# RESONANCE EXCITATION OF LONGITUDINAL HIGH ORDER MODES IN PROJECT X LINAC

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*Abstract*

Results of simulation of power loss due to excitation of longitudinal high order modes (HOMs) in the accelerating superconducting RF system of CW linac of Project X are presented. Beam structures corresponding to the various modes of Project X operation are considered: CW regime for 3 GeV physics program; pulsed mode for neutrino experiments; and pulsed regime, when Project X linac operates as a driver for Neutrino Factory/Muon Collider. Power loss and associated heat load due to resonance excitation of longitudinal HOMs are shown to be small in all modes of operation. Conclusion is made that HOM couplers can be removed from the design of superconducting RF cavities of Project X linac.

## INTRODUCTION

Fermilab is currently developing a multi-MW proton source, Project X [1], which will provide intense muon, kaon, neutrino and nuclei beams, allow study of applications of proton accelerators for energy production, and may become a driver for a future Neutrino Factory and/or Muon Collider. Fig. 1 shows general layout of Project X.

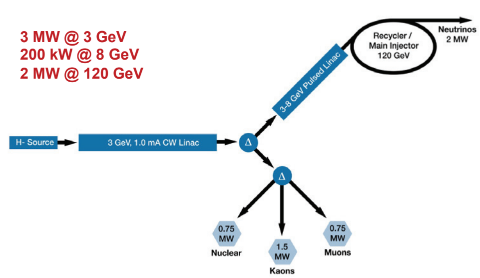


Figure 1: Project X layout.

A key component of Project X is the CW SRF linac, which accelerates bunches of $\sim 16 \cdot 10^7$ $H^-$ ions from 2.1 MeV to 3 GeV. It includes a section of half-wave resonators (HWR) at 162.5 MHz, two sections of single-spoke cavities (SSR1 and SSR2) at 325 MHz and two sections of 5-cell elliptical cavities at 650 MHz, as shown in Fig. 2.

The bunch sequence frequency is 162.5 MHz. A broadband chopper provides the beam structure needed for experiments. Three regimes of operation are considered: 1) bunch timing structure required for muon, kaon and nuclear

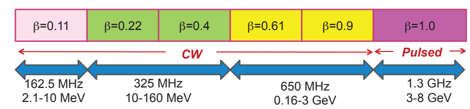


Figure 2: Project X linac technology map.

experiments at 3 GeV, shown in Fig. 3. Average beam current in this mode is 1 mA; 2) 3 GeV structure combined with 10 Hz pulses with a 5% duty factor (DF) for injection into the Fermilab Main Injector (MI) for a 120 GeV neutrino program; 33% of the bunches within pulses are removed to match the phase of $\sim 50$ MHz of MI RF; 3) 3 GeV structure combined with 15 Hz 10% DF pulses, which can be used to drive future Muon Collider; within these pulses, bunches are structured in 1 $\mu$s "micro"-pulses with a 50% DF. Pulsed current in this mode is 5 mA.

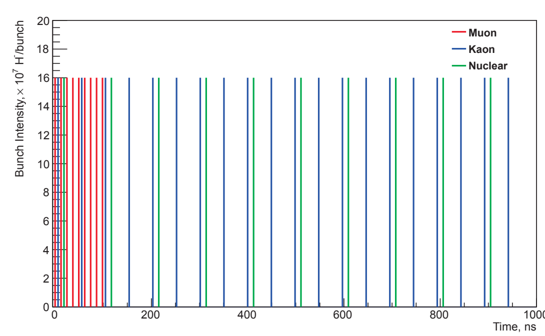


Figure 3: Beam structure for 3 GeV program

Excitation of high order modes in SRF cavities is always a concern. Heating caused by beam power lost to HOMs adds to the cryogenic losses and increases the operational cost of the linac. The interaction of the beam with excited HOMs may also deteriorate the quality of the beam. An analysis of non-propagating HOMs in Project X linac has been presented in [2]. In this paper we extend the results of previous work by: 1) taking into account modifications to the 3 GeV program beam structure, which have been suggested after the publication of [2]; 2) analyzing non-propagating and propagating HOMs; 3) considering combinations of CW and pulsed regimes; and 4) including the calculation of power loss in SSR1 cavities.

