# HOM AND IMPEDANCE STUDY OF RF SEPARATORS FOR LCLS-II*

S. U. De Silva#, B. R. P. Gamage, R. G. Olave, J. R. Delayen, G. A. Krafft, T. Satogata
Old Dominion University, VA 23529, USA

*Abstract*
The LCLS-II upgrade requires an rf spreader system to guide bunches into a switchyard delivering beam to two undulators and the primary beam dump. The beam pattern therefore needs a 3-way beam spreader. An rf deflecting cavity concept was proposed that includes both superconducting and normal conducting options. We characterize the higher order modes (HOM) of these rf separator cavities and evaluate beam dynamics effects due to potential HOM excitation. This study includes both short term wake and multi-bunch effects.

## INTRODUCTION

The LCLS-II upgrade includes a superconducting linac that will deliver an electron beam with energy of 4 GeV to one of three destinations of the SXR undulator, the HXR undulator and the beam dump. The beam switching and transporting system that separates the beam therefore, requires a three-way beam spreader [1]. Among the options considered for the beam separation are fast magnet kicker systems or a set of rf separator cavities.

An rf separator system operating at a frequency of 325 MHz is required to provide a transverse voltage of 4.0 MV that deflects the beam in vertical direction with a separation of 1 mrad [1].

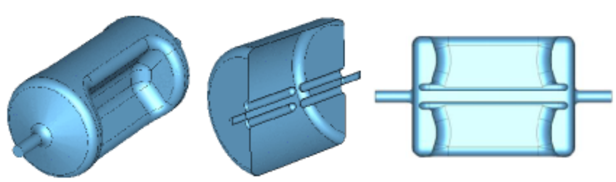

Figure 1: The three rf separator designs: superconducting rf-dipole design (left), normal conducting 4-rod design (center) and normal conducting rf-dipole design (right).

Three preliminary cavity options have been studied, including a superconducting rf-dipole design and two normal conducting designs: the 4-rod design, and normal conducting version of the rf-dipole design [2]. The design requirement of 4.0 MV can be achieved with one superconducting rf-dipole cavity, or by 6 cavities for each of the normal conducting cavity options.

The LCLS-II linac is expected to accelerate an electron beam with an average beam current of 0.02 mA consisting of very short bunches and high bunch repetition rate. The operating beam parameters are shown in Table 1.

The beam may generate single pass beam effects including both transverse and longitudinal effects. This paper presents the higher-order mode properties with further analysis of longitudinal and transverse impedances for the superconducting rf-dipole cavity.

Table 1: Operational Electron Beam Parameters

| Parameter | Nominal Value | Range | Units |
|---|---|---|---|
| Electron energy ($E_f$) | 4.0 | 2.0-4.0 | GeV |
| Electron bunch charge ($Q_b$) | 0.1 | 0.01-0.5 | nC |
| Bunch repetition rate (CW) ($f_b$) | 0.2 | 0-1 | MHz |
| Average current ($I_{avg}$) | 0.02 | 0.001-0.3 | mA |
| Peak current ($I_{pk}$) | 1000 | 500-1500 | A |
| rms bunch length ($\sigma_z$) | 8.3 | 0.6-52 | $\mu$m |

## LOM AND HOM PROPERTIES

The lower-order mode (LOM) and higher-order modes (HOM) are determined for the three rf-separator cavities using CST Microwave Studio and compared to the values obtained from Omega3P package of the SLAC ACE3P suite [3]. The modes are categorized as accelerating modes and transverse modes with a net deflection in the horizontal and vertical directions, respectively.

### *Superconducting RF-Dipole Cavity*

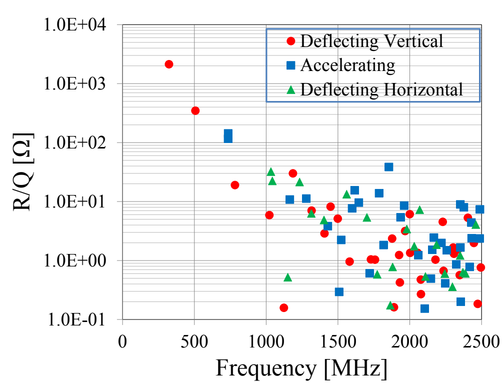


Figure 2: Mode spectrum of the superconducting rf-dipole cavity.

The HOM spectrum of the superconducting rf-dipole design is shown in Fig. 2. The fundamental deflecting mode is the lowest mode with no lower-order modes existing in the rf-dipole geometry where the $[R/Q]$ values decrease as a function of the mode frequency.

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#sdesilva@jlab.org

### *Normal Conducting 4-Rod Cavity*

Figure 3 shows the HOM spectrum of the normal conducting 4-rod cavity. This particular design has a lower mode, which is an accelerating mode at 226 MHz. The nearest LOM and HOM have low frequency separation from the fundamental deflecting mode with narrow mode separation.

