Simulation of LB650 Cavity with Weld Profile

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Abstract

Superconducting cavities have long found their use in linear accelerators but have recently, found their use in other fields, such as the exploration of dark photons, quantum computing, and other dark matter searches due to their capability to store and harness electromagnetic energy with high efficiency. The need to understand various properties, such as multipacting, cavity geometry, material property, etc., is of the essence.

As part of the PIP-II linac, several types of cavities are in use, such as HWR, SSR1, LB650, and HB650. Our research project aims to understand multipacting in LB650 cavity with weld profile by a simulation method, a first step to replicate the actual cavity, whereas previous studies have ignored the same. As part of the project, we extracted weld profile data from multiple LB650 cavities and used the data to model the cavity on FishPact for simulation. We present the simulation results of the LB650 cavity where we have observed a leftward shift in the peak i.e. Impact Energy vs Accelerating Gradient, in comparison to the same cavity when the weld bead is not taken into account.

INTRODUCTION

SRF cavities have been under extensive research since the 1970s, primarily used for particle acceleration in linear accelerators. RF cavity designs began with simple shapes such as the pillbox and cylindrical design, wherein simple analytical solutions were derived from the Maxwell equations to solve for the EM fields generated. Pioneering development of cavities of such geometries occurred at Stanford University both for SLAC and HEPL [1,2,3]**.** As experiments went underway, the drawbacks of such geometrical cavities became evident with the observation of a phenomenon known as multipacting (MP). This led to the optimization of such cavity shapes, in order to suppress or nullify this effect, and hence cavities evolved into elliptical-shaped cavities.

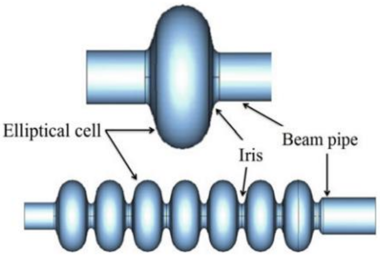


Figure 1: Modern Elliptical Cavities

BACKGROUND

Multipacting is an undesired build-up of electrons inside the RF cavity, where the multiplication of the electrons inside the cavity causes absorption of RF power rendering it useless for the purposes of accelerating particles. The effect of multipacting is observed when two conditions are met, the electron synchronization with the RF fields and the multiplication of electrons via secondary re-emission.

The mechanism of multipacting begins with electrons that originate from cosmic rays, impacting field emission electrons or photoemission are caught in the RF fields, which then accelerate and impact against the walls of the cavity. Upon kinetic impact of primary electrons, it penetrates the surface of the metal. As the primary electron travels through the surface of the metal, the kinetic energy of the primary electron is used to excite the free electrons in the metal, as a result of which these secondary electrons make their way to the surface of the metal and escape. The newly generated secondary electrons also get accelerated by the RF fields and impact the surface of the metal, causing the generation of more electrons, and the cycle continues until all the available RF power is used in accelerating these secondary electrons. The necessary conditions needed for this cycle to sustain are if electron trajectories satisfy specific resonance conditions and of the emitted electrons exceed the number of impacting electrons. The number of electrons being ejected is dependent on two properties, (i) the impact energy of the primary electron (K) and (ii)the secondary emission coefficient δ [5]. From the figure below, the multipacting range for impact energy is K1<K<K2.

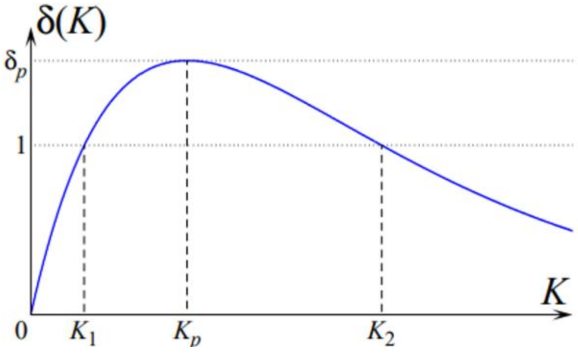


Figure 2: Typical SEY curve

Upon continuous impact of the electrons at localized positions within the cavity, there is heat deposition which leads to the temperature of the cavity being raised, the result of which is quenching of the superconducting cavity.

