RESONANCE EFFECTS OF LONGITUDINAL HOMS IN PROJECT X LINAC*

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Abstract

Results of analysis of losses due to excitation of longitudinal high order modes (HOMs) in the accelerating RF system of the CW proton linac of the Project X facility are presented. The necessity of HOM dampers in the superconducting (SC) cavities of the linac is discussed.

INTRODUCTION

Project X is a multi-MW proton source which is under development at Fermilab [1]. The facility is based on a 3 GeV CW linac [2]. The main fraction of H^- beam from the linac is split into three parts for Mu2e experiment, kaon experiments, and another which is not yet decided. The layout of the linac is shown in Figure 1. It includes three sections based on 325 MHz single-spoke cavities, and a low-energy and a high-energy sections of 650 MHz elliptical cavities with geometrical beta of 0.61 and 0.9, respectively.

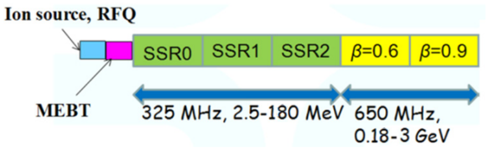

Figure 1: 3 GeV CW Project X linac layout.

The linac provides a beam with an average current of 1 mA and time structure (shown in Figure 2) devised to satisfy specific requirements of the experiments.

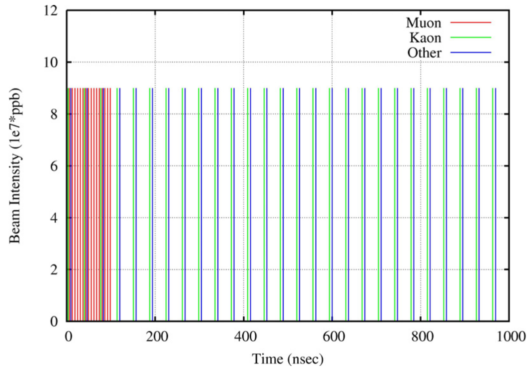

Figure 2: Time structure of the beam. Bunches for Mu2e experiment are shown in red, bunches for Kaon experiment are shown in blue, and bunches for other experiment are shown in green.

Each bunch contains $9 \cdot 10^7$ H^- ions. The bunch sequence frequency for the Mu2e experiment is 162.5 MHz with a total pulse duration of 100 ns and pulse repetition rate of 1 MHz. The bunch sequence frequency for Kaon and other experiments is 27.08 MHz. Figure 3 shows the idealized beam current spectrum, which contains harmonics of multiples of 27.08 MHz and harmonics of multiples of 1 MHz.

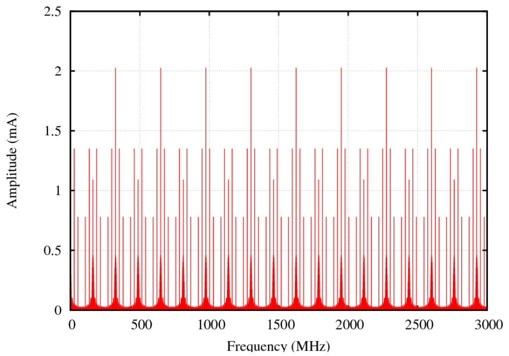

Figure 3: The idealized beam spectrum.

The 5-cell 650 MHz cavities for Project X are currently under development. A critical design decision is to define the necessity of HOM dampers for these types of cavities.

GENERAL

The cumulative effects of HOM excitation have been considered in [3]. There was no significant emittance dilution found. In this paper we calculate losses due to resonant HOM excitation.

The cavity eigenmodes are excited by the passing beam. The main accelerating mode is compensated, but excitation of HOMs leads to the loss of beam power.

An alternating current, $\tilde{I}_n$, with circular frequency, ω_n, passing through the cavity excites HOMs with frequency, ω_m, and impedance, $(R/Q)_m$,with resulting magnetic field

$$\vec{H}_{nm} = \frac{\omega_m\sqrt{\omega_m}}{i\left(\omega_n^2 - \omega_m^2 - i\frac{\omega_n\omega_m}{Q_m}\right)}\frac{\tilde{I}_n}{2\sqrt{W_m}}\sqrt{\left(\frac{R}{Q}\right)_m}\,\vec{H}_m,$$

where $\vec{H}_m$ is the eigenfunction of the mode normalized to energy stored in the cavity, W_m, and Q_m is quality factor. The accelerator definition of $(R/Q)_m$ is used: $(R/Q)_m = V_m^2/\omega_m W_m$ (V_m is the cavity voltage.) If the HOM spectrum is known, one can calculate the total magnetic field excited by a current harmonic $\tilde{I}_n$:

$$\vec{H}^{(n)} = \sum_m \vec{H}_{nm}.$$

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The total power loss caused by HOM excitation can be calculated from the formula

$$P = \sum_n \frac{R_n}{2} \oint \vec{H}^{(n)} \vec{H}^{(n)^*} ds,$$

where R_n is surface resistance. It consists of residual and BCS resistance. Residual resistance was evaluated as 10 nΩ, and the average value of BCS resistance is

$$R^n_{BCS}[\Omega] = \frac{2 \cdot 10^{-4}}{T[K]} \left(\frac{f_n[GHz]}{1.5}\right)^2 e^{-\frac{17.67}{T[K]}},$$

where f_n is frequency of the beam spectrum line, and $T = 2\ K$.