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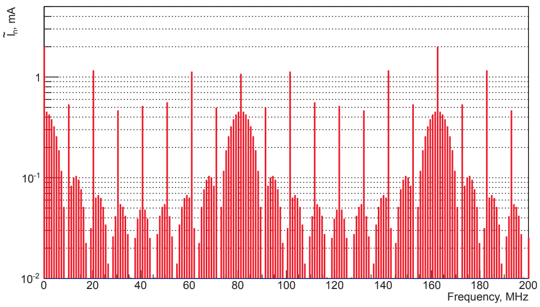


Figure 4: Beam spectrum of 3 GeV program

## METHOD

Following the method outlined in [2], we perform our calculations in the frequency domain. Given the timing structure of the beam we evaluate the spectrum of the beam current. Fig. 4 shows the spectrum for the idealized 3 GeV beam structure, assuming very short bunches of equal charge and in the absence of timing jitter. The main lines are harmonics of 162.5 MHz, 20 MHz and 10 MHz corresponding to the three components of the beam for muon, kaon and nuclei experiments. Sideband lines of 1 MHz quickly fall below 0.1 mA.

The magnetic field of the HOM $m$ with frequency $\omega_m$ and impedance $(R/Q)_m$ excited by an alternating current $\tilde{I}_n e^{i\omega_m t}$ of the beam spectrum line $n$ is

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

where $\vec{H}_m$ is the mode eigenfunction normalized to the stored energy $W_m$, and $Q_m$ is loaded quality factor. The total magnetic field excited by the current harmonic $\tilde{I}_n$ is

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

The total power loss can be evaluated as

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

where the surface resistance is $R_n = R_s^n + R_{BCS}^n$. We use the value of $R_s^n = 10$ n$\Omega$ for the residual resistance and approximate the BCS part as the following [3]:

$$R_{BCS}^n[\Omega] = \frac{2 \cdot 10^{-4}}{T[\mathrm{K}]} \left(\frac{f_n[\mathrm{GHz}]}{1.5}\right)^2 \exp\left\{-\frac{17.67}{T[\mathrm{K}]}\right\} .$$

Here $f_n$ is the linear frequency of the beam current harmonic and $T = 2$ K is the cavity operational temperature.

## RESULTS

During production and surface processing, the shape of the cavities deviates within allowed mechanical tolerances from the idealized shape used in the RF simulation. This results in shifts of the cavity HOM spectrum, while the accelerating mode is tuned to the specifications. Measurements show that the spread of HOM frequencies can be as large as 7 MHz in SSR1 cavities [4], and is about 1 MHz in 9-cell ILC-type cavities[1]. In order to take into account the effect of the HOM frequency spread, we randomly sample HOM frequencies assuming Gaussian distributions with the central values taken from RF simulation and standard deviation varying from 1 MHz (for 650 MHz cavities) up to 7 MHz (for SSR1 cavities). Our results show that a larger spread of HOM frequencies lessens the power loss.

### *650 MHz $\beta = 0.9$ cavities*

In 650 MHz cavities we calculate the power loss for non-propagating and propagating longitudinal HOMs. In general, modes with frequency above the beam pipe cut-off frequency[2] will escape from the cavity into the beam pipe and will not contribute to the cryogenic losses. However, in periodic structures, like a string of cavities in the cryomodule and a string of cryomodules in the linac, some of the propagating modes can become effectively trapped in the cavities. In our rather conservative approach, we assume that all propagating HOMs with frequencies up to 5.6 GHz are trapped inside the cavities and, moreover, we use the maximum value of the modes' $(R/Q)$ with respect to the beam velocity $\beta$.

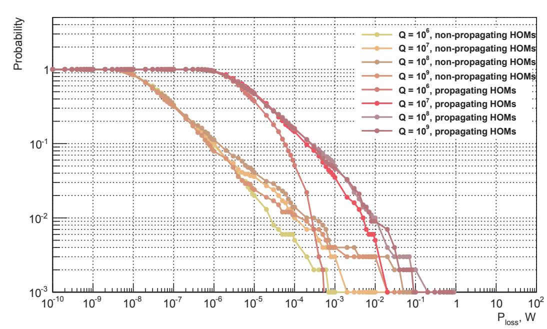


Figure 5: Power loss in 650 MHz cavities for 3 GeV beam structure

*Beam timing structure for 3 GeV program.* Results of the calculation of power loss for 1 mA average beam current are shown in Fig. 5 for loaded quality factors ranging from $10^6$ to $10^9$ for both propagating and non-propagating modes. The plot shows the tail distribution of the power loss per cavity, or the probability to find $P_{\mathrm{loss}}$ higher than a certain value on the $x$-axis. With a probability of 99%, the power loss is less than a fraction of a mW for non-propagating modes. For the propagating HOMs, $P_{\mathrm{loss}}$ will not exceed 10 mW with the same probability.

[1] T. Khabiboulline and P. Berrutti, Private communication.

[2] Cut-off frequency is the frequency of the lowest waveguide mode of the beam pipe. In 650 MHz section of Project X linac the beam pipe radius is 5 cm, which corresponds to the cut-off frequency of 2.3 GHz.