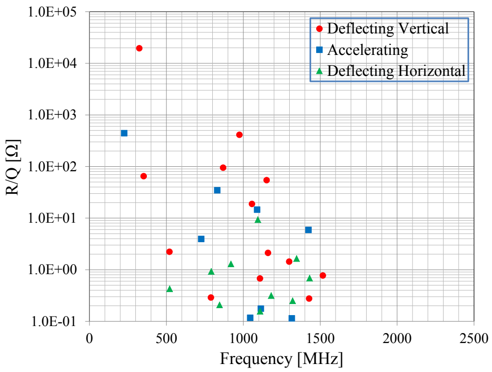


Figure 3: Mode spectrum of the normal conducting 4-rod cavity.

### *Normal Conducting RF-Dipole Cavity*

The HOM spectrum for the normal conducting rf-dipole cavity shown in Fig. 4 has few higher-order modes with considerably high [$R/Q$]. As frequency increases the modes are well separated with decreasing [$R/Q$] in the order of 10 or lower.

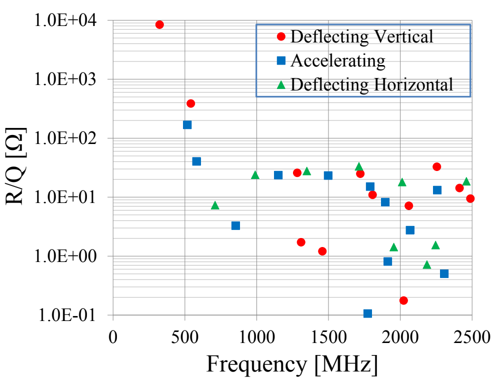


Figure 4: Mode spectrum of the normal conducting rf-dipole cavity.

The unloaded quality factors of the excited HOM in normal conducting rf cavities are in the order of $10^4$~$10^5$ compared to $10^8$~$10^{10}$ in superconducting rf cavities. Therefore, the effects due to HOM excitation in normal conducting cavities are negligible compared to that from superconducting cavities. Further analysis on beam cavity interactions are carried out for the superconducting rf-dipole cavity option.

## BEAM LOADING

A beam traversing through a deflecting cavity may excite all the modes including longitudinal and transverse modes [4, 5]. Subsequently, the beam loses energy due to the beam-induced voltage, which also adds to the cryogenic losses in superconducting cavities.

The superconducting rf-dipole cavity has a transverse [$R/Q$] of 2130 Ω and sees a reduction in the transverse voltage by 0.2% at an offset of $\Delta x$ = 5 mm. The beam loading in the fundamental mode for an off-axis beam requires about 1.5 kW with a resultant loaded $Q$ ($Q_L$) of $5.5\times10^6$ for the average beam current ($I_{avg}$) of 0.02 mA.

The beam-induced transverse voltage in the fundamental deflecting mode [4] is

$$V_{t,induced} = \left[\frac{R}{Q}\right] Q_L k \Delta x I_{avg} = 8 \text{ kV} \qquad (1)$$

where $k$ is the wave number. The corresponding induced power is 0.16 W.

The beam-cavity interactions due to excitation of HOMs can be categorized as single bunch effects and multi-bunch effects. These effects are primarily governed by the decay time of each excited modes given by $\tau_d=2Q_{ext,n}/\omega_n$ where $Q_{ext}$ is the coupled quality factor and $\omega_n$ is the mode frequency.

## SINGLE BUNCH EFFECTS

The superconducting rf-dipole cavity is designed with a fundamental power coupler (FPC) that couples at a $Q_L$ of $5.5\times10^6$. The study presented here evaluates the feasibility of extracting the excited HOM power through the FPC and operating the cavity with no additional HOM couplers. Therefore, the $Q_{ext}$ values for each mode are determined by considering the coupling of HOMs to the FPC as shown in Fig. 5. Deflecting modes with a net deflection in the vertical direction and most of the accelerating modes couple to the FPC, whereas the modes with the net deflection in horizontal direction do not. For those modes that do not couple to FPC, the decay time is governed by the unloaded quality factor ($Q_{0,n}$) at 4.2 K.

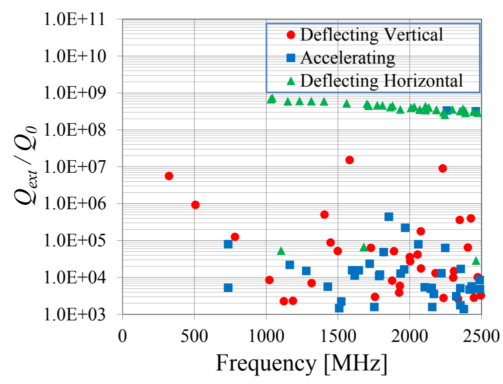


Figure 5: $Q_{ext}$ as a function of mode frequency for the superconducting rf-dipole cavity.