Monopole HOM spectrums for low and high energy sections are shown in the Figures 4 and 5. We assume that the fundamental mode is perfectly tuned and HOM frequencies have Gaussian distribution with r.m.s. of 1 MHz.

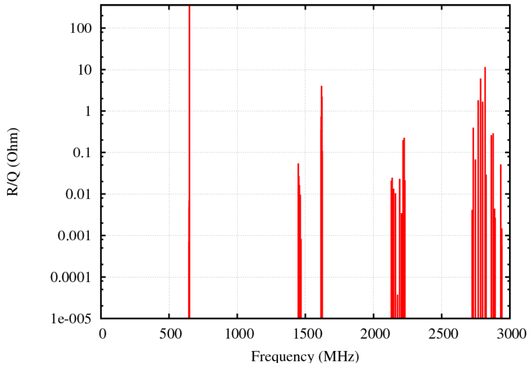

Figure 4: Monopole HOM spectrum for low energy 650 MHz cavity (beta is 0.61).

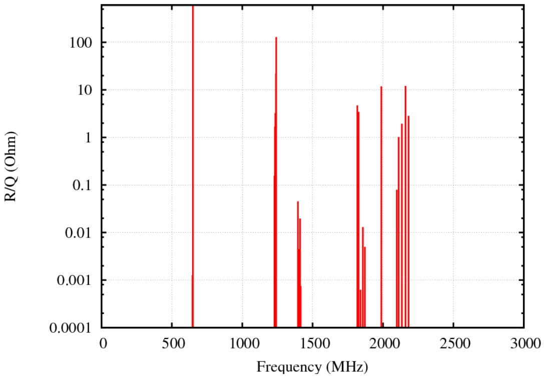

Figure 5: Monopole HOM spectrum for high energy 650 MHz cavity (beta is 0.9).

RESULTS

The dependence of power loss on the beam energy was studied. Quality factors for the HOMs, Q, from 10^7 to 10^{10} were considered. About 3,000 sets of HOMs were simulated for each type of cavity for each value of beta. A range of values of particle velocity β was selected to cover the full range of energy the cavities will be used for. The power loss distribution for the case of the low energy cavity and $Q = 10^{10}$ is shown in Figure 6. Different values of the beam particle beta are shown on the plot.

The results of calculations of the power loss are shown in the Figures 7 and 8 for the low and high energy cavities, respectively. The average power loss and "99% level" were calculated, where "99% level" is the value of losses such that 99% of the simulated cases have losses below this level. One can see that for all cases losses are smaller or about 0.1 mW per cavity, which is negligible compared to approximately of 25 W/cavity losses from the fundamental mode.

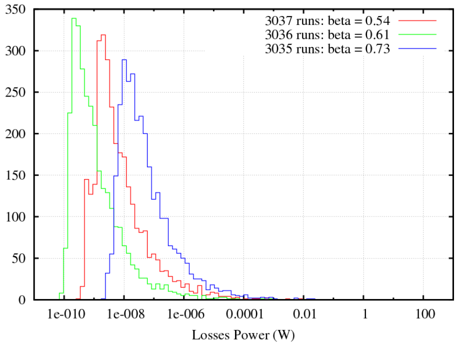

Figure 6: Power loss distribution for the low energy cavity for $\boldsymbol{Q = 10^{10}}$. Beta of 0.54 and 0.73 are considered, in addition to the nominal beta of 0.61.

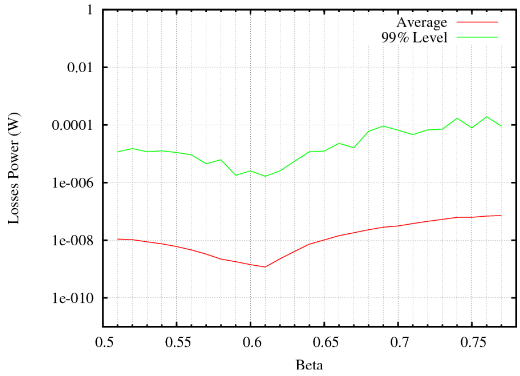

Figure 7: Power loss due to HOM excitation for the low energy cavity as a function of beta. (The nominal beta is 0.61.) The average power loss is shown in red. 99% of simulated cases show losses lower than the green line.

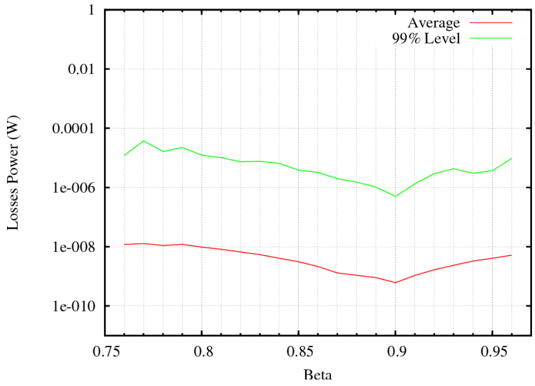

Figure 8: Power loss due to HOM excitation for the high energy cavity as a function of beta. (The nominal beta is 0.9.) The average power is shown in red. 99% of simulated cases have losses lower than the green line.