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*Pulsed regime for injection into MI.* Because of the small duty factor of 5% and chopping of 33% of bunches during the pulses, there are only very minor modifications to the beam current spectrum of the 3 GeV timing structure. Indeed, in this case, 10 Hz sidebands are added to 1 MHz lines of the 3 GeV spectrum shown in Fig. 4. The amplitude of these lines falls quickly from 0.1 mA to the sub-$\mu$A level. Since we are already considering variations of HOM frequencies of the order of 1 MHz, the effect of MI pulses on the power loss is negligible.

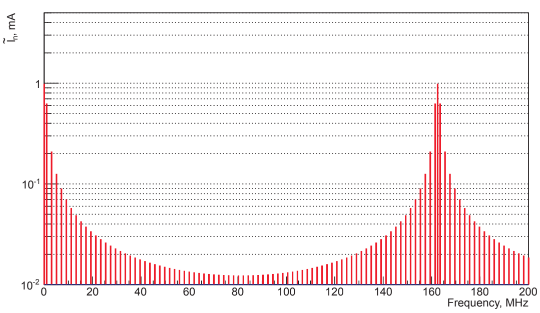


Figure 6: Beam spectrum of Muon Collider pulses

*Pulsed regime for Muon Collider operation.* The spectrum of the beam current corresponding to the pulses for Muon Collider operation is shown in Fig. 6. The main lines of this spectrum are the harmonics of the bunch sequence frequency, 162.5 MHz, with an amplitude of about 1 mA[3]. The amplitude of the sideband lines, separated by 2 MHz (due to 50% DF during the "micro"-pulse), drops quickly below 0.1 mA. Fig. 7 shows distribution of power loss for the Muon Collider pulses for both propagating and non-propagating HOMs for the quality factors in the range from $10^6$ to $10^9$. One can see from this plot, that with a probability of 99.5%, losses will be not higher than 1 mW during Muon Collider operation.

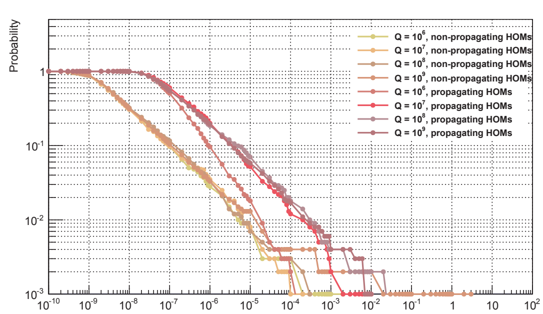


Figure 7: Power loss in 650 MHz cavities for Muon Collider beam structure

[3] Note that the average pulsed current is 5 mA, but there is a 10% pulse DF and 50% DF at the 1 $\mu$s "micro"-pulse level.

### *SSR1 cavities*

The spectrum of longitudinal HOMs of SSR1 cavities is quite sparse, compared to that of the 650 MHz elliptical cavities. The mode impedance, $(R/Q)$, falls quickly with frequency and is of the order of a few m$\Omega$ at about 2 GHz. Given that, we do not expect large losses in SSR1 cavities. Indeed, the results of the simulation, shown in Fig. 8, confirm these expectations: the probability to encounter losses above 10 $\mu$W is less than 0.5%.

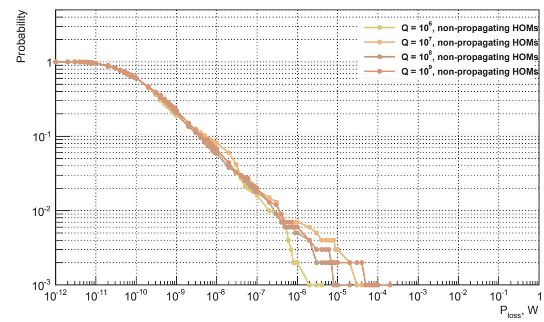


Figure 8: Power loss in SSR1 cavities for 3 GeV beam structure

## CONCLUSION

We studied resonant excitation of the longitudinal HOMs in 650 MHz $\beta = 0.9$ and SSR1 SRF cavities of the Project X CW linac. We considered various modes of linac operation: a CW regime for the 3 GeV physics program with an average current of 1 mA, and two pulsed regimes for a 120 GeV neutrino program and Muon Collider combined with the CW mode. We performed calculations of beam power loss and the corresponding cryogenic load for non-propagating and propagating HOMs for the range of loaded quality factors from $10^6$ to $10^9$. We found that in all cases power losses are small and the probability for losses to exceed 10 mW is less than 1%. We conclude that HOM couplers are not needed for the Project X cavities.

## ACKNOWLEDGMENT

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