Another aspect of multipacting that is observed in SRF cavities are nth-order multipacting and n-point multipacting. A one-point multipacting occurs when the stable electron trajectory involves the electron returning to the same impact site after an integral number of half RF periods. Under one-point multipacting, it is observed that electrons follow a different trajectory based on their order; the first order corresponds to a return to the original impact point after one RF period, the second order corresponds to a return to the original impact point after two RF periods, and so on. The most common form of multipacting in modern SRF cavities is two-point multipacting which involves the electron oscillating between two impact points

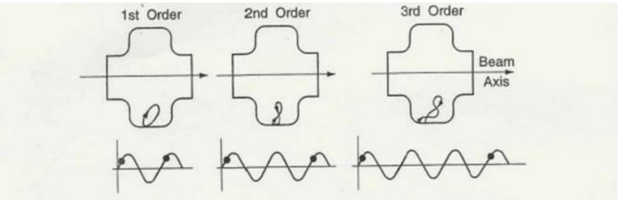


Figure 3: One-Point Multipacting of First, Second, and Third Order

EXPERIMENT

In order to incorporate the weld profile into the simulations, we are first required to obtain the parameters for the weld bead. An experiment was designed and carried out to obtain the weld profile for the LB650 cavity. The procedure involves taking an epoxy mold of the SRF cavity, particularly around the region where the two Niobium shells are welded together. The mold is then imaged under an optical microscope and subsequently analyzed to make measurements.

This experiment was carried out with different LB-650 cavities proposed to be used in PIP-II, the result of which yielded an average radius of 10.6304 mm.

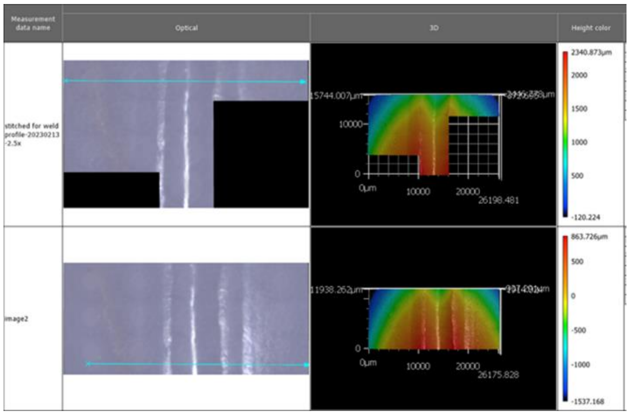


Figure 4: Microscopic Analysis of LB650 Welds

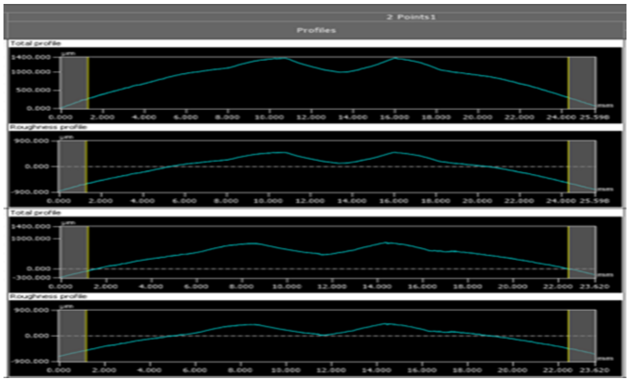


Figure 5: Weld Profiles extracted from LB650 Cavities

SIMULATION METHODOLOGY

In order to aid our understanding of multipacting in LB650 cavities, numerical tools have been built to analyze RF structures. Since LB650 cavities are axisymmetric in nature, we resorted to the use of 2D simulation tools and modelers. The first step to analysing potential multipacting is the requirement for an electromagnetic field modeler. Specific emphasis was placed on the quality of RF fields generated on the RF surface; for this purpose, we resorted to the SUPERFISH EM modeler. The input parameters involve the geometrical description of the LB650 cavity, the initial guess for the frequency, and the drive point of the magnetic field based on which the EM fields are generated [5].