If a HOM frequency is in resonance with a strong beam spectrum line, losses are significant. Nevertheless, there is a way to reduce them. It was shown in [3] that one can move the HOM frequency away from the resonance. If one detunes the cavity by tens of kHz and then tunes the operating mode back, HOM frequencies change by hundreds of Hz.

As it is shown in Figures 9 and 10, even a 50 Hz displacement from the resonance is enough to reduce losses down to an acceptable level of 1 W per cavity.

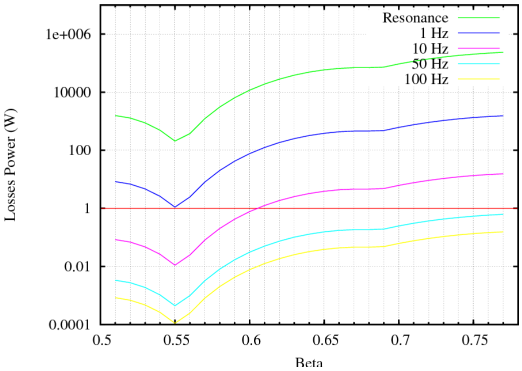

Figure 9: Power loss reduction by HOM frequency shift for a low energy cavity as a function of beta for $\boldsymbol{Q} = \mathbf{10^{10}}$. (Nominal beta is 0.61.)

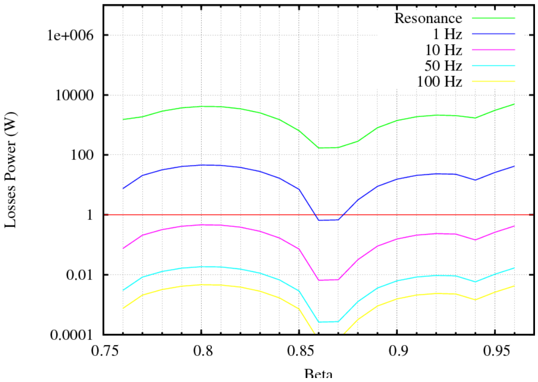

Figure 10: Power loss reduction by HOM frequency shift for a high energy cavity as a function of beta, for $\boldsymbol{Q} = \mathbf{10^{10}}$. (Nominal beta is 0.9.)

The fact, that monopole HOMs are loaded to the main power coupler, limits their quality factors to 10^7–10^8 (Figure 11). The only exception is the fifth pass band of the high energy cavity, which contains a mode with Q-factor greater than 10^9. The preliminary simulations show the possibility to reduce it below 10^7 by increasing the pipe radius from 50 mm to 55 mm.

A similar approach has been used in order to obtain a conservative estimation of losses on the resonant excitation of propagating HOMs with frequencies above the beam pipe cut-off and up to 5.7 GHz. We considered all of these modes to be effectively trapped in the periodic structure of multiple cavities. We varied the length of the beam pipe and found the maximum value of (R/Q). Losses per cavity were found to be of the order of few µW in walls and approximately 50 mW in bellows in the range of Q from 10^6 to 10^9. From the conservative nature of this estimation we conclude that losses into HOMs above cut-off frequency are negligible.

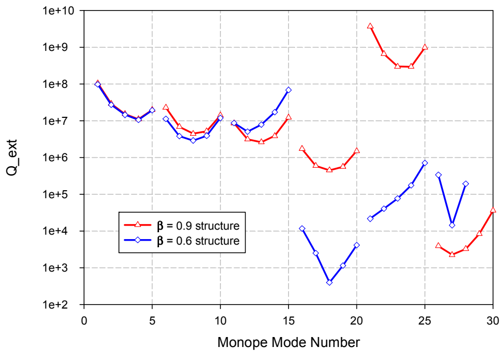

Figure 11: Monopole HOM quality factors for low and high energy cavities, for $\boldsymbol{Q} = \mathbf{10^{10}}$.

DISCUSSION

Results of calculations of the power loss due to HOM excitation show that even for quality factor of 10^{10} these losses are small enough. There is a low probability of approximately 10^{-5} that the HOM frequency is in resonance with a beam spectrum line. In this case it is shown [3] that there is a technique to move the HOM frequency away from the resonance enough to dramatically reduce the power loss. Losses due to HOMs with frequencies above the beam pipe cut-off are extremely small too. Besides, it is shown that the actual quality factor for HOMs will be much smaller than 10^{10}.

Negligible losses may allow removal of HOM dampers from the cavity design for both 650 MHz sections of the linac. HOM dampers are an expensive and complicated part of a SC acceleration structure. Moreover, they create different problems: multipacting, and the leak of power from operating mode. The experience of SNS shows that HOM dampers may cause cavity performance degradation during long-term operation [4]. At the same time, the SNS linac experience does not show any necessity of HOM dampers.

ACKNOWLEGEMENTS

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