU)[13]. Fig. 5 is the CAD model of the beta = 0.53 HWR cavity. Four ports have been added to the top shorting plate for ease of cavity processing and a superconducting plunger is used for fine-tuning of the frequency. This cavity is designed to provide 3.7 MV of accelerating voltage at an optimum beta = v/c =0.539. The detailed physical parameters of the HWR can be found in [12].

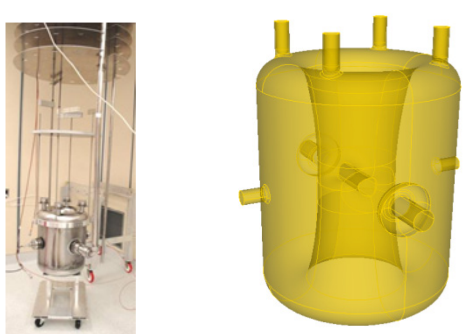

Figure 5: Beta=0.53 superconducting half-wave resonator cavity for the FRIB. Left: setup of the HWR cavity; Right: simulation CAD model.

Simulation results show that there are different kinds of resonant particles occurred in different regions, according to typical Niobium SEY curve shown in Fig. 6 and the distribution of resonant particle impact energies. Potential MP was found to be located at the tip region [6]. Detailed MP studies were performed at the tip region by changing the plunger location and modifying the tip shape. The particle impact energies decrease while the plunger is in an extracted position, and the resonant particle impact area shrinks with intruding plunger. The multipacting barrier is hardest at zero intrusion (Fig. 7).

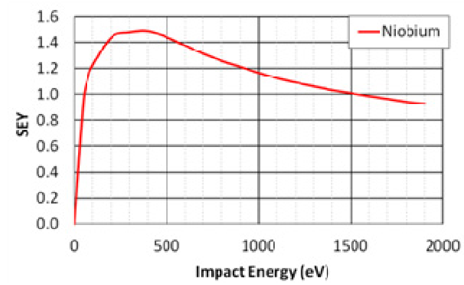

Figure 6: Impact energy dependence of SEY for Niobium. The peak SEY is around 150-700eV. Resonant particles with impact energies within this range likely contribute to MP.

The impact energy of the resonant trajectories on the tip of the plunger is well around the peak of Niobium SEY. It is desirable in the design to minimize such resonant conditions to avoid potential strong multipacting. Based on Omega3P and Track3P results, two ways have been suggested to mitigate MP at the rinse port. One method is to round the plunger tip with full radius and the other to remove the plunger completely from the cavity. Both are very successful in mitigating MP effects. Details can be found in [6].

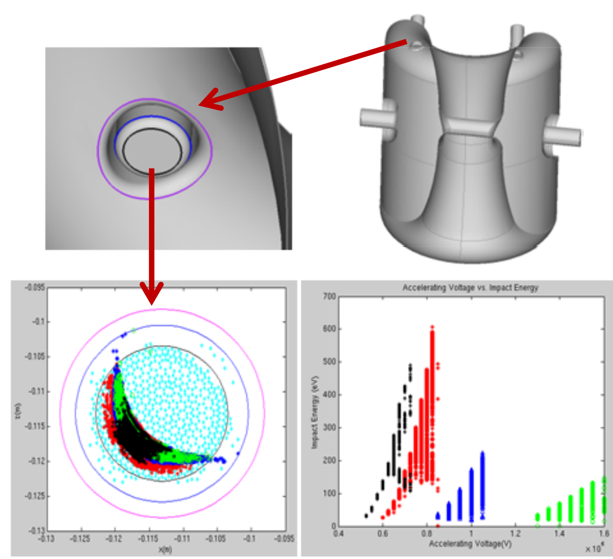

Figure 7: Left: Resonant trajectory distribution; Right: Impact energy vs field level. Cyan: initial electron distribution; Red 0 mm plunger insertion; Black: 3 mm insertion; Blue: 5 mm retraction; Green: 10 mm retraction.