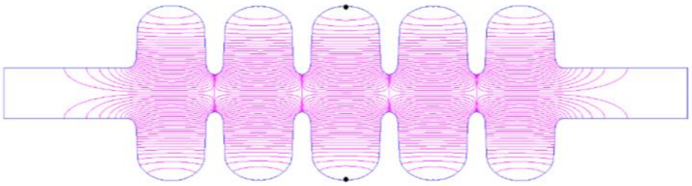


Figure 6: EM Field Generated in LB650 Cavity

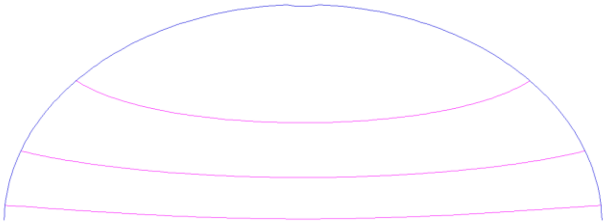
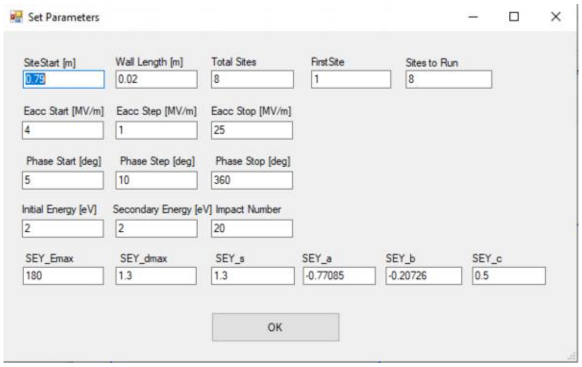


Figure 7: Weld Profile Incorporated into Geometrical Description of Cavity

The second step of the simulation process involves using the obtained EM field description for the purposes of tracking electrons in SRF cavities, where a wide range of initial conditions are introduced. These electrons are then tracked over several RF periods, and results such as impact energy, impact energies, and impact time are recorded. For the purposes of this research, the brute force approach was employed for particle tracking, using FishPact code [6]. The brute force method involves using a range of impact energies of electrons using varying starting conditions such as different phases, positions, and field levels. These ranges are user defined in FishPact code. We assume that the initial energy of the primary electrons is 2 eV, and the emitted electrons also have an initial impact energy of 2 eV. These electrons are then tracked, and their trajectories are computed via numerical solutions to the equation of motion. The tracking is stopped if the impact energy is out of range or if the RF phase is wrong.



SiteStart [m]	Wall Length [m]	Total Sites	FirstSite	Sites to Run	
0.79	0.02	8	1	8	
Eacc Start [MV/m]	Eacc Step [MV/m]	Eacc Stop [MV/m]			
4	1	25			
Phase Start [deg]	Phase Step [deg]	Phase Stop [deg]			
5	10	360			
Initial Energy [eV]	Secondary Energy [eV]	Impact Number			
2	2	20			
SEY_Emax	SEY_dmax	SEY_s	SEY_a	SEY_b	SEY_c
180	1.3	1.3	-0.77085	-0.20726	0.5

Figure 8: FishPact Parameters used for Simulation

RESULTS AND DISCUSSION

The inclusion of the weld profile in the simulation has yielded different MP trajectories from the typically observed trajectories of similar cavities (Figure 10 and Figure 11). From the graph (Figure 12), a leftward shift in the peak is observed when the weld bead is taken into account in the cavity. The implication is that electrons achieve peak kinetic energy at a lower accelerating gradient for such cavities. Further studies need to be done in order to understand the underlying theory behind this shift.

In terms of multipacting in the cavity, we assume multipacting sustains if the electron trajectory continues after 20 impacts. Another primary cause of concern for multipacting would be when the impact energy is greater than 20 eV, as this causes the SEY coefficient to be greater than unity hence electron multiplication (Figure 9). We observe from the graph (Figure 12) that when the accelerating gradient is greater than 7 MV/m, the impact energy of the electrons on an average is observed to be 20 eV, thus crossing the threshold for SEY coefficient of unity, hence a potential for multipacting.

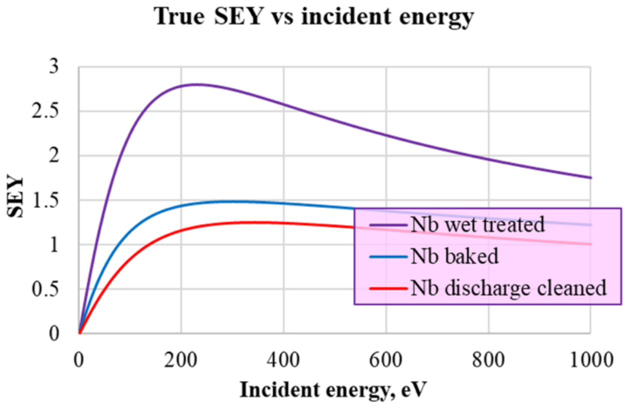


Figure 9: SEY vs Impact Energy for Nb baked at 300K(?)

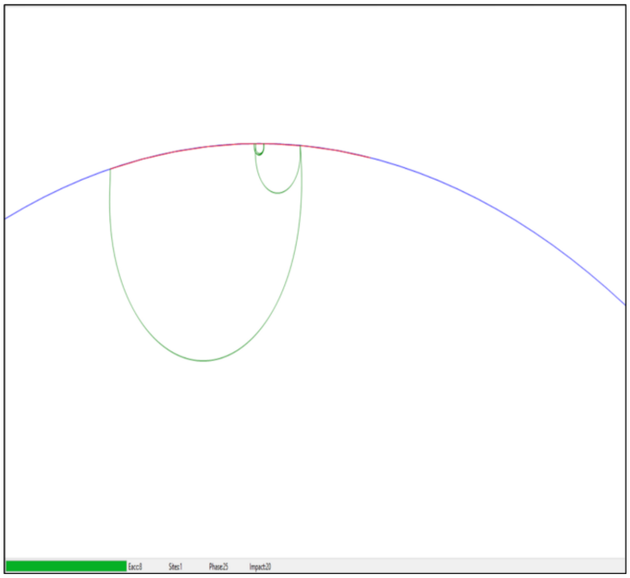


Figure 10: Electron trajectory in LB650 Cavity without Weld

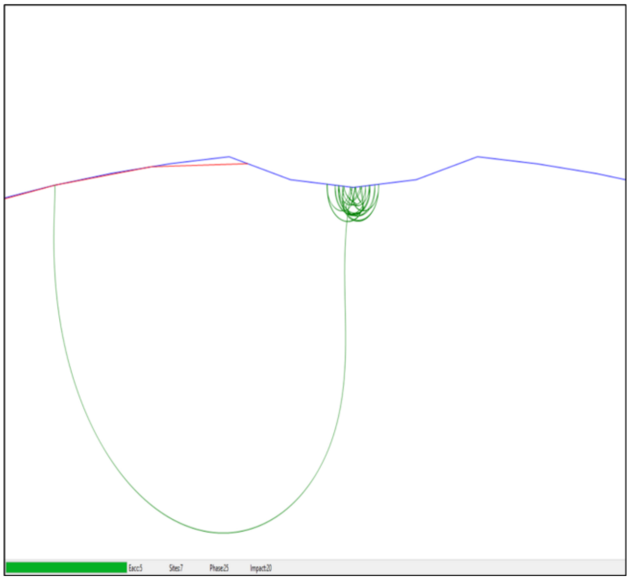


Figure 11: Electron trajectory in LB650 Cavity with Weld

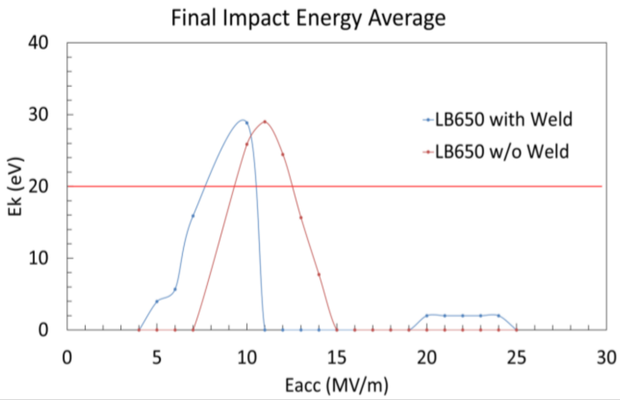


Figure 12: Impact energy vs Accelerating Gradient

CONCLUSIONS AND FUTURE WORK

The analysis of multipacting for LB650 cavity with weld profile is the first of its kind. These results are only a preliminary indication of multipacting. But the simulations' predictions are inconsistent with the experimental results, where multipacting is not observed in the LB650 cavity. Thus, further analysis is required, wherein the more realistic form of electron simulation is accounted for. Such statistical methods include the Monte Carlo method, and Furman and Pivi's secondary emission model [7]. Another avenue for further exploration of MP of cavities with weld profile is the 3D simulation of multipacting with CST Particle Studio, which can take into consideration space charge effects [8] (usually ignored by most multipacting simulation codes) and help develop quantitative parameters of multipacting process such as discharge current, power, energy spectrum, etc.

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