LCLS-II Average Current Monitor Cavity Multipacting Analyses*

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1 Abstract

With an abundance of caution, we undertook two analyses of the possibility of multipacting in the LCLS-II Average Current Monitor Cavity (ACM). The concern is that beam-generated fields might cause multipacting and change the RF characteristics of the cavity, such as the loaded Q or frequency, and lead to erroneous current measurement. Two types of analysis were performed. One used conventional, analytic, order of magnitude estimates for the amount of energy electrons could gain. The other use a full 3-D simulation, including the probes where there is some enhancement of the electric field. For multipacting to occur, at a minimum, electrons must be able to gain enough energy that the secondary emission coefficient is greater than 1, which typically occurs around 100 eV or more. For example, see pp. 183 of [1]. The result of both analyses is that, for the types of beams that might be encountered at LCLS-II, multipacting is not possible because the maximum energy gain is too small to generate secondary electrons. This is due to a combination of the high frequency of the cavity, which limits the time during which electrons can gain energy, and the low fields generated by the beam.

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2 Analytic Estimate

Following the discussion in 'One-Point Multipacting' in [1], we make a rough estimate of the maximum energy gain an electron can get from the RF fields generated by the beam. Electrons gain energy from the local electric field and are turned around by the local magnetic field. The highest energy gain case is the so-called first order case, where electrons are turned around in one RF cycle. In addition we assume the magnetic field strength is just what is required for resonance, and that the electric field is simply the cavity voltage divided by the gap. Both of these assumptions are crude, but only an order of magnitude result is desired.[1]

With these assumptions and integration of Newton's laws for the electron velocity, the maximum energy electrons can gain is of order,

$$K \sim \frac{e^2E^2}{m\omega^2},$$

where e is the electron charge, m is the electron mass, E is the electric field (assumed perpendicular to the local magnetic field), and ω frequency of the cavity field.

Estimates of the cavity voltage due to various beam excitations are given in [2]. The highest cavity voltage is 653 V for an R/Q of 160. It occurs for a hypothetical beam of 1000 pC bunches. That bunch charge is more than three time higher than the operational charge and is an upper bound on space charge limited emission from the cathode.

[1] Field enhancements around the coupler are explore in the Simulation section.

Given the effective gap of 50 mm, $E \approx 653/0.05 = 13\ kV/m$. Carrying out the rest of the calculation we have,

$$K \sim \frac{1.6 \times 10^{-19}(1.3 \times 10^4)^2}{9 \times 10^{31}(2\pi \times 1.3 \times 10^9)^2} \approx 0.5\ V.$$

This is more than two orders of magnitude less than the 100 V needed for secondary emission coefficient to be greater than one, so no multipacting is expected. The combination of low electric field and high frequency, both of which are squared in the energy gain equation, make the maximum energy gain small enough to avoid multipacting.

3 Simulation

An analysis based on simulations was carried out, independently of the analytic analysis, and is discussed in this section. In addition to the general fields in the cavity, the simulation looked in detail at the effects of the electric field enhancement of the loop coupler.

The RF field in the cavity is purely generated by the energy loss of the bunch. The energy loss of a bunch is determined by the loss factor k_{loss}.

$$k_{loss} = \frac{\omega}{4}\frac{R}{Q},$$

$$U = k_{loss}q^2,$$

where q is the bunch charge and U is the energy lost by the charge.

The gap voltage seen by a speed of light particle on the cavity axis due to the energy loss by a bunch of charge q is

$$V_{gap} = \sqrt{\omega U \frac{R}{Q}} = \frac{1}{2}q\omega\frac{R}{Q}.$$

A preliminary design for the 1.3 GHz current monitor cavity has an R/Q of 150. For an 1 nC bunch, the induced gap voltage is estimated about 613 V. This corresponds to an average gap gradient of 12 kV/m (613 V/0.05m, 0.05m is the cavity gap). The peak electric field strength in the center of the cavity gap is roughly a factor of two above the average gradient,

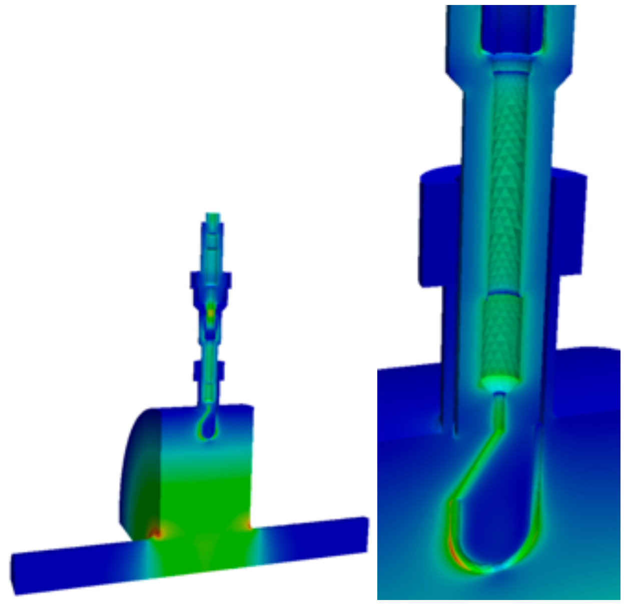

Figure 1: Contour plot of the electric field of the TM mode.

This estimation gives a rough scaling of the electric field distribution shown in Figure 1.

At a preliminary design Q_{ext} of 1300, or lower, the field produced by a bunch will decay to less than 7% when the next bunch comes (at Max 1 MHz). So the field build up due to a multi-bunch beam is not expected to be significant.

There is a field enhancement around coupler loop. Because the loop is placed far away from the high electric field region, the enhanced field on the loop surface is only slightly higher than the electric field at the center of the cavity (which is 24 kV/m). This field enhancement is localized only within a small region around the loop. An electron emitted at near zero velocity on the loop surface would not gain significant energy. Similarly, any electron emitted on the outer surfaces of the cavity where multipacting could potentially exist, would not gain much energy due to the low electric field. This analogy suggests that multipacting is not likely to happen in the current monitor cavity.

To further confirm this analogy, numerical analysis of multipacting was performed using the Track3P/ACE3P multipacting simulation tool developed at SLAC. The RF fields, as shown in Figure 1, were calculated using the eigensolver Omega3P/ACE3P and scaled to the field levels of interest. In the Track3P multipacting simulations, electrons of 2 eV initial energy were emitted from the cavity metal surfaces at different RF phases over a full RF period. These electrons were tracked under the electromagnetic fields until they hit a metal surface at which secondary electrons were emitted. The tracking of electrons continued for a specified number of RF cycles, after which resonant trajectories were determined and the multipacting types were identified. A necessary condition for multipacting is that the trajectory of an electron, after a number of these consecutive emissions, is in resonance with the RF. In a resonant case, if the impact energy of the electron falls in the range of secondary emission yield greater than unity, the resonant trajectory is considered as a multipacting trajectory. This energy range is typically from a coupler of hundred eV to a few hundred eV.

No resonant trajectories were found in the LCLS-2 current monitor cavity.

References

[1] H. Padamsee, J. Knobloch, and T. Hays, *RF Superconductivity for Accelerators.* Wiley Series in Beam Physics and Accelerator Technology, John Wiley & Sons, Inc., 1998.

[2] J. Welch, "Average current monitor beam generated signals," Tech Note LCLS-II-TN-19-01, SLAC, 2019.