Multipacting Study for QWR Cavity of FRIB

Figure 8 shows the CAD model and electric and magnetic field profiles of the 80.1 MHz $\beta = 0.085$ Quarter Wave Resonator [12][14]. The cavity will operate at a

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maximum peak electric field of 30 MV/m. The corresponding accelerating voltage for a β = 0.085 beam is 1.5MV. Omega3P [4] was used to obtain the RF parameters and field maps required for multipacting (MP) simulation. Track3P [7] was used to track the particles and identify resonant trajectories. Calculations were performed on the NERSC Franklin machine [11], which has 38,128 Opteron compute cores. Typical Niobium SEY curve shown in Fig. 6 was used to estimate the MP strength.

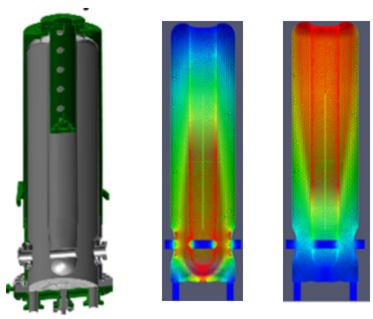

Figure 8: CAD model and field profiles of the β=0.085 superconducting quarter-wave resonator for the FRIB.

The distribution of resonant particles is shown is Fig. 9. There are two potential MP bands, one at low field levels with impact energies from tens of eV to about keV, and the other at high field levels from 360kV to 600kV with low impact energies around 100 eV, which are below the peak SEY energy (Fig. 6). The latter MP band is expected to be a soft barrier and could be processed through without many difficulties.

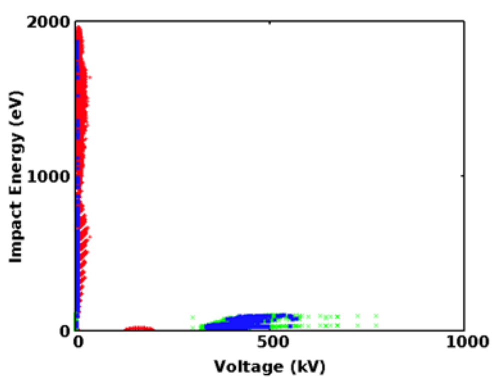

Figure 9: Impact energy vs. accelerating voltage for particles with resonant trajectories.

Stable resonant particles are observed at voltage levels from 800V to 7.5kV. Fig. 10 shows the impact energies of the resonant particles within this MP band. It appears to be a relatively hard barrier as the impact energies of the particles are around the peak of the SEY curve (Fig. 6). This simulated hard MP band agrees with the high power test data which showed processing barriers from 1.2kV - 7.2kV accelerating voltage [7].

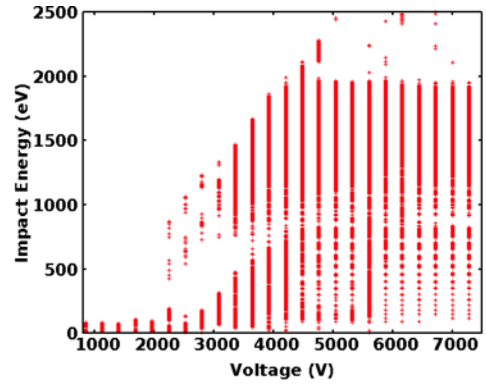

Figure 10: Resonant particle distributions for accelerating voltage between 800V - 7.5kV.

Four snapshots of particle tracking are shown in Fig. 11 to illustrate MP resonances at 23kV accelerating voltage.

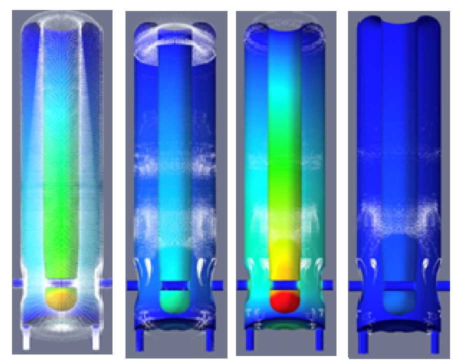

Figure 11: a-d) Evolution of particles survived at increasing RF cycles. Particles survived a large number of RF cycles are considered potential MP particles.

Multipacting Study for Muon Cooling Cavity

Experimental studies using an 805 MHz pillbox cavity at Fermilab's MuCool Test Area (MTA) have shown that its gradient significantly degrades and rf breakdown related damage occurs in high rf field regions when the cavity is operated in a DC solenoidal magnetic field up to 4 Tesla. These effects are believed to be related to the dark current and/or multipacting activities in the presence of the external magnetic field. The 805 MHz cavity under investigation has a pillbox geometry and was the first such cavity to be tested. ACE3P was used to optimize the cavity shape to minimize peak surface fields and to study the dark current and multipacting dependences on cavity RF and geometry parameters under a strong external magnetic field [9]. Using these simulations tools, we analyzed the characteristics of the dark current energy deposition at various cavity lengths; identified high field enhancement areas that could have resulted in high dark current damage; optimized the surface profiles in those areas to minimize the field enhancement; and identified potential multipacting bands. An improved 805 MHz

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cavity design was obtained with significantly lower surface field, and strong MP zones were minimized by locally modifying the cavity geometry (Fig. 12).

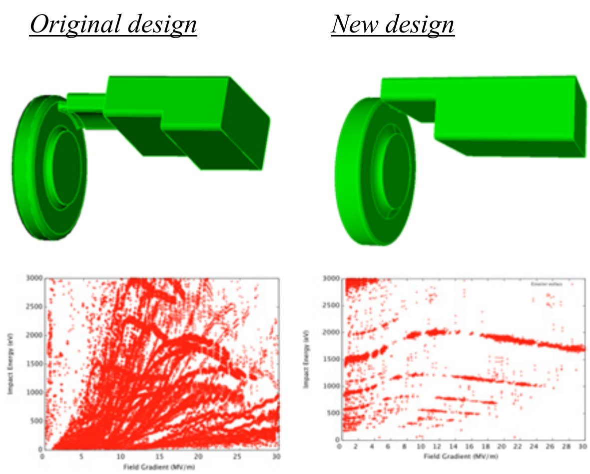

Figure 12: Original and new cavity design with corresponding resonant particles distribution on coupling slot region.

Multipacting Study for BNL SRF Gun Coupler

Scientists at BNL have successfully applied ACE3P to studying MP bands of the fundamental power coupler of an SRF gun. A paper [8] has been published based on the simulations using ACE3P and experiments performed at BNL. Simulations and test results match reasonably well as shown from Fig. 13, in which the shaded areas indicate the observed multipacting zones. It should be noted that Track3P simulations predicted multipacting zones that were later found during conditioning.

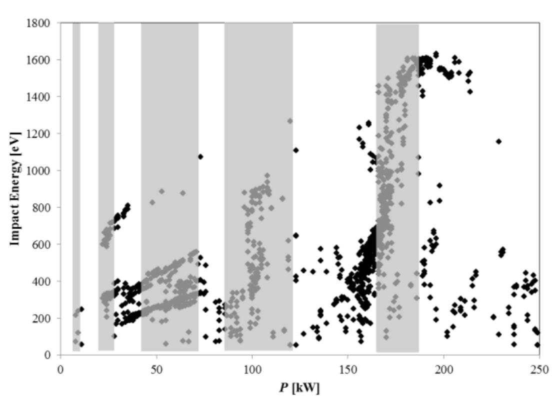

Figure 13: Comparison of multipacting zones from FPC conditioning test (grey-shaded areas) and simulation results at 703.9MHz with 0 degree (black dots).

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 multipacting simulation tool in identifying multipacting barriers, locations and types of trajectories for the accelerator community. Track3P has been extensively used to study multipacting activities in many accelerator cavities and help scientists successfully mitigate multipacting activities and improve cavity design.

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