The single bunch effects in its simplest form do not produce regenerative effects as the wake potential from the bunch decays before the arrival of the next bunch. The LCLS-II beam has a bunch repetition rate of 1 MHz with a bunch separation of 1.0 $\mu$s. The decay times of most modes are higher than the bunch separation therefore; the beam-cavity interactions are mainly due to the multi-bunch effects.

## MULTI BUNCH EFFECTS

The bunch cut-off frequency for an rms bunch length of 0.6 $\mu$m given in Table 1 relates to a limit of $f_{rms}$=500 GHz, up to which the effects due to HOM excitation needs to be evaluated. However, the modes above the cut off frequency related to the beam aperture radius propagate out of the cavity through the beam pipe. As shown in Fig. 2 above ~2GHz the resultant [$R/Q$] drops significantly therefore, multi-bunch effects are calculated for a reasonable range of 2.5 GHz.

### *Longitudinal Effects*

Accelerating modes or monopole modes get excited as the beam traverses on-axis through the cavity. The HOM excitation due to accelerating modes contributes directly to the power loss in the beam. The induced voltage acts back on the beam and may lead to energy spread in the beam [6].

In this particular case, the excited modes contribute to the dynamic heat load through the FPC. The modes that are not coupled to FPC dissipate through the cavity surface increasing cryogenic losses. Figure 6 shows the induced beam power for the accelerating modes up to 2.5 GHz. The total induce beam power is ~32 mW with a total induced voltage of 0.11 kV that contributes negligibly to the energy spread.

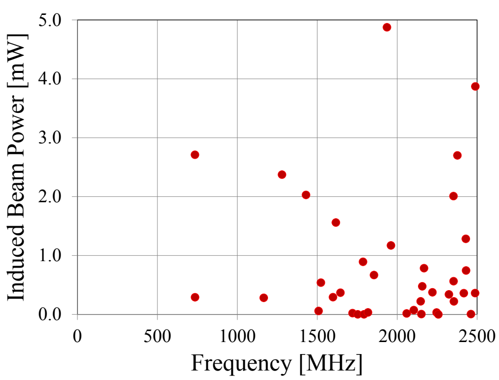


Figure 6: Induced beam power due to excitation of accelerating modes.

### *Transverse Effects*

Transverse effects are generated by a train of bunches that passes through the cavity at an offset. These effects may lead to beam instabilities and, if not controlled, to a beam break up situation, especially with multi-pass beams. The excited transverse modes may deflect the beam further enhancing the transverse effects. For a single pass beam the regenerative beam effects gives a threshold current above which the effects grow exponentially [5]. The threshold current is given by

$$I_{th} = \frac{\pi^3 E_f k}{2 Z_t L}, \tag{2}$$

where $E_f$ is the beam energy, $k$ is the wave number, $L$ is the length of the cavity and $Z_t$ is the transverse impedance. The operational beam current must be below the threshold current to prevent generating any transverse beam instabilities. Therefore, the corresponding transverse impedances must satisfy the following

$$Z_{t,n} = k_n \left[\frac{R}{Q}\right] Q_{ext} < \frac{\pi^3 E_f k_n}{2 L I_{avg}}. \tag{3}$$

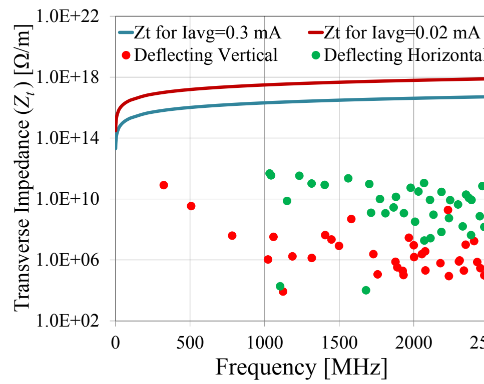


Figure 7: Transverse impedance from HOM and due to average beam current.

Figure 7 shows the transverse impedance for modes with a deflection in both vertical and horizontal directions. The horizontal deflecting modes have higher impedances calculated with the unloaded quality factor. The impedances due to transverse mode excitation are significantly below to that from the impedances due to the nominal average current of 0.02 mA, also for the maximum of 0.3 mA in the average current range.

## CONCLUSION

The multi-bunch effects evaluated here do not produce significant longitudinal or transverse effects that lead to beam instabilities. The induced beam voltage is very low for the modes with high [$R/Q$]. However, the excited HOMs increase the total power dissipation adding to the cryogenic losses at 4.2 K. The 325 MHz rf-dipole cavity option therefore can be operated with LCLS-II design beam parameters with no additional HOM couplers